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Changing of scrap handling to increase the net value of Villares Metals

Masterarbeit

eingereicht von

Clemens Krapscha

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Abstract

Villares Metals is a special steel producer in Brasil and is operating two electric arc furnaces. One main topic of this master thesis was the analysis of the electric arc furnace process in order to evaluate the main causes of downtime as well as the influence of the scrap size, the elctric power level and the concept to charge premelted scrap on the operation of the furnaces.

For the evaluation various tests in the melt shop were carried out. Charges with three different sizes of scrap with the same chemical composition were used to test the effect on tap to tap time of the electric arc furnaces. Chips were charged as scrap with the smallest size and the lowest density and blocks of premelts were tested as scrap with the biggest size and highest density. Subsequently scrap with a fairly optimized size distribution was used. To guarantee a fast and safe scrap size reduction, rolling tests with premelted material were performed.

A second topic of the thesis was the physical metallurgica investigation of the production of a supermartensitic, stainless steel. This steel is produced out of pre melted material. Pre melted scrap allows a reduction of expensive elements beside phosphorus reduction.

The impact of phosphorus on material properties was investigated. The target was to change the production by modifying the chemical composition of the material. If a higher content of phosphorus is allowed, pre melts with low phosphorus contents are not necessary. This would simplify the process and would reduce the costs.

Tensile tests, charpy impact tests and pitting corrosion tests were made to demonstrate the effect of phosphorus on supermartensitic stainless steels. The microstructure was analyzed too.

It was found that Mo and Fe forms a Laves phase, which weakens the segregation of P to the grain boundaries. In addition, a finer grain with increasing phosphorus content was found. These results had a strong influence on various test results.

Kurzfassung

Im Rahmen der Diplomarbeit wurde die Verfahrweise zweier Elektrolichtbogenöfen untersucht und die Hauptursachen für Stillstandszeiten analysiert.

Die Reduzierungen der Stückgrößen von Schrotten, höhere Energien für den Elektrolichtbogenofen und Konzepte mit Vorschmelzen wurden auf ihre Wirtschaftlichkeit überprüft.

Zur Ermittlung der für die Berechnung benötigten Daten wurden verschiedene Versuche durchgeführt. Je Ofen wurden drei Schrottzusammenstellungen gewählt, die sich in ihrer chemischen Zusammensetzung sehr ähnlich waren, sich jedoch in ihrer Stückgröße wesentlich unterschieden. Um eine Zusammenstellung mit möglichst kleinen Stückgrößen zu simulieren, wurden Chargen mit fast 100% Späne als Schrott zusammengestellt. Chargen mit großen Stückgrößen wurden durch vorerschmolzene Blöcke realisiert. Anschließend wurde bei jedem Ofen eine Zusammenstellung gewählt, bei der Schrott mit vermeintlich optimaler Stückgrößenverteilung eingesetzt wurde. Um diese Stückgrößen herzustellen, wurden an vorerschmolzenen Brammen Versuchswalzungen unternommen, um ein rasches und sicheres Reduzieren des Querschnittes zu garantieren.

Des Weiteren wurde die Herstellung eines supermartensitischen, rostfreien Stahles mittels Vorschmelzen genauer untersucht. Das vorerschmolzene Material ist wichtig, um den geringen Phosphorgehalt ohne Abbrand teurer Legierungselemente zu bewerkstelligen. Ziel war den Einfluss des Phosphors auf das Werkstoffverhalten des Materials zu analysieren um die Produktion durch Veränderung der chemischen Zusammensetzung zu vereinfachen und zu verbilligen. Ein höherer Phosphorgehalt würde zu einer Herstellung ohne Vorschmelzen führen und den Prozess wesentlich günstiger gestalten. Um den Einfluss des Phosphors darzustellen wurden mechanische Kennwerte aus Kerbschlagbiegeversuchen, Zugversuchen und Lochfraßkorrosion ermittelt. Auch Gefügeuntersuchungen wurden durchgeführt.

Die Resultate wurden miteinander verglichen und die Auswirkungen des Phosphors auf das Materialverhalten eines supermartensitischen, rostfreien Stahles analysiert.

Es zeigte sich, dass Molybdän und Eisen eine sogenannte Laves-Phase bilden, die die Seigerung des Phosphors an die Korngrenzen behindert. Außerdem wurde mit steigendem Phosphorgehalt ein zunehmend feineres Korn festgestellt.

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Affirmation

I hereby declare that the master thesis submitted was in all parts exclusively prepared on my own, and that other resources or other means (including electronic media and online sources), than those explicitly referred to, have not been utilized.

All implemented fragments of text, employed in a literal and/or analogous manner, have been marked as such.

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Clemens Krapscha

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General Formular Symbols

[ ]	Melt
( )	Slag phase
R$	Real (Brazilian Currency)

Acronym

LfM	Chair of Ferrous Metallurgie
VM	Villares Metals
EAF	Electric Arc Furnace
LF	Ladle Furnace
VIM	Vacuum Induction Melting
VOD	Vacuum Oxygen Decarburation
VD	Vacuum Degasing
VAR	Vacuum Arc Remelting
ESR	Electro Slag Remelting
P5000	Forging Press with about 50MN
P2000	Forging Press with about 20MN
HSS	High Speed Steel
VSM13A	Steel Brand of Villares Metals
VM	Steel Brand of Villares Metals
VMO	Steel Brand of Villares Metals
H11	Tool Steel Brand
H13	Tool Steel Brand
AC	Alternating Current
DC	Direct Current

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1 Introduction

Higher societal requirements relating to economical agreeability, performance and cost efficiency always tend towards more precise production processes and a higher quality of the total amount of products [4], which is achieved by decreasing the number of products with failures [4]. To achieve a high customer satisfaction, companies around the world have to work on these tasks. Villares Metals produces special steel products in Brazil. The company has a very good reputation on the national and international markets. Nevertheless, Villares Metals is competing on these markets against a lot of other excellent special steel producers. With incremental changes and occasional large-scale improvements, Villares Metals continually tries to always be one step ahead of the competition.

The Oil and Gas market is of especial interest to the company. Over the next couple of years a significant increase in worldwide oil consumption is expected [29]. Reservoirs, where oil or gas can easily be extracted, are not common anymore. In addition, drilling processes and extraction of the resources are becoming more and more complicated [29]. Materials with special properties are required in high quantity and extraordinary quality. Villares Metals is an expert in delivering such materials, which have to operate under extreme conditions.

The restrictions of products used in the oil and gas industry are very high. Elements such as P, S, Sn, Pb and others, are classified as steel tramps [4]. The tramp quantity in such special materials has to be very low in order to fulfil requirements. The oil and gas industry is extremely sensitive about phosphorus because of its tremendous effects on steel [30]. However, in recent years, the demand for ultra-low phosphorus steel has increased [29]. Higher-efficiency dephosphorization has been required in the metal pre-treatment and decarburization processes in order to reduce refining costs and minimize slag generation [1].

1.1 Villares Metals

Villares Metals is a special steel company in Brazil. It is located about 100km west of Sao Paulo, close to the cities of Sumare and Campinas. The company has 3 sales departments in the Brazilian market and one in the Netherlands, to provide a better local contact and service to the customers. The production plant with its sales departments is part of the Austrian VÖST-Alpine Special Steel Division.

The company itself has about 1500 employs in four different departments: steel plant, forging, blooming/rolling and finishing with heat treatment. The production quantity of the year 2013 was about 13500 tons with an average product price of more or less 3 € per kg.

1.1.1 History of Villares Metals

The first company which became one of the founding companies was Aco Villares S.A. in Sao Caetano. This company was established in 1944 and was mainly producing bars, plates and grey cast parts. The company was growing fast and was regularly installing new big equipment like Electric Arc Furnaces and Rolling Mills. In 1957 was the year when the former company Böhler and Acos Villares made their first small cooperation. Engineers from Villares Acos got technical assistance and trainings from European engineers.

In 1988 Aco Villares S.A. bought the two companies of Nosso Senhora Aparecida and Aco Anhanguera. The following year, the company installed a sub company in Europa. This sub company was named Villares Steel International B. V. and was located in Dordrecht in the Netherlands. 1996, Villares took over Elektrometal and renamed the whole group Villares Metals S.A. The factory at Sao Caetano do Sul in the state Sao Paulo was closed and a lot of the equipment was transferred to Sumare, close to Campinas. Sumare is a city in the state of Sao Paulo too.

In 2000, a Spanish company named Sidenor, bought Villares Metals. The biggest investment was a new 3000 ton press.

2004, the Austrian company Böhler-Uddeholm AG bought Villares Metals S.A. and three years later the Austrian company was bought from another big Austrian steel company, named voestalpine. A new group division was established named Special Steel. This division includes the main companies of the former Böhler-Uddeholm AG.

At the same time, Villares Metals installed the most modern multi rolling mill of all of America. One year later a brand new 5000 ton press was built up and 2011 the introduction of an own distribution centre took place. The distribution centre is located in Joinville in Santa Catarina.

Today, Villares is a very important production company of the Voestalpine Special Steel division. It supplies the national Brazilian market as well as the international market with high end steel products. [32]

1.1.2 Product Mix of Villares Metals

Villares Metals is famous for the high quality of its special steel products. The most produced steel grades are:

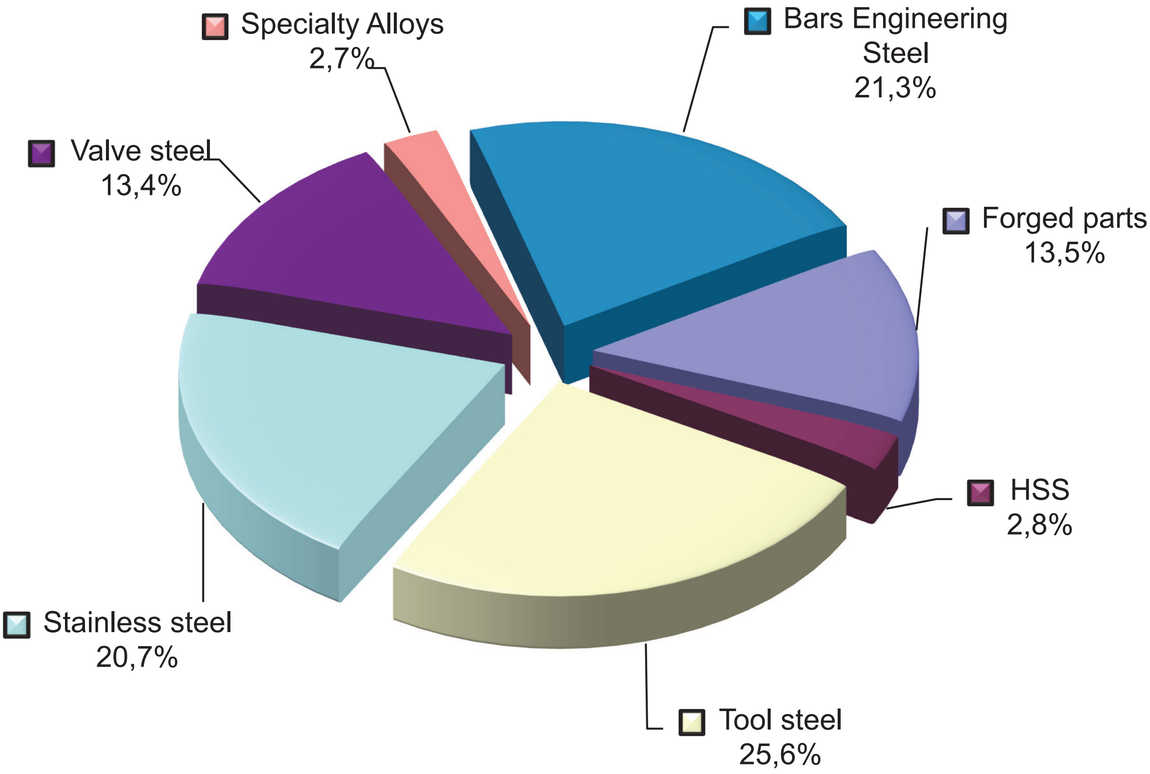

Figure 1-1: Product Mix of Villares Metals in 2012 (% of annual tons) [31]

The main market areas of Villares Metals are in Brazil. 60% of the produced quantity is for the domestic market. Half of the exported materials are for the North American market. 25%

of the exported goods are for Europe and 25% for South America and Asia combined. Over the last few decades, the amount of exported goods has increased [31].

1.2 General Information about Steel

Iron is a material, which fits perfectly as a construction material to many different requirements. The reason for this is the enormous range of adjustable characteristics, for which two properties are mainly responsible. The first one is the possibility to implement non-ferro atoms in the microstructure of the material, which interact with other atoms in many different ways. The second important point is the allotropic transformation of the crystal system. With these two possibilities, it is possible to change all of the characteristic properties of iron, within certain limits [33].

The high quantity of different types of steel with different properties means that the number of standardized steels is also enormous [18]. Historically, different countries have different standardizing systems and companies create special names for better marketing for the same materials.

In order to not get completely lost in the jungle of steel designations, the DIN EN 10020 categorizes steel in two different ways [18]

- *“The chemical composition”*
- *“Main application and property characteristics”*

The following types of steel are distinguished [18]:

- *“Unalloyed steel has an alloying content under a certain limit for each element”*
- *“Alloyed Steel grades reach these limits or have higher contents of specific elements than the limit allows”*

The distinctions between the main quality classes are [18]:

- *“Quality steel, which is unalloyed or alloyed, but has no uniform response to heat treatment. It also has no specific requirements relating to the purity of non-metallic inclusions.”*
- “*Special Steel, which can be also unalloyed or alloyed, is intended to be heat-treated. Through very precise chemical composition and special production and testing conditions, diverse performance characteristic are reachable. For example, high tensile strength within narrow tolerances combined with good deformability and weldability. Because of the special production route, special steel is purer than quality steel. The maximum content of phosphorus and sulphur in the melt is*

> *≤0.035% for each of these elements. Special steel is accordingly well suited for the production of heavy used parts and as additional material for welding.”*
>
> A more precise nomenclature is the deviation of special steel into construction steels and mild steel (unalloyed mild steel, tempered steel, machining steel, spring steel, case hardened steel, heat resisting steel, cold tough steel) [18]. All of these steel types also have their own specific properties.

Villares Metals produces special steel of high quality. The detailed product portfolio is shown in **Figure 1-1**.

1.3 Effects of Tramp Elements on Steel

Every tramp, including chromium, molybdenum, vanadium etc, is a steel hardener [4, 35]. Only about one-third to two-thirds of chromium can be removed. Fortunately, V is seldom high enough to be troublesome, although makers of some high alloy heat resisting steel would object to this statement [4]. If steel is hardened, its cold formability goes down – and formability is a basic prerequisite of light gage deep drawn steels, cold extrusion steels and others [33].

Low melting contaminants tend to segregate into steel grain boundaries. Copper and tin have this unfortunate tendency, which is grossly increased by sulphur in the steel or from reheating furnace fuel. Arsenic, antimony and nickel sulphides fall into the same category [4]. Consequently, steel high in these elements, especially if carrying more than about 0.05% sulphur or with surface enriched by sulphur absorbed from the fuel, becomes increasingly prone to surface cracks [33]. Entire heats had been scrapped in account of grossly torn billet corners when tin + arsenic + antimony exceeded 0.1%.

Steel for nuclear applications must have practically zero cobalt, which behaves like nickel since it is not oxidized out. Specifications usually call for a maximum of 0.001% Co. Lead may be more lenient, at a maximum of 0.002%. For some enamelling applications, copper is specified as a maximum of 0.03%. In many high alloy grades the sum of Sn + As + Sb + Pb must not exceed 0.02% [4].

1.3.1 The Effects of Sulphur on Steel:

Sulphur has a positive effect on steel when good machinability is desired [34]. In some other steel products, sulphur content is refined to its minimum, due to its negative effect on the mechanical properties. The following effects of sulphur become more significant when the oxygen content is successfully reduced [9].

- *"Formation of undesirable sulphides, which promote granular weaknesses and cracks in steel during solidification."*
- *"It lowers the melting point and the inter-granular strength and cohesion of steel."*
- *"Sulphur contributes to the brittleness of the steel and, when it exists in its sulphide phase, it acts as stress raiser in steel products."*

To counter the negative aspects of sulphur, manganese is added as an alloying element to the steel. Manganese and sulphur combine to form manganese (II) sulphide. In some special cases, manganese (II) sulphide in steel is desired to increase the machinability of the material, which is achieved by breaking the chips [34].

1.3.2 The Effect of Copper on Steel

Copper has two main effects on the properties of steel. Copper increases the weather resistance and decreases the fracture strain significantly [34].

Even a little amount of copper in the microstructure of special steels is not adaptable. Copper is one of the elements with the lowest affinity to oxygen [9]. It is very difficult to decrease the percentage of copper in contaminated steel [3].

For this reason, a very organised and functional scrap sorting is necessary.

1.3.3 The Effect of Hydrogen on Steel

This element decreases the elongation and constriction without increasing the yield and tensile strength. Hydrogen is responsible for the formation of unwanted flakes. During etching, hydrogen can enter the microstructure of steel and form bubbles. At high temperatures most hydrogen decarburises steel [34].

1.3.4 The Effect of Nitrogen on Steel

This element can occur as a steel parasite, as well as an alloying element [9]. It is harmful because it decreases the toughness by excretions. It can also cause aging sensitivity and blue brittleness in steel [34].

Besides this, it is possible that the nitrogen will initiate inter-granular stress corrosion cracking in carbon and low-alloyed steel [9, 24, 34]

1.3.5 The Effect of Arsenic on Steel

Arsenic reduces the weldability and the toughness and increases the temper brittleness. It constricts the austenitic area and has a strong tendency to segregate, similar to phosphorus. However, the elimination of segregation by diffusion annealing is even more difficult than with phosphorus [34]

1.3.6 The Effect of Antimony on Steel

This element is a steel tramp because of the increasing brittleness that comes as a result of an increased arsenic content. Arsenic constricts the austenitic area of the steel [34].

1.3.7 The Effect of Lead on Steel

Lead is insoluble into the microstructure of steel [34].

Lead is not actually a ‘’real’’ alloying element because it has hardly any effect on the properties of steel. It is used in amounts of 0.2% to 0.5%, which improve the machinability significantly. Shorter chips and clean cuts arise because of this. Another application of lead can be seen in the excellent sliding property of bearings [9].

In the furnaces, lead is an unwanted element [3].

Part of the lead is oxidised, and the oxide fumes removed along with the exhaust gases, to form troublesome deposits in the dust collection system. However, most of the lead melts and seeps into the furnace bottom, corroding bricks and finally destroying the best bottoms sometimes with the ultimate calamity of a hearth break-out [9].

1.3.8 The Effect of Phosphorus on Steel

Villares Metals claims to produce steel with very high performance and specific properties, tailored to certain applications.

Close control of the impurity levels is essential for production of quality steel [14]. The removal of phosphorus in steelmaking operations has been a subject of extensive research. Phosphorus removal remains a key area of research because of its detrimental effect on the mechanical properties of steel [7, 14, 48]. The tendency of phosphorus to impart cold shortness in steel has been known for a long time [14]. The effects of phosphorus on steel are listed in **Table 1-I**.

Table 1-I: Effect of Phosphorus in Steel [14]

Property	Effect of phosphorus
Strength	++ (Ferrite strengthener)
Bake hardening	+
Ductility	--
Fe-Zn galvanneal	May improve resistance to powering
Phosphatability	+
Enamelling steels (Pickling)	+
Enamelling steels (Fish-scaling)	-
Core loss in motor laminations	--
Fracture toughness	--

+ increase ++ strong increase - decrease -- strong decrease

There is an increasing demand for lower phosphorus steel [6]. The customer demands specific norms and high material performance. On the other hand, a huge amount of scrap, which is used in the Electric Arc Furnace for the production of new steel grades, is made impure by phosphorus [4]. Thus, the steel makers are facing stiffer challenges to achieve the desired phosphorus levels in the finished products [7].

1.3.8.1 Mechanism of Phosphorus in Steel on Material Science Scale

McLean and Northcott proposed in 1948 that embrittlement was due to segregation of diluted elements to grain boundaries [16]. The driving force was to be the difference in distortion energy caused by a solute atom in the grain interior and in the grain boundaries. The solubility of impurities in boundaries is higher than in the matrix [15, 19, 22 – 26, 28]. Thermodynamically, this is due to the lowering of grain-boundary energy by the impurity. Gibbs explained that elements that lower the surface energy are enriched at the surface [12].

$\Delta G = \Delta H - T\Delta S$ [27]

ΔG is the Gibbsche Free Energy, which depends on the Enthalpy H, the entropy S and the temperature. The energy level always pedants to achieve a minimum. The enthalpy stands for the energy of the thermodynamic system [27]. The solubility, in both the interior and the grain boundaries, is temperature dependent. Prolonged annealing in the embrittlement temperature range causes a diffusion-controlled migration of solute impurity atoms to the grain boundaries until an equilibrium state is reached. The enrichment of impurities lowers the cohesion state across them, resulting in grain-boundary failure. The model has been termed the equilibrium segregation model [12].

To segregate, the elements need activation energy. B. Ule found out, that the activation energy for the phosphorus segregation in H11 tool steel is about 160 kJ per mol [13]. This energy is the reason, why hardly no phosphorus segregation takes place at temperatures under 500°C in a H11 tool steel.

The maximum segregation of the phosphorus was mainly found at temperatures of 500°C to 650°C in many steels [10, 28]. Lower than this time range, the phosphorus has not enough thermal activation energy to start a proper segregation [10]. Wang at all sais, with increasing temperature, the solubility of the phosphors increases in the microstructure [10]. With increasing solubility, the segregation decreases. That is the reason, why the amount of phosphorus close to the grain boundaries decreases with increasing temperature above 625°C.

By increasing the temperature, the entropy coefficient increases. Enthalpy is increasing, while ΔS decreases with increasing homogeneity [27]. A high concentration of phosphorus at the grain boundaries is increasing ΔS, which leads to a decrease of ΔG. For a low ΔG, temperatures about 500°C are necessary for the segregation of phosphorus. To summarise: At high temperatures, the activation energy is given, but the driving force is absent. That is the reason, why a peak of phosphorus segregation appears.

Former investigations at Villares Metals have proven the correctness of Gibbs theory. The investigated material was Tool Steel called H11 and H13. The chemical composition of this material is shown in **Table 1-II** [28].

Table 1-II: Chemical composition of experimental steels in weight per cent: symbol 'LP' indicate compositions with about 0.010%P, which is lower than the traditional content [28]. The content of phosphorus for LP qualities was corrected by using original test results.

Steel	C	Si	Mn	Cr	Mo	V	Ni	P	S	O
	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%	wt%
0.05%Si	0.35	0.05	0.36	5.02	1.27	0.42	0.20	0.026	0.0035	0.0032
0.3%Si	0.35	0.29	0.35	5.09	1.29	0.42	0.20	0.027	0.0040	0.0012
1%Si	0.36	0.98	0.35	5.03	1.30	0.41	0.19	0.026	0.0038	0.0021
2%Si	0.38	2.06	0.35	5.05	1.33	0.40	0.20	0.029	0.0040	0.0012
0.05%Si LP	0.35	0.06	0.36	4.99	1.31	0.42	0.20	0.011	0.0035	0.0032
0.3%Si LP	0.35	0.30	0.35	4.98	1.30	0.42	0.21	0.010	0.0040	0.0012
1%Si LP	0.36	1.03	0.35	5.03	1.31	0.43	0.20	0.010	0.0038	0.0021
2%Si LP	0.35	1.96	0.35	4.97	1.28	0.41	0.20	0.012	0.0040	0.0012

The results show clearly, that with increasing phosphorus content, the absorbed energy impact is decreasing. The samples were Charpy impact samples with V-notch. Especially for this type of steel, the effect of a higher temperature (650°C) of tempering shows better toughness results. The reason is the slower segregation of phosphorus at 650°C than at 625°C. Phosphorus segregates to austenitic grain boundaries. The reduction of phosphorus shows a strongly positive effect on steels with high content of silicon. The low toughness of steels with high content of silicon is caused by the formation of M_7C_3 carbides [28] as shown in figure **Figure 1-2**.

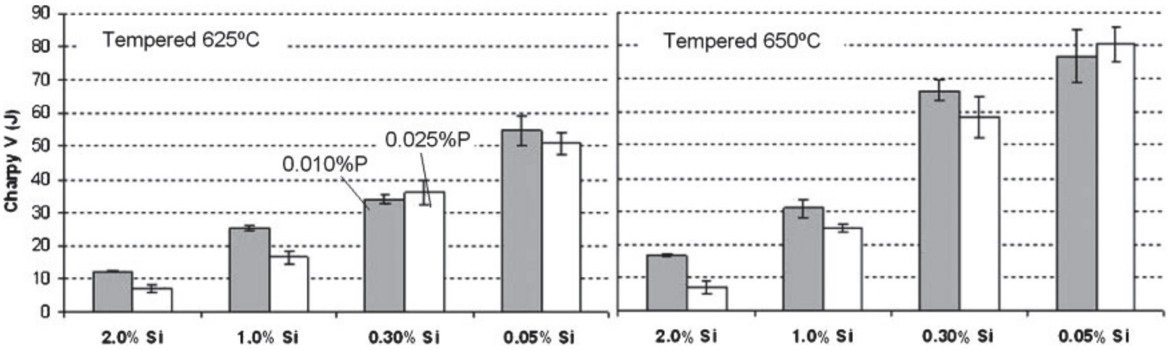

Figure 1-2: Comparison of low and high P H11 steels, for different silicon levels and different tempering temperatures [28]

1.3.8.2 Effect of Phosphorus in a Steel with high Concentration of Molybdenum

Tests were done with a 2wt% molybdenum material. The results were different to the expectations. The toughness of the material was just a little bit decreasing with increasing phosphorus content. Also at lower temperatures, VSM13A is showing hardly any difference between materials with different phosphorus contents.

Amaya mentioned, that such results are normal for steels with molybdenum concentrations of about 2wt% and more [22]. The binding energy of molybdenum and phosphorus is high [22, 36, 37]. Molybdenum segregates at temperatures around 650°C [22, 36, 37]. The atoms are moving to the grain boundaries, like the phosphorus. The molybdenum combines with the iron and builds up a intermetallic phase [22, 36, 37]. The phase is called Laves phase and consist of two atoms of iron and one atom of molybdenum. Considering the literature, two different models of creating a Laves phase exists [22]:

- The Laves phase induces at the very beginning of quenching.
- The Laves phase can only exist after a specific enrichment of molybdenum and iron. The concentration must be beyond the threshold concentration for precipitation of the phase.

It is difficult to identify the correct theory, because the threshold concentration for participation on microscale is not known.

The positive effect of this phase is the catch up of phosphorus. It catches the phosphorus atoms on their way to the grain boundaries and neutralises the negative effect of the element [22, 36]. Even if a phosphorus atom does not get caught by the lave phase, the molybdenum lowers the diffusion velocity of the phosphorus. These two effects reduce the amount of phosphorus content at the grain boundaries, compared to steels with lower molybdenum content [22, 36 – 38].

If molybdenum and phosphorus segregates at grain boundaries, the molybdenum atoms may change the electric phosphorus character at grain boundaries. This character is similar to Fe_3P. Such interactions may decrease the effect of phosphorus segregation. The grain boundaries recover the cohesion in iron reduced by phosphorus [22].

1.4 Aim of this Master Thesis

The aim of this thesis is to identify opportunities for further process improvements, especially at the steel plant, focusing on the scrap yard, the charging and operating of the Electric Arc Furnace. The annual amount of produced tons is increasing year by year [31]. Increased capacity at the furnaces will be needed without investing extraordinary amounts of money. This will only be possible by increasing the annual operation time and decreasing the average tap-to-tap time of the furnace. Many different possibilities are under investigation to prove the expected increase of utilisation of the furnaces in this thesis.

Following this, the focus of improvement is mainly on products with low phosphorus content. The reason for this is a newly installed system to reuse metal dust from grinding as a scrap source for the furnaces. The advantages and disadvantages of producing ingots with low content of phosphorus, for a later second melt in the furnace, is part of these studies, as well as other possibilities to create low phosphorus products. The current limits of this concept, concerning the energy, alloying elements and utilisation, in comparison to other concepts, is shown.

The last part of this thesis is the study of the effect of the phosphorus on steel and also the investigation as to whether the limits of phosphorus in the oil and gas industry for a specific material are appropriate or not. The investigated steel quality will have a huge percentage of the total amount of produced products of Villares Metals in the years to come.

Many papers have been published about the dephosphorization in the Bessemer converter and oxygen converter for low-alloyed steel. But only few researchers have investigated the dephosphoration in an electric arc furnace and have carried out research into the effect of phosphorus in high-alloyed steel, especially on super martensitic steel. This is used for applications with tough requirements for the oil and gas industry and just few results from similar previous investigations have been found. Villares Metals has a high interest in the results of these investigations, because of the challenges that have to be solved at the production day by day. Possible solutions are described for increasing the utilization and finally the margin of this product by operating the electric arc furnace more economically.

2 Steel Plant of Villares Metals

The steel plant is at the beginning of the process chain of Villares Metals. The different areas of the steel plant are the scrap yard, the electric arc furnaces, the two ladle furnaces, the vacuum oxygen degasing equipment, the vacuum decarburation installation, the continues casting aggregate, the area of conventional casting and the big area of special melt shop with its equipment [37].

2.1 General Processes of Special Steel Production in the Steel Plant of Villares Metals

At Villares Metals, two Electric Arc Furnaces of 35 tons and 25 tons respectively melt the scrap. Internal sources and external suppliers deliver the scrap for the furnaces. The internal scrap comes from various departments of the company, where the products are forged, rolled or mechanically processed [37]. The flow chart of the steel plant is shown in **Figure 2-1**.

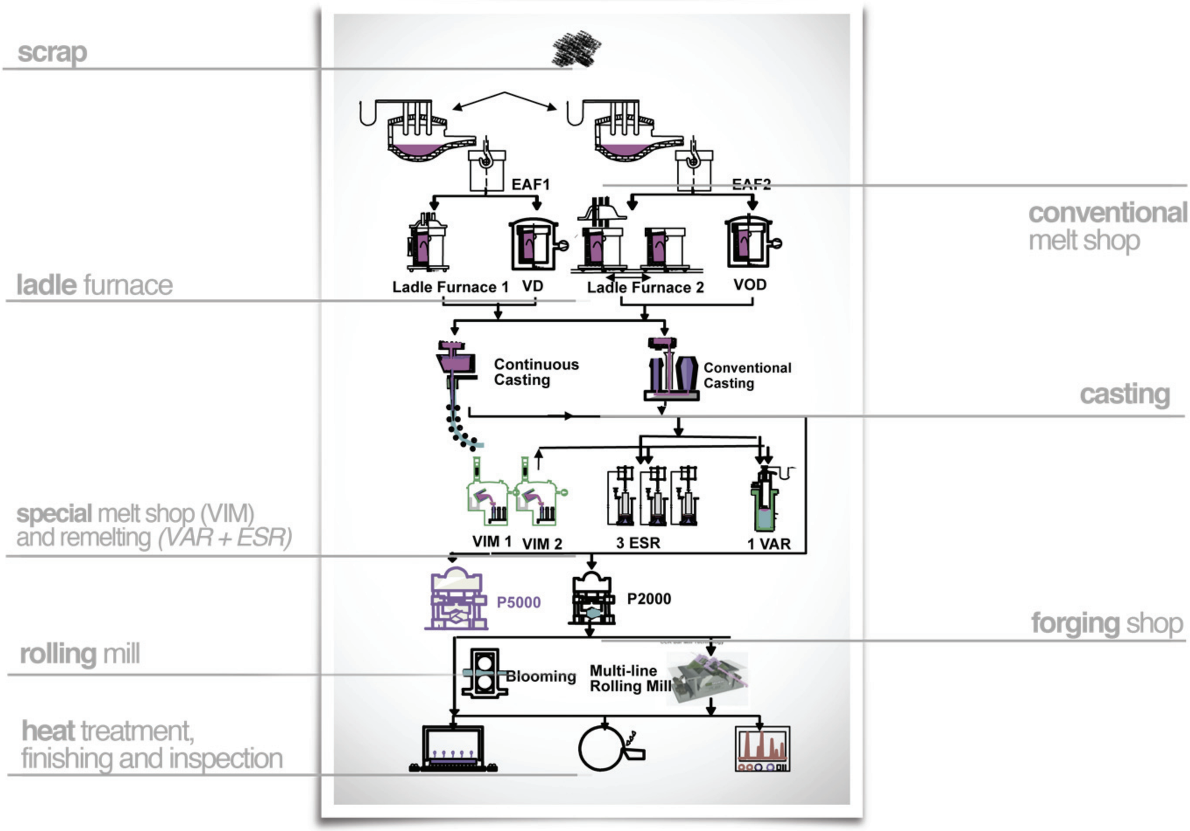

Figure 2-1: Process of Production by Villares Metals [37]

The internal and external scraps are collected and partly tested at the scrap yard. The preparation of the scrap according to size and density, as well as the scrap assembling, takes place in the scrap yard. Pieces that are too big for the furnace are cut. Some materials with low density are pressed into cubes. All of the scrap is collected in specific areas in order to avoid mixtures of materials with different chemical compositions [37, 38].

With the assistance of a computer program, the operators assemble the correct mixture of scrap for the final steel composition. The program tries to assemble the cheapest possible mixture, which still reaches the targets of chemical composition for a specific amount of tons [39, 41]. After assembling the scrap in a computer program, the different types of scrap are collected onto a truck, which then delivers them to the steel plant. At the steel plant, baskets are filled with this scrap. These baskets are used to charge the furnaces. There are certain regulations governing the filling of the baskets, depending on the program of the furnace and the material being produced. Some rules are general, pertaining to all kinds of scrap loadings. These are:

- Parts with a high density and high volume have to be charged at the bottom of the first basket along with at least 1500kg of scrap with low density. This is mainly to protect the refractories.
- The amount of charged material decreases with every basket. (E.g. first basket 50%, second 30%, third 20% of the total charged volume)
- The amount of used baskets for charging must be minimized as much as possible.
- Alloying elements have to be added to the second basket or immediately afterwards.
- Stainless steel always has to be placed at the bottom of the second basket.

The furnaces are normally charged with two baskets, a quantity that can go up to four. The quantity of baskets depends on the density of the scrap [39, 41]. Electric Arc Furnace #1 is the bigger furnace. The boiling operation is used quite frequently in this furnace. This method of production is used for materials with a low content of alloying elements and especially to produce low phosphorus contents. Electric Arc Furnace #2 is able to melt 25 tons and mainly materials with high percentages of alloying elements are melted down in this aggregate. Furnace #2 is also able to melt with the boiling process, but is rarely operated with this technique.

Very often after tapping, the liquid iron is transferred to secondary metallurgical equipment. At cell number one, where the Electric Arc Furnace #1 is located, the operators are able to transfer the liquid steel to a Ladle Furnace and/or to a Vacuum Oxygen Degasing aggregate. After these treatments, the liquid material can only solidify at the conventional casting aggregate, due to logistical restrictions.

In the area of Electric Arc Furnace #2 all of the equipment is theoretically reachable. A ladle furnace and a vacuum decarburation make up part of the equipment for cell number two. After adjusting the correct chemical composition and reaching the temperature for casting, the material is transferred to the Conventional Casting area or the Continuous Casting plant.

After solidification at the Continuous casting plant or the Conventional casting area, the steel is moved to the department of Forging, to the Blooming machine, or to the Special Melt Shop for further chemical treatments.

2.2 Scrap sorting

Contamination with undesirable elements is a great danger for steel [33, 34]. Due to this, and the ability to produce products high quality steel at reasonable, affordable prices, the scrap has to be sorted as well as possible. The European Commission for technical steel research says *“A significant improvement of the scrap quality is thus not mandatorily requested for the long product route but the need will grow in the future for preventing the occurrence of any recycling problem. The processing of scrap in the solid state before melting seems the only way which presently allows an upgrading of the scrap quality [4]”.*

2.2.1 Recycling of Scrap

Scrap metals are being recycled and substituted for their equivalent amounts of virgin material resources to an even greater extent by the metals producing nations of the world, than ever before [4, 9, 46]. 80% of the ever produced steel is still in use [46].

Several significant advantages result from this replacement. The primary ones are [3, 4, 9, 43, 44]:

- Irreplaceable metallic minerals resources are conserved.
- No loss of quality.
- Irreplaceable fuel resources are also conserved, because substantially less energy is required to produce a given quantity of metal from recycled scrap.
- Usually, the capital investment to manufacture a given amount of metal from returned scrap is much lower than it is for smelting the metal from its ores and concentrates.
- Usually, the overall cost of producing a ton of metal from scrap is appreciably lower than it is when reducing it from it ores.
- Pollution of the air, water, and earth are often decreased as a result of replacing natural ores with recycled scrap.
- Aesthetic blight in the community is minimized, when obsolete goods are recycled, rather than allowed to accumulate.
- National dependence on often unreliable foreign sources of virgin materials is decreased, when scrap is effectively recycled.

Because of these many advantages, and few disadvantages, there is no question that the recycling of scrap metals of all kinds will continue to grow in importance the world over [9].

Problems mainly appear from the steel heterogeneity on market. Uncountable varieties of scrap exist, which make cause technical recycling problems, although virgin iron units are obtained as pellets or lump ore of very uniform and well-defined characteristics all over the world. Furthermore, the chemical compositions of these grades of scrap vary substantially. Scrap is often complex, poorly understood, and contaminated with impurities [9]. The European Commission of Technical Steel Research has come to the conclusion that simple dismantling and better hand picking practice are the two methods that are feasible and economically reasonable [4].

2.2.1.1 Scrap Categories

Basically there are three principal categories of sources [9]:

- Home scrap
- Prompt industrial scrap
- Obsolete scrap

Home scrap is the crops from ingots and billets, the fish tails and heads from sheets, the cobbles and occasional mistakes made in the plant in the production of steel. This is an important source used by the steel and foundry industries, and accounts for about 51% of the scrap used every year [4, 9]. Villares Metals is using almost 100% of their internal home scrap for the further production.

After home scrap, the second important source is prompt industrial scrap. This comprises about 21% of annual scrap usage and it is generated by customers as they stamp, shape, forge, machine, drill, trim or otherwise utilize the steel that they buy in the creation of their own products for market [4, 9]. Many different companies are selling their prompt scrap directly or indirectly to Villares Metals.

The remaining major category of scrap produced is obsolete scrap, and it, of course, comes out later in the cycle of life of metallic items. Obsolete scrap is the cast-offs civilization, such as worn out refrigerators, equipment, old buildings and many more things. Everything that humans use in industry and in every day of life that is made of metal and subsequently wears out becomes obsolete scrap when it is discarded [9].

2.2.1.2 Scrap Price

The scrap price determine on supply and demand. Scrap is a free market commodity, whose price is determined by the fundamental interplay between supply and demand. Since the bidders are competitive entrepreneurial types, who are seeking to maximize the volume of their business, the suppliers, in this arrangement, are assured of a fair interpretation of the market price and a proper return on their scrap through the mechanism of the bidding process [9].

The aim of the operators is to assemble the scrap with the alloying elements, that the chemical composition is fast adjusted. Other aims are to melt the scrap in a short time, to avoid damages of the electrodes and refractories and to spend not more money on the scrap source as really necessary. For the price and the chemical composition, a computer system is assisting the operators. The operators with all their routine must select the optimal scrap for a fast melting and the protection of electrodes and refractories.

2.2.1.3 Current situation of sorting and loading of scrap

All of the Villares Metals scrap is collected at three scrap areas. The internal and the external scrap are stored at the main scrap yard, which is close to the steel plant. Individual scraps or entire scrap groups are stored in different coves. The coves are necessary to avoid mixing of individual types of scrap [4, 9, 38]. Groups of scrap consist of similar types of scrap. Groups are necessary to keep the number of storage coves and kinds of scrap for the calculation of the scrap assembling manageable.

Another scrap area is close to the area of slag preparation. Here, the slag of the last 10 to 15 years is sorted again. This is separated into different slag sizes and materials. The slag often includes pieces of metal. These metal pieces are of different sizes and range from a few millimetres to one or two meters in diameter. A magnet separates the smaller ones whilst the bigger ones are pulled out with big machines. Afterwards, the material is stored, separated mainly by size and roughly by alloying content.

Trucks deliver the external scrap and the trucks are weighed and tested for radioactivity. The discharge takes place either at the scrap yard or in the steel plant, where the baskets are loaded. Cranes place the scrap into the correct area. External scrap is completely checked by examining the optical appearance, the balance and some chemical tests.

A truck is used to deliver internal scrap at the scrap yard. To avoid the delivery of scrap mixtures, the internal scrap is checked. There is a high risk of polluting the furnace with unwanted elements, such as Ni and Cu [3], which are then almost impossible to reduce. The testing of the scrap quality is done using X-ray spectroscopes and arc spectroscopes.

The scrap compilation for the basket is made from operators with the assistance of a computer program. The result of the calculation is sent to the loading zone, where the scrap is finally sorted into the baskets. Trucks are organized to carry the material from the scrap areas to the steel plant. Cranes put the amount of ordered scrap on the trucks. At the loading zone, cranes fill the baskets with the correct scrap.

The crane uses a claw for materials that are not magnetic. An electric magnet is used to handle all the other magnetic material.

2.3 Acquisition of material flow quality

The acquisition of the material starts at the very beginning of the processes at Villares Metals. As soon as new scrap is delivered, the material is analysed. Viewing the new delivered scrap is the first investigative procedure, which is done by the employers. The quality, determined by type, size, density and the amount of scrap, is taken into consideration. The weight of the scrap loading of trucks is weighed on a scale. Sensors, which detect radioactive scrap, also scan the load.

The delivery of internal scrap is very similar to the external one. Parts, which are obtained as scrap after processing the material, are collected in boxes. Every box should always contain only one type of chemical scrap composition. In order to achieve this, visual and chemical composition testing takes place. The internal scrap of all different areas of Villares Metals is placed on a scale, whereupon the exact weight is measured and a chemical and optical analysis is carried out. After that, the scrap is sent to the correct area at the scrap yard.

Unfortunately the amount of investigated internal scrap is only about 40%. All the scrap that is delivered to the scrap yard between 5pm and 8am is not analysed. The weight and the chemical composition should always be known, from the processing process, but unwanted mixtures of scrap are not detected. The amount of faulty detected internal scrap is about 1% of all the tested materials. The quality of testing is very superficial. Boxes with chips are tested by carrying out a chemical analysis on some chips from the surface of the box. Visual comparison of all the others should help to identify inhomogeneous charges. Much bigger parts, such as from the forging area or the blooming process, are also chemically tested: some parts of the upper area and parts which have different shapes in comparison to the tested one. A detailed chemical investigation is not possible in these boxes. To improve the situation, more employees are needed, as well as more boxes to store the scrap, before it can be tested [38].

Hardly any tests on material are done at the scrap yard. Unfortunately, the possibility of mixing scrap is very high at this place. A new project of Villares Metals is taking place, in which the scrap will be stored in a totally new scrap yard. At this new scrap yard the handling and the separation will be improved.

The quality of the unloaded scrap, the exactness of scrap handling and the assembling of the baskets are easily detected following the first chemical analysis of the electric arc furnace. The difference between the calculated desired chemical composition and the real chemical composition shows the quality of internal and external scrap, plus the accuracy of the assembling process. The figures, which are showing the differences of the chemical composition of the calculated, the calculated loaded and the first sample of the Electric Arc Furnace, are shown in **Figure 2-2**, **Figure 2-3** and **Figure 2-4**. The figures are of heat number 0801864. The material is a VSM13A. The absolute deviation from the target value is shown. The graphic does not show whether too little or too much of alloying elements has been added.

$$\frac{Xcalculated - Xsample}{Xcalculated} * 100\% = Xresult$$

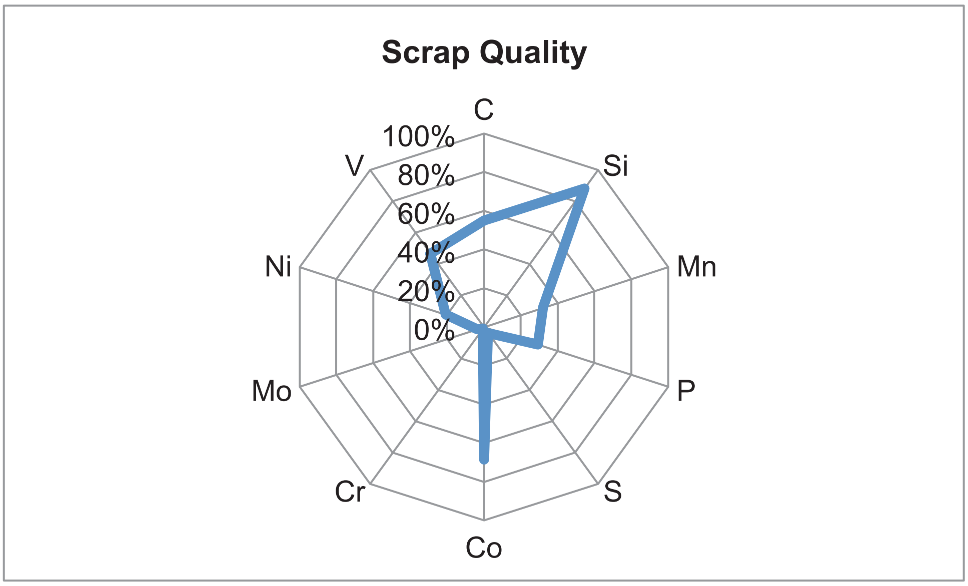

Figure 2-2: Scrap quality with the relative difference of chemical composition between the calculated chemical composition and the composition of the first melted sample number 0801864 as absolute deviations, VSM13A

$$\frac{Xcalculated\ loaded - Xsample}{Xcalculated\ loaded} * 100\% = Xresult$$

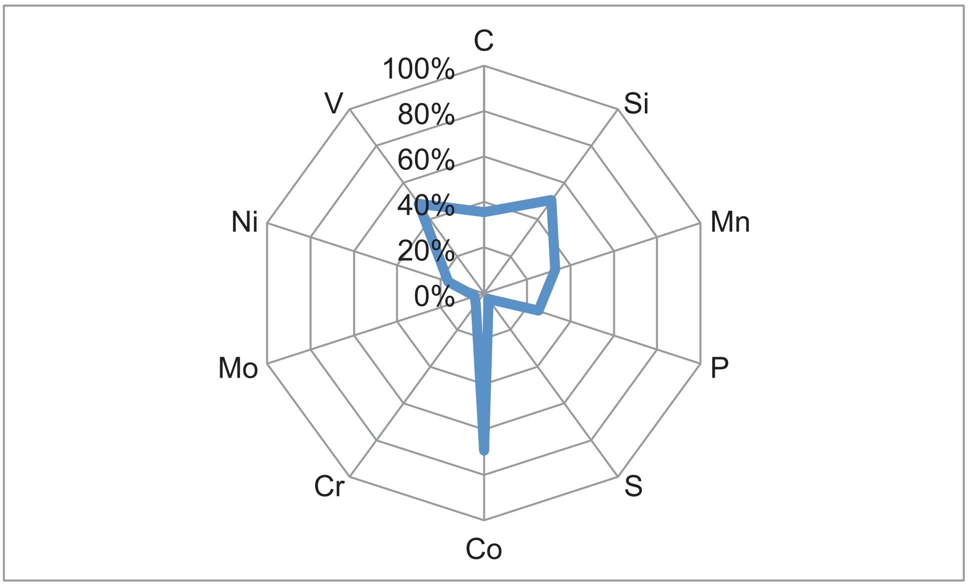

Figure 2-3: Scrap loading quality with the relative difference of chemical composition between the calculated loaded chemical composition and the composition of the first melted sample number 0801864 as absolute deviations, VSM13A

$$\frac{Xcalculated - Xcalculated\ loaded}{Xcalculated} * 100\% = Xresult$$

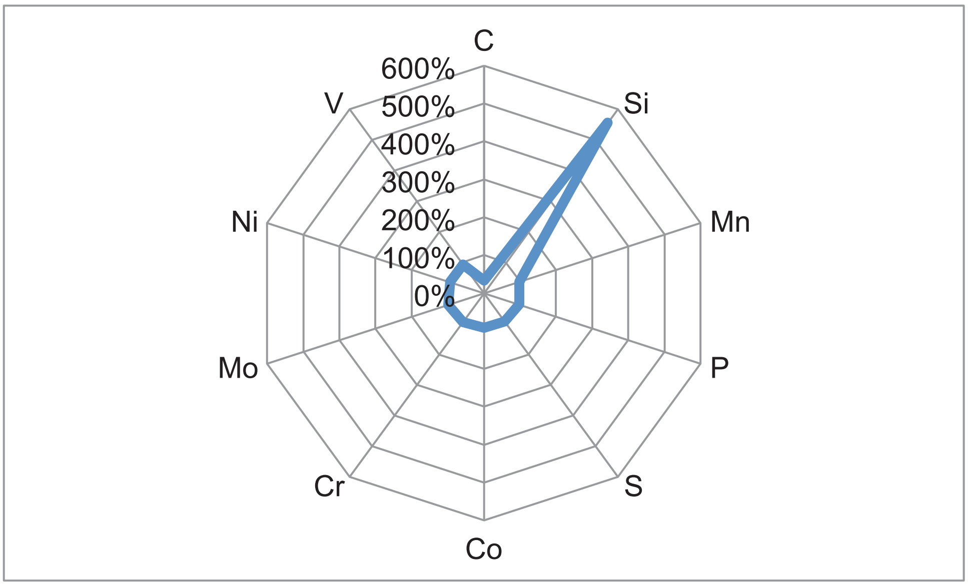

Figure 2-4: Calculation Quality with the relative difference of chemical composition between the calculated loaded chemical composition and the calculated loaded chemical composition of the first melted sample number 0801864 as absolute deviations, VSM13A

The difference between the first chemical analysis of the melted material and the calculated chemical composition of the weighted material in the basket is the quality of the scrap. By comparing these figures, the impact of the exact scrap handling plus scrap assembling can be calculated.

Both of the results have sometimes shown a big variation between the calculated chemical composition, which is the aim of chemical composition and the composition of the first sample. The imprecise scrap handling causes the big difference of silicon between the chemical composition of the calculated scrap and the calculated composition of the loaded scrap.

For the quality of the furnace process, four main figures are meaningful. The quality of the furnace process also depends on a very high scale of the loaded material. For this reason the mentioned figures also depend on the scrap quality and the exactness of the scrap handling.

- The tap-to-tap time
- The consumption of the total electric energy per heat
- The refractory wear
- The electrode consumption

These four parameters depend on several adjustable factors:

- The chemical difference between loaded material and tapped material
- The finally produced steel grade (program of furnace)
- The type and amount of added alloying elements
- The amount of slag
- The quantity of added forming elements
- The slag basicity
- The scrap size
- The type of scrap
- The experience of the operating stuff
- The finally produced steel grade (furnace program)

In order to increase the productivity, the most important figure is the tap-to-tap time. The tap-to-tap time is a good indicator of the control over the whole process. The shorter the tap-to-tap time and the smaller the standard deviation, the more the process is under control. To give an impression about the actual performance of the furnaces, the tap-to-tap time of the most produced material in both furnaces is shown in **Figure 2-5** and **Figure 2-6**. The improvement of the process after "Semana Kaizen" is shown by comparing **Figure 2-7** and **Figure 2-8**. "Semana Kaizen'' is a tool of the lean management philosophy, which is focused on the avoidance of waste. Waste can be any kind of material, time or energy.

The statistic data are in **Table 11-I** and **Table 11-II**. **Table 11-III** and **Table 11-IV** show the statistic data of the Electric Arc Furnace #2 and #1 of the tap to tap time before and after the "Semana Kaizen".

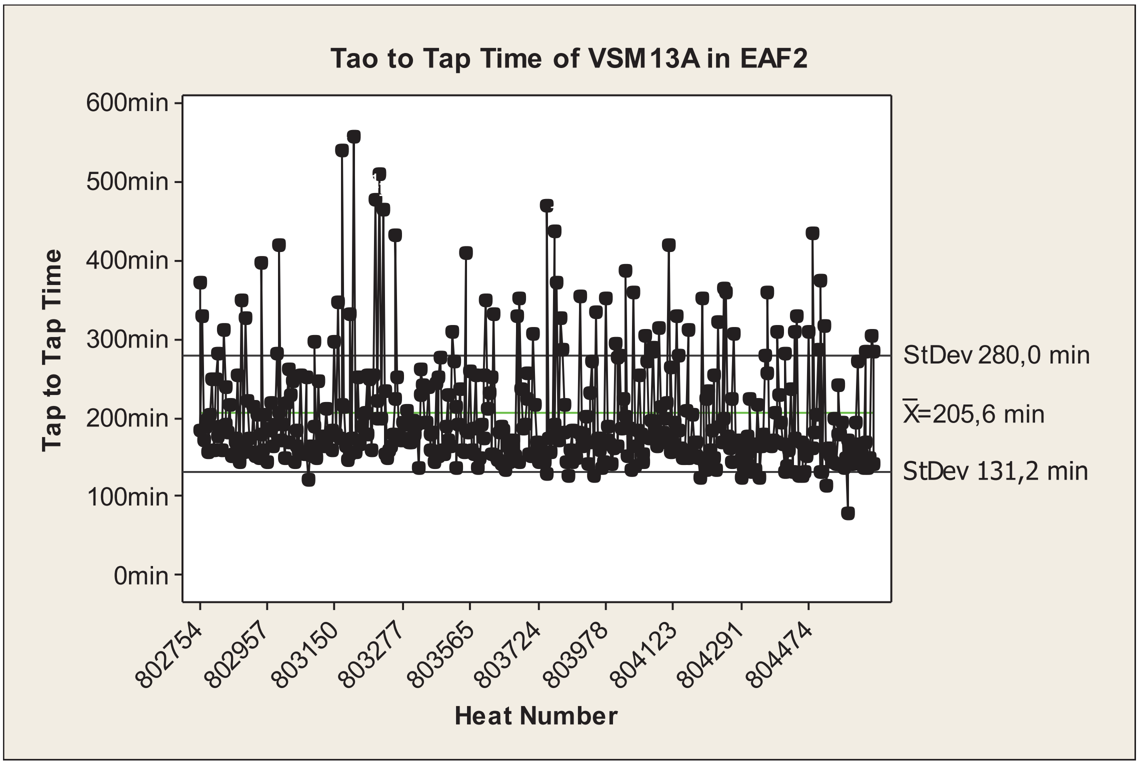

Figure 2-5: VSM13A Tap to Tap Time in EAF2 April 2013 to September 2013

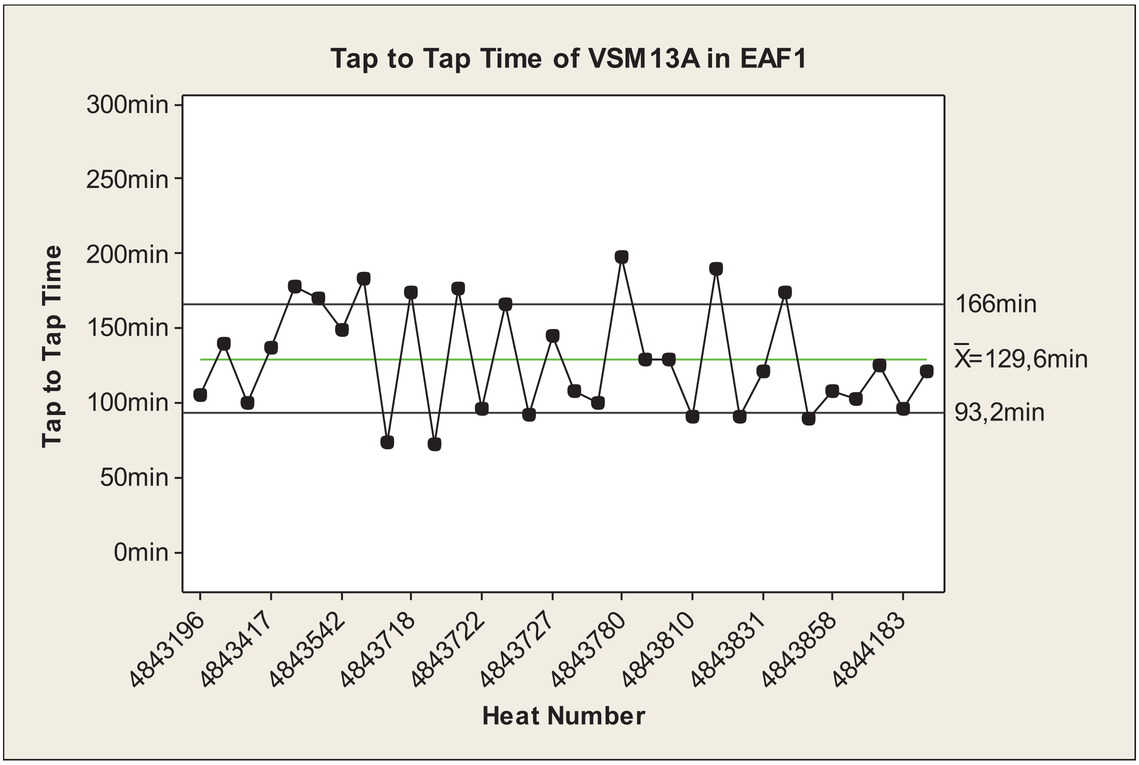

Figure 2-6: VSM13A Tap to Tap Time in EAF1 April 2012 to March 2013

Even with the smaller amount of heats of VSM13A during a much longer period in EAF 1, it is easy to see that the process in EAF 1 is under better control. The standard deviation is, just 33 minutes. This is much shorter than that in EAF 2 with 60 minutes. The average tap-to-tap time is also shorter, even with the higher capacity. EAF 1 had an average tap-to-tap time of 133 minutes, while EAF 2 needed 204 minutes. These differences can be attributed to the higher power performance of EAF 1.

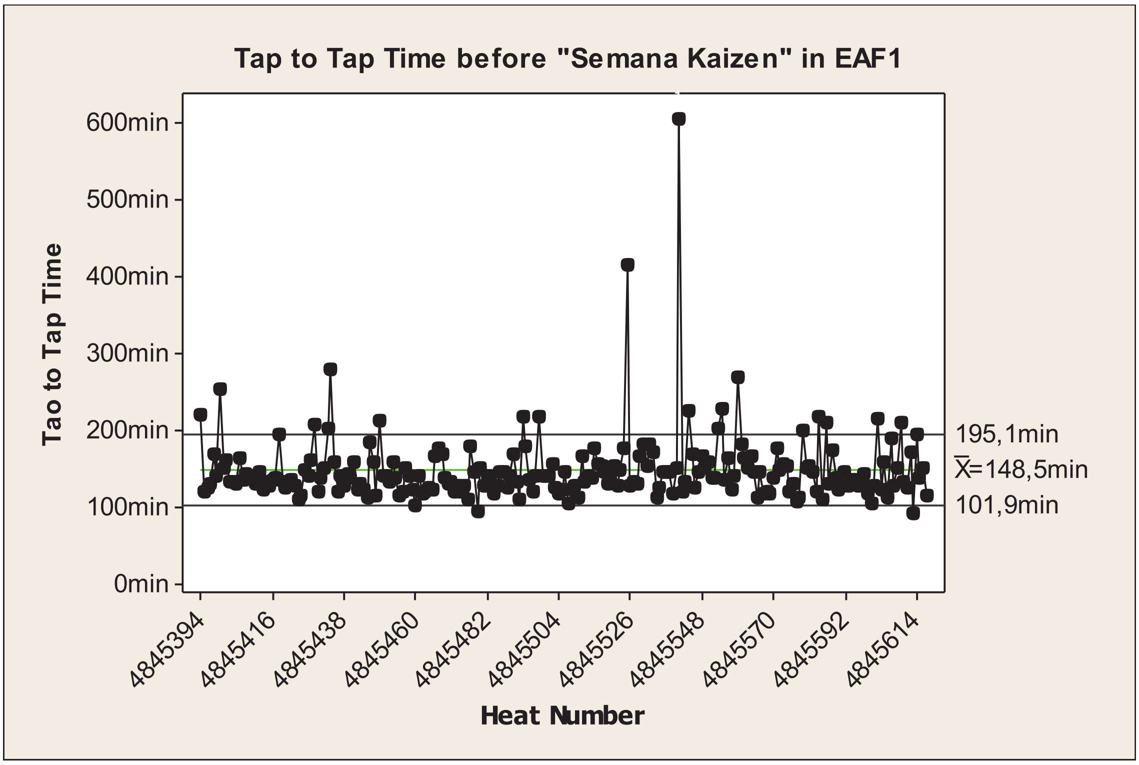

Figure 2-7: VSM13A Tap to Tap Time before “Semana Kaizen” in EAF 1

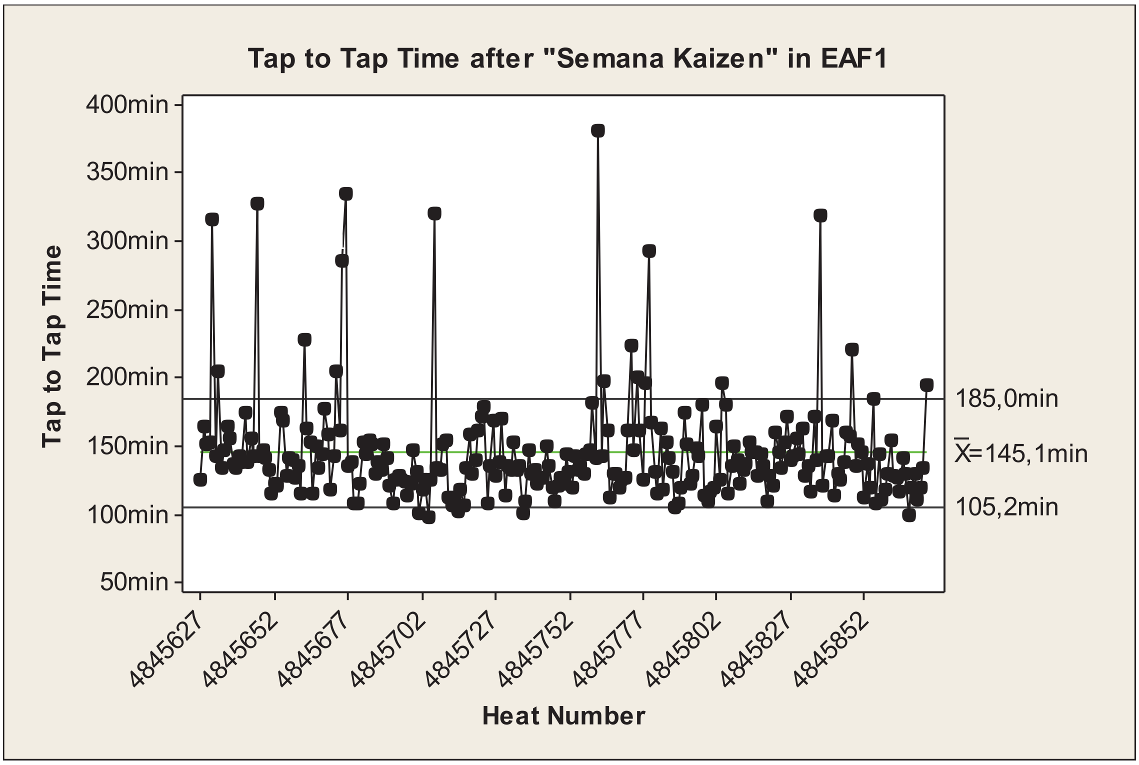

Figure 2-8: VSM13A Tap to Tap Time after “Semana Kaizen” in EAF 1

The aim of the “Semana Kaizen” in September 2013 was to reduce the average tap-to-tap time by approximately 3 minutes. By comparing the tap-to-tap times before this week and the tap-to-tap time afterwards, it can be seen that the target was fulfilled. The implemented suggestion improvements had the expected effect and the average tap-to-tap time decreased by more than 3 minutes and the standard deviation decreased from 46,6 minutes to 39,9 minutes.

The week of Kaizen had a positive effect on the performance of Electric Arc Furnace #1. But to establish a much more stable process, the standard deviation has to decrease dramatically. In order to achieve higher efficiency, the average tap-to-tap time has to be shorter too. A successful approach might be to work on both of these figures at the same time by decreasing the amount and the duration of process interruptions.

2.4 New scrap yard concept

The new scrap yard has already been initiated. This new area yard will offer more space for the operators and for storing scrap. Beside this, many of the scrap boxes will be with an inclined base to ensure the automatic movement of the scrap to the front of the box. This could be an important innovation to avoid long terms of scrap handling inside boxes [38].

A press for the small parts and a big oxygen-cutting machine for the big ones will be installed. These installations are important to be able to buy big parts of scrap. It is important to be more flexible in scrap size. Inaccurate scrap size definition is making scrap cheaper than scrap with well-defined scrap deviation [4].

The scrap will be moved by crane and trucks, which will load the baskets for the Electric Arc Furnaces. The baskets will be placed on wagons with on-board equipment that measures the load. After finishing the loading of a basket, the basket will be carried to the steel plant on its wagon. Close to the furnace, the basket is taken by a crane and moved to the furnaces. The basket opens and fills the furnace with scrap.

Afterwards, the wagon moves back to the scrap yard with an empty basket. This one will be refilled with other scrap for a different heat again.

One of the main ideas of the concept was a clear separation of the external scrap supplier and the internal operators. This has to be done for three reasons.

- To keep the whole process as productive as possible.
- To avoid accidents of internal and external stuff, by only allowing briefed stuff to enter the loading zone.
- To avoid external spying and price changes of suppliers, accordingly the needs of Villares Metals.

2.5 The Electric Arc Furnace

Technological developments have been continuously taking place in the EAF process over the past 40 years to improve the capacity, efficiency and quality of the steels with huge emphasis on cost reduction [2]. In general there are two conventional possibilities of producing steel: the oxygen converter process or the electric furnace process [2, 3, 6, 35, 50, 51]. In the case of the converter process, hot metal is decarburised and dephosphorised for the production of mainly common steel grades (e.g. unalloyed and low alloyed structural steel for plates and sheets). The electric arc furnace process re-melts scrap to produce alloyed quality steel mostly for bars and rounds [16, 35]. The performance of Electric Arc Furnaces was impossible to imagine 20 to 30 years ago. Many positive innovations have reduced the tap to tap time about 30 to 35 minutes for the best 100 to 130 t furnaces. Electric energy consumption has been reduced almost half times, from 630 to 340 kWh/t. Electrode consumption was reduced about six times [3].

The main technological processes in the modern furnaces are the melting of solid charge materials and the heating of liquid bath. Melting the scrap is done in the Electric Arc Furnaces [3, 35]. To get these processes going, it is necessary to obtain heat from other kinds of energy and transfer it to zones of solid charge or liquid bath. Electric Arc Furnaces turned out to be very flexible in terms of charge materials selection [3]. Villares Metal is only charging solid scrap and no pig iron. But there are hardly two heats of the same material following each other. Caused by logistical problems and a specific workflow the finishing are mainly sets the workflow.

In brief, Electric Arc Furnaces can be either ac or dc powered and they melt steel by applying electric power to a steel scrap charge by means of graphite electrodes [3].

From the chemical standpoint, all steelmaking processes must occur under oxidizing conditions. Carbon removal using oxygen is the primary chemical objective in steelmaking. With respect to oxidation, the common residual elements fall into several distinct families [9].

- *“Elements recovered 100% in the molten steel.*
  Mo, Ni, Sn, Cu”
- *“Elements lost completely to the slag.*
  Si, Al, V, Zr, Ti, B, Cb”
- *“Elements whose recovery depends on the degree of oxidation of the slag/metal system.*
  Cr, Mn”
- *“Elements those are volatilized and oxidized in the furnace.*
  Pb, Zn, Sn”
- *“Elements those are controlled by manipulating of slag chemistry [9, 38].*
  S, P”

Villares Metals has two Electric Arc Furnaces. The two furnaces are quite old. The furnace in cell #1 was extended to have a larger capacity in 2010. The actual capacity of this furnace is 35 tons per heat. The smaller furnace in cell # 2 was first implemented in 1952 and is the older one of the two. The mechanical, hydraulic and electrical systems have been changed several times. Today, only a few construction elements are from the first furnace of 1952. The actual capacity of furnace # 2 is 25 tons.

The tap-to-tap times of the two furnaces are quite different. In Electric Arc Furnace #1, the average tap-to-tap time is 145 minutes (2013). Electric Arc Furnace #2 needs 190 minutes (2013) on average. The main reason for the faster melting in furnace # 1 is the higher electrical power, which is maximal 250kWh/min for Electric Arc Furnace #1 and. Electric Arc Furnace #2 is a little bit weaker. It only generates about 170kWh/min.

2.5.1 Costs of the Electric Arc Furnace

The electric arc furnaces are some of the most expensive equipment for Villares Metals. Only the Multi Line Rolling Machine and the Blooming Aggregate are more expensive than Electric Arc Furnace #1. Electric Arc Furnace #2 is a little bit cheaper in terms of fixed costs and variable costs and is the fifth most expensive aggregate of the company.

The costs for the two furnaces are important for further economical calculations:

Electric Arc Furnace 1:

3142 €/h in total

1263 €/h fixed costs

1879 €/h variable costs

Electric Arc Furnace 2:

2443 €/h in total

859 €/h fixed costs

1584 €/h variable costs

The proportion of the fixed costs to the total costs for the Electric Arc Furnace #1 is, at 40.2%, a little bit higher than the proportion of fixed costs to total costs for Electric Arc Furnace #2 at 35.2%.

The energy cost of each furnace is mostly a variable cost. Electric Arc Furnace #1 consumes 801€ per ton. 662€ per ton of this is variable. Electric Arc Furnace #2 needs only 558€ per ton and the variable amount of energy costs is proportionally higher as in EAF #1. The variable energy consumption is 470€ per ton for this furnace.

Because of the high fixed costs, when compared to other aggregates of Villares Metals, one procedural is heavily purposed. The highest possible utilization with the shortest tap-to-tap time for each product is economically viable.

An increase in annual production will lead to the creation of additional capacity at the Electric Arc Furnaces. An increase of the furnaces capacity will only be possible with a high level of financial investment. The more efficient way would be to reduce avoidable stops and the abolition of planned downtime. The potential is huge. In 2013, the Electric Arc Furnace #1 was not working for 20% of the total operating time because of unforced stops. Electric Arc Furnace #2 didn’t operate to an even higher degree. The difference in the number of stops was mainly caused by the low power limit and shut downs, in the case of Electric Arc Furnace #2, every time the limit was exceeded.

2.5.2 The tap-to-tap circle

At the Electric Arc Furnaces of Villares Metals are both DC (Direckt Current) furnaces. The smaller furnace is able to melt 25 tons at once. The bigger one has a capacity of 40 tons per heat. Materials with a quite lower amount of alloying elements are produced with furnace # 1, which is the one with the 40 tons capacity. The tap-to-tap circle starts normally immediately after taping of the previous heat. The furnaces open the roof and get filled with the first basket of scrap. After the empty basket moved backwards, the roof closes the furnace. Three carbon electrodes, which have all their own manipulator, move down and start the ignition. The material starts to melt down under the arcs of the electrodes. The material, which keeps longer solidified at the wall of the furnace, protects the refractory from the high intensity of the arcs. The length of the arc is adjusted by the voltage limit [3]. The furnaces of Villares Metals have a cooling system for the electrodes. Tiny water drops are sprayed on the electrodes, which evaporate and cool down the electrode a little bit. This is done to reduce the electrode consumption of the furnace [2, 3, 6, 50, 51]. At the final stage, when there is a nearly complete metal pool, the arc is shortened to reduce radiation heat losses and to avoid refractory damage and hot spots [2, 3, 50, 51]. When the material is melted, different processes can occur. Normally an oxygen blowing starts, which reduces different elements. This can be done by using a lance. During this period the heat raises because of the exothermic reactions of these elements with oxygen [3]. After the oxygen blowing, alloying and/or oxygen blowing adjust the final taping composition. At Villares Metals is no automatic system for alloying. The greater the difference from the chemical target, the more needs to be alloyed by hand. The alloying elements are put into a funnel. The funnel is pulled over the open furnace and opens. The alloying elements fall into the liquid metal bath.

Some alloying elements may be added by injecting with a lance. Such elements can be carbon or silicon, but the majority is added with the funnel.

In furnace # 1, foam slag is often generated, which is good for energy consumption and lining. If such a slag is generated on material with a high alloying content, elements like chromium, vanadium, carbon, … are fast removed and lead to economical disadvantages. Therefore furnace # 2 almost never operates with foamed slag.

When the correct temperature is reached and the chemical content fits to the required specification, the slag gets removed. The furnace tilts to one side to remove the slag, and later on to the other for tapping the liquid iron [3].

The ovens at Villares Metals, do not have a special spout openings. There are only two holes in each furnace, which are offset by 180 ° and are used for conventional slag removing and conventional tapping. While tilting in the one direction the lighter slag is poured off. When tilted in the other direction, the oven is emptied as good as possible. It is tried to completely empty the furnace, because the next batch often has a totally different chemical composition.

Afterwards, the full pan with liquid steel will be brought to other agreagtes, where the next steps will take place.

2.6 Secondary Metallurgy

Modern technology is used to produce steel economically. The steel production process can be divided into two steps, known as the primary metallurgy step and the secondary step [17]. The primary step takes place nowadays at the Electric Arc Furnace or the Blast Furnace and subsequent basic oxygen furnace. The liquid iron is tapped into the ladle [3, 17, 34]. The temperature is quite low to preserve the refractory materials and the construction of the furnace and the ladle [17]. Using the ladle furnace, the chemical composition can be adjusted. To produce high-grade steel, aggregates and chemical processes are needed. This kind of ‘’ladle metallurgy’’ is called secondary metallurgy [17].

Many different processes are possible using secondary metallurgy [3, 17, 34]. The main difference between the processes is that some are vacuum treatments and others are processes without vacuum. Aggregates with the vacuum technology are able to reduce the amount of carbon, oxygen with carbon, nitrogen and hydrogen [17].

Table 3: Objectives of the secondary metallurgical process [17]

conditions	type of processing	removal of elements							processing	
		ΔC	ΔO		ΔP	ΔS	ΔN	ΔH	alloying + homog.	reheating
			by C	by Al						
atmospheric pressure	stirring treatment			●	(●)	●			●	
	power injection					●				
	wire feeding			●					●	chemical
	chemical heater			●		●			●	chemical
	ladle furnace			●		●			●	chemical
Vacuum	RH	●	●	●			(●)	●	●	
	RH + top blowing	●	●	●			(●)	●	●	chemical
	VD	●	●	●		●	●	●	●	
	VD-OB	●	●	●		●	●	●	●	chemical
	VOD	●	●	●	(●)	●	●	●	●	chemical

2.6.1 Ladle Furnace

The Ladle Furnace is the most common secondary metallurgical equipment at steel plants and the aim of it is to increase the overall productivity. Deoxidation and alloying are carried out in the ladle at the Ladle Furnace station [34]. The principle function of a ladle furnace is similar to that of an electric arc furnace [17, 34], but the power is much lower than at the electric arc furnace.

The furnaces of Villares Metals have three electrodes on the roof. The electrodes are smaller in diameter than those on the electric arc furnace. The material is boiled and heated with electrical energy. An automatic wire device causes the alloying process, by using a small basket or by adding solidified material.

The temperature and the alloying content are measured during the operating time of the furnace. The chemical composition of the material is analysed in the laboratory, which gets the samples from the furnace by airmail.

The electrical heating is usually divided into two heating periods. The purpose of the first heating period is the homogenisation of the melt regarding temperature and chemical analysis. During this time, and if it hasn’t yet been done, the melt is deoxidised, pre-alloyed and slag formers are added. The duration of the first heating period generally amounts to 15 min [16].

When the first heating period is completed, heating is stopped for a short time to take a sample and to measure oxygen activity and temperature. The required energy input is calculated for the second heating period based on this temperature [17].

After the second heating period, for very low sulphur content, the electrodes are lifted and a desulfuration treatment starts with strong argon stirring through the bottom plugs or the top lance [17].

The main advantage of the ladle furnace at Villares Metals is reduction of the production cost. This can be achieved by:

- Reduction in tap-to-tap time of the melting furnace
- Avoiding of excessive tapping temperatures
- More precise temperature control
- Increase in overall productivity
- High alloy recovery

- Desulfuration
- Reasonable heating rates
- Alloying to narrow specification
- Production of clean steel
- Application as holding furnace to avoid back-charging of a melt, in case an interruption occurs at the continuous casting machine. This can be done, if needed, without any time restriction.
- Possible to achieve required temperature control and alloying content for conventional casting cheaper than with Electric Arc Furnaces.

Because of the contact with deoxidised melt, a continuous high risk of reoxidation during the following process steps exists. Therefore ‘’slag free’’ tapping is highly recommended. A complete deslagging is recommended in the case of very low phosphorous specifications, because of the big risk of phosphorus reduction from slag after deoxidation [14, 17].

2.6.2 Vacuum Degassing

Tank degassing units work in combination with the ladle furnace at Villares Metals. This is very common in most of the special steel plants because of the more efficient degassing process after ladle treatment [16]. Without any crane work for transferring of cover or tank both processes are executed in the same position.

The tank degasser consists of a tank with a vacuum cover unit at Villares Metals. When the cover is lowered onto the tank the system is sealed vacuum tight. A rubber ring on the upper border of the tank preserves the vacuum condition. A vacuum chamber is installed at the top of the ladle. This chamber is used to add alloying elements. A device is also provided for sampling and temperature measurement under vacuum. The affordable oxygen can be delivered via water-cooled oxygen lance or by specific alloying elements [17].

In order to stir the melt during vacuum treatment, argon is purged through the bottom of the ladle. Depending on the metallurgical aim and the ladle size, up to 3 porous plugs can be fitted [17].

2.6.3 Vacuum Oxygen Decarburation

For the decarburation of the melt, oxygen gets on the surface of the melt under low pressure. The CO gas, which is formed under these conditions, is pumped off. By blowing oxygen on the surface, the amount of argon and oxygen is minimised. The VOD is perfect for the fast changing production mix of Villares Metals. It offers several operation possibilities. The production schedule can easily be changed from simple engineering grades to stainless grades of high purity, or vice versa, according to the actual orders [17]. The risk of contaminating the material with unwanted elements such as Ni, or Cr does not exist.

The obvious benefit of this method is the higher reduction of carbon under low pressure. This can be seen in the equilibrium curves of carbon and oxygen at different pressures. **Figure 2-9** is showing this condition [17].

Taking into account the influence of the alloying elements (mainly chromium) by the introduction of the activity coefficients (a_c a_o) and the interaction coefficient (f_c, f_o) for carbon and oxygen respectively, the equilibrium curves are defined by the law mass action (Vacher-Hamilton equation) [17]:

$C + O \rightarrow CO$ gas

$a_c * a_o = k * P_{CO}$

$f_c * \%C * \%O = k * P_{CO}$

Figure 2-9 shows a set of C-O equilibrium curves (solid lines) calculated for various temperature and pressures. If the oxygen content exceeds the equilibrium line, carbon will be extracted from the melt. The dashed lines depict Cr-oxidation for different temperatures. Under conditions above these lines, Cr will be oxidised. In the figure, the sequence of C removal by conventional practice, and during the VOD process respectively, is indicated [17].

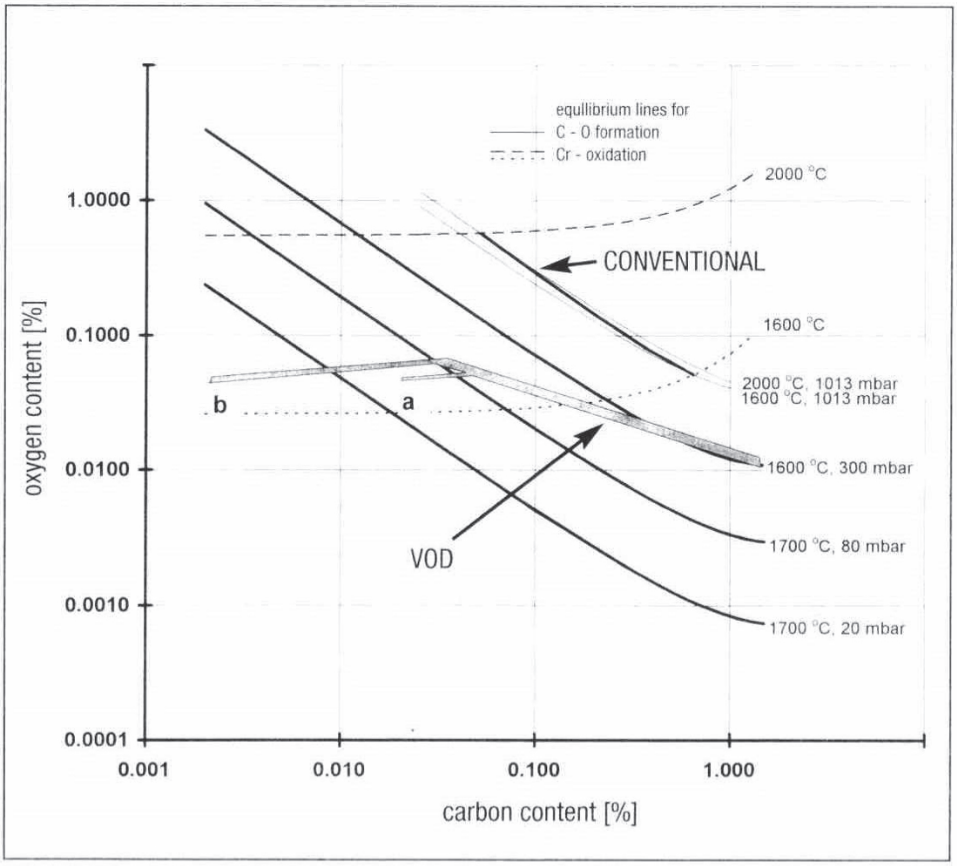

Figure 2-9: Comparison of the production of stainless steel with 18% Cr by the conventional practice and by the VOD process respectively [17]

3 Production of low phosphorus products

3.1 Possibilities contaminations with phosphorus

To produce steel grades with a very low content of phosphorus, it is economically prudent to avoid contamination with phosphorus containing material. At the scrap yard area, several opportunities exist to create a charge of steel with a higher content of phosphorus than planned during the charging of the furnace and the melting processes. There are only two main possibilities for where the contamination can come from:

- The composition of the loaded scrap is different to the composition calculated.
- The furnace is not totally clean and/or contamination with a further material occurs.

Tapping as much as possible of the liquid iron can only minimize the contamination with an earlier melted material. Production of material with low phosphorus content should never be melted immediately after materials with much higher content. Liquid steel should only be left in the furnace if the steel has the same composition than the following heat.

There are however many possible ways of getting charged scrap with different chemical compositions. It is therefore difficult to ascertain the correct step where the pollution happened, because of the high number of possibilities for that. The possibilities for using scrap with higher phosphorus content are as follows:

- Scrap compositions with higher contents of phosphorus were not detected and unloaded at the scrap yard.
- One of the operators is using the wrong type of scrap without noticing it. It is possible that the scrap can be stored in the wrong boxes.

- A mixture is often created at the internal scrap yard. During basket loading, parts of the materials can fall on other different scraps and can get mixed because of the limited space and the missing bays.
- Unsorted scrap is used, which contains parts with high contents.
- It can easily be the case that a mixture of scrap at the internal scrap area is being affected by the crane charging the baskets.

3.2 Scrap sorting

The basic activity for a product with a low content of undesired alloying elements is a precise scrap sorting [4]. The final quality of the liquid metal depends heavily on the charged material [3, 4].

Well-sorted scrap is normally more expansive than mixtures of scrap. But sorting the internal scrap as good as possible and storing it well separated from other scrap groups at the scrap yard is a very important step in the whole process [4]. Inaccurate working methods at the beginning of the process usually lead to costly, long and complicated corrections during the production.

The identification of the material can be done in several ways:

- Visual identification
- Testing the physical properties such as magnetic property, density, electric resistance, …
- Marking chemical analyses with spectroscopes to detect the amount of alloying elements. The usual equipment for fast chemical analysis is the portable x-ray spectroscope.

The possibility of requiring an additional dephosphoration process decreases a lot, if a clean Electric Arc Furnace gets charged with well sorted scrap..

3.3 Oxidation

Oxidation is a very important chemical reaction in metallurgical equipment [1, 3, 4, 12, 14, 15, 16, 50, 51]. With these reactions and some others, it is possible to adjust the chemical composition and to generate heating energy [3]. The chemical reaction is very similar in different aggregates, such as the electric arc furnace and the ladle furnace, resulting in the same oxides. But the quantity of the performed reactions is very different.

3.3.1 Oxidation in Electric Arc Furnace

The products after oxidation can be gasses or particles. Unfortunately, phosphorus combines with oxygen to particles. To get rid of the undesired particles, a slag is necessary. It is widely known that steel quality heavily depends on slag refining capacity [15].

A slag formed primarily consisting of CaO, SiO_2, MnO, FeO, P_2O_5 and MgO. MgO is added to the slag to reduce refractory wear [15]. The graph of MgO saturation is shown in **Figure 3-1**. The more acidic the slag is, the more MgO has to be added to protect the MgO containing refractories. If the slag saturation of MgO is high and a lower content of MgO is added, the slag takes the MgO out of the refractory.

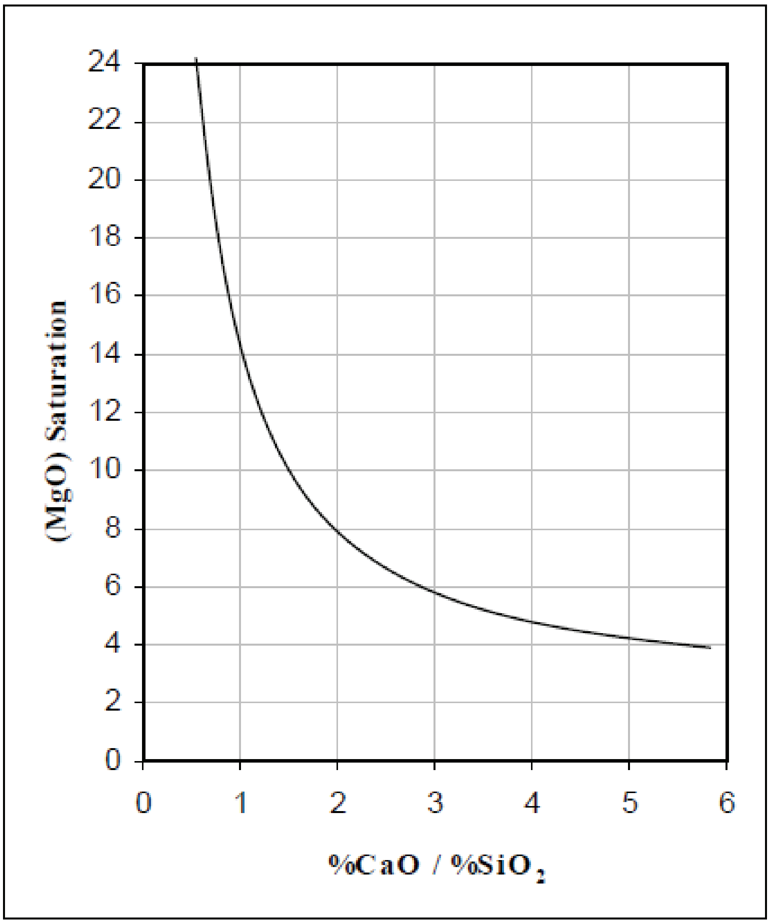

Figure 3-1: MgO saturation depending on slag acidity [16]

The activity coefficient of P_2O_5 is quite low. That is why a basic slag is an excellent phosphorus acceptor [7]. This process is very common at Basemer converter and also at Electric Arc Furnace. It increases the productivity and adjusts the composition for tapping. Often the aggregate productivity increases and the tap to tap time decreases, because of the exothermic reactions of several oxygen reactions [7,15].

Figure 3-2, shows the percentage of phosphorus, absorbed in the slag phase. Line number one is the result of adding all the lime at the beginning of the heat. Line number two is the result, after adding the lime continuously. The final result is almost the same [17]. The FeO concentration in the slag increases continuously, while correspondingly the concentration of CaO decreases. At more than 6 Nm^3 oxygen it is to less CaO in the slag, so that the negative effect of the FeO concentration decreases the amount of P_2O_5 in the slag. At line numer one, where the whole amount of phosphorus was added at once, is no critical limit of CaO and therefore no reduction of phosphorus in the slag [17]. For Villares Metals just line number one is important. This is because in many processes all the lime is added at once.

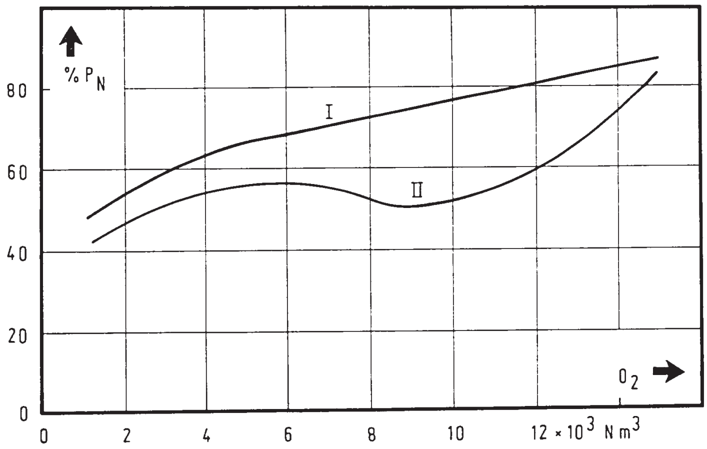

Figure 3-2: Percentage of phosphorus input into the converter absorbed in the slag phase as a function of the oxygen volume inject into the converter [7]

All elements, except C, are more difficult to reduce at high temperature. Si, Mn, C, V and Cr are easier to oxidase than P, because of the lower Gibbs energy level. Some of these elements are shown in the Ellingham Diagram. This means, before the amount of phosphorus can be reduced, a high quantity of these elements get reduced too. Because of high market prices and often-required high quantities of elements (Chromium often < than 12%), phosphorus oxidation is costly.

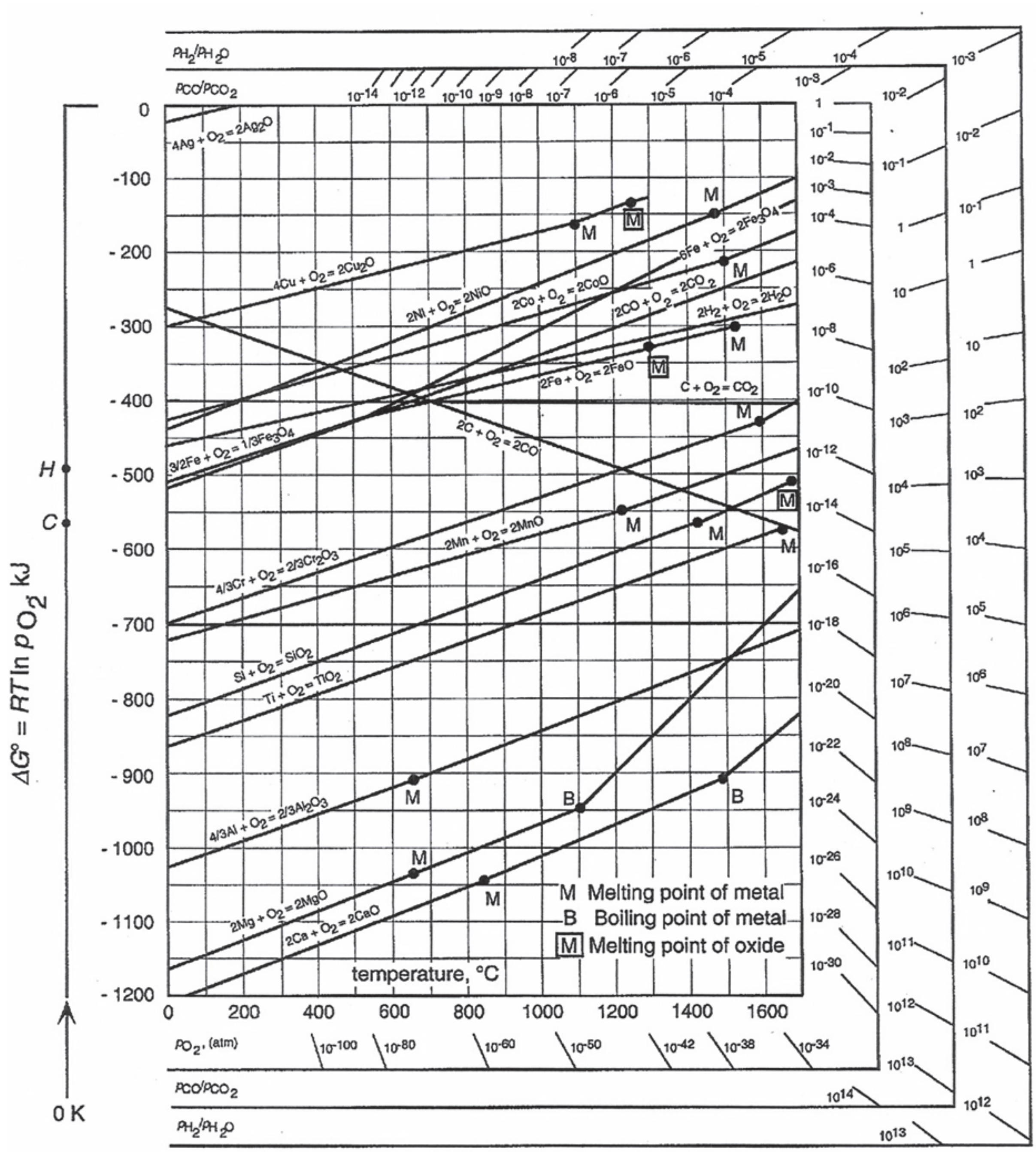

Figure 3-3: Ellingham Diagram [42]

3.3.2 Oxidation in Ladle Furnace

Under actual plant conditions, it is sometimes difficult to produce phosphorus content below 50 ppm in furnaces (Electric Arc Furnaces and Basic Oxygen Furnace) economically. By integrating the Ladle Furnace these grades are produced as following: The primary furnace is tapped (with slag) into a ladle with at least 0.5 m freeboard. Slag formers such as lime, fluorspar and iron ore or mill scale are added during tapping [17]. A typical new slag composition could be: 40 % CaO, 35% FeO, 8 % SiO_2, 5 % MgO, 2 % MnO and 10 % CaF_2 or Na_2O with SiO_2 [7].

A very strong argon-stirring period of about 10 min follows. Stirring is stopped when the temperature of the melt has dropped to about 1560°C [41]. The ladle has to be deslaged carefully. The synthetic slag is added stepwise during the reheating period [17].

The operation time is shifted from more expensive aggregates to cheaper ones with similar oxidation possibilities. Steels with low phosphorus content can be produced with lower production costs.

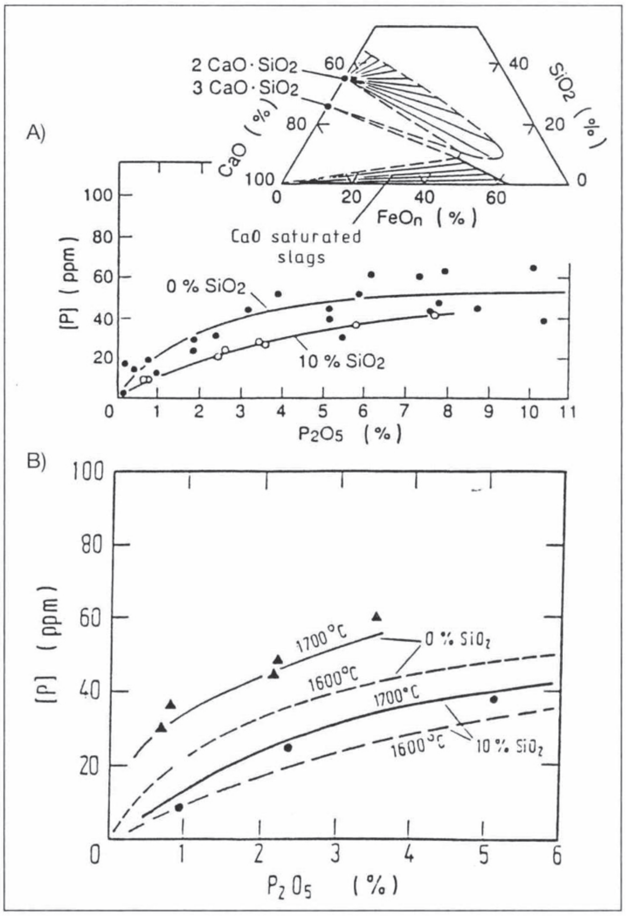

Figure 3-4: Phosphorus equilibrium with lime saturated CaO-FeO-P_2O_5 slags at 1600°C (A) and 1700°C (B) [17]

The equilibrium curves of dephosphoration under a lime saturated slag of the system CaO-FeOn-SiO_2-P_2O_5 at 1600°C is indicated **in Figure 3-4**. 10 % of SiO_2 in slag shifts the equilibrium line to lower phosphorus contents. High temperature tests have shown that it is necessary to have less than 1 % P_2O_5 in the slag to obtain 20 ppm in the melt.

Figure 3-4 shows that higher temperature decreases the efficiency of phosphorus removal. Low temperatures are necessary for a good dephosphoration process.

3.4 Pre Melts

Pre melts are used to avoid the loss of too many expensive alloying elements during dephosphoration or similar oxidising processes. Scrap with a relatively high content of phosphorus and a low content of elements, which can easily be oxidised is put into the furnace. After melting the scrap, the oxidation of the elements starts. Inhomogeneities during oxygen blow lead to deviations in temperature and chemical profiles. It is impossible to adjust the content of one element without changing the content of all the other oxidizing elements too. The reduction of several elements takes place until the concentration of the elements fits the target range of the Electric Arc Furnace. Afterwards the material is taped.

Normally, low phosphor pre melts have a low content of Si, Mn, C and Cr as well. This material is used later as a material resource for creating low phosphorus material. The intermediaries mainly dilute the amount of phosphor, which is included in the scrap, in the liquid steel bath.

This procedure is used for several products at Villares Metals, to protect costly elements such as chrome from reduction.

The negative aspect of this concept is the inappropriate seize of the ingot, which makes the second melting procedure longer, the occupation of the aggregate and the variable costs of melting for the additional process.

4 Oxidation of phosphorus

Many articles and publications were written about the dephosphoration of high chromium and high nickel steels. To produce high chromium materials, iron ores with a specific amount of chromium is used. The dephosphoration is not only important for high chromium stainless steels, but also for all steels with special low content of phosphorus and for the production of low phosphorus ferro chrome [50].

At the end of the 19th century, Pourcel carried out some investigations. He compared the efficiency of phosphorus removal in Bessemer-type converters. He found some interesting key points for a successful remove of phosphorus [23, 38]:

- *"A basic lining and addition of basic fluxes were essential for the removal of phosphorus".*
- *"The slag, after oxidation of silicon during the early part of the blow, contained a considerable amount of* P_2O_5*".*
- *"Low phosphorus steel could be consistently produced if the initial slag was removed and blowing was resumed after the addition of fresh basic fluxes".*
- *"Hard-burnt magnesio-lime refractory bricks were most suitable for such operations".*
- *"The degree of dephosphoration was inversely dependent on temperature".*

These points were applied to the open-hearth steelmaking furnace and culminated in the development of the basic oxygen process as well [16].

In more than 60 years of experimental research into dephosphoration, a range of chemical reaction has been proposed to describe the transfer of phosphorus between metal and slag [16].

$2[P] + 5[O] \rightarrow (P_2O_5)$ …(1)

$2[P] + 5[O] + 4(CaO) \rightarrow (4CaO.\ P_2O_5)$ …(2)

$2[P] + 5\ (FeO) \rightarrow (P_2O_5) + 5[Fe]$ …(3)

Some researchers had doubts about the correctness of these phosphorus reactions. In the 70's, the majority of researchers were using the ionic species to describe the phosphorus transfer [16].

This resulted in different expressions for the phosphorus reaction:

$[P] + 5/2[O] + 3/2(O^{2-}) \rightarrow (PO_4^{3-})$ …(4)

$[P] + 5/2[FeO] + 3/2(O^{2-}) \rightarrow (PO_4^{3-}) + 5/2FeO$ …(5)

$[P] + 5/2(FeO) + 3/2(CaO) \rightarrow ½(Ca_3(PO_4)_2) + 5/2[Fe]$ …(6)

Despite it is generally accepted that dephosphoration occurs through an ionic dissociation into the slag. Many researchers still use Reaction [1] to perform their analyses [16].

4.1 Thermodynamics

The solubility of phosphorus in the slag metal phase of a converter is described in equation number (7) [16].

$L_P = (mass\%P) / [mass\%P]$ …(7)

If no data about the phosphorus behaviour is known, ideal conditions are assumed as an approximation. The quotient of reaction number (1) is shown in equation number (8). It is common to use equation number (1) for the phosphorus transfer [16, 50].

$K_1 = (\%P_2O_5) / [P]^2\ [O]^5$ …(8)

The extent to which the free energy of a species I in solution differs from the free energy of that species under standard conditions, is quantified by the activity of the species [16].

$a_i = \gamma_i \times N_i$ … (9)

Where N_i is the mole fraction of the species i in solution, and γ_i is the Raoultian activity coefficient of the species. The activity coefficient γ_i is usually experimentally determined.

With the Henrian constant h_i, it is possible to calculate the free energy.

$$h_i = f_{i^*}(\%i) \qquad \ldots(10)$$

The equilibrium constant K_1 for reaction (1) is given in Equation (10) [16, 50]:

$$K_1 = (a_{P2O5})/[a_P]^2\,[a_O]^5 \qquad \ldots(11)$$

Equation (11) can be re-written using Equation (9) and (10) to give:

$$K_1 = y_{P2O5}{*}N_{P2O5} / (f_{[P]}{*}[\%P])^2\,(f_{[O]}{*}[\%O])^5 \qquad \ldots(12)$$

The value of K_1 is a function of temperature and is reported in Equation (13) [16]:

$$\text{Log } K_1 = 37160 / T - 29.67 \qquad \ldots(13)$$

4.2 Slag Basicity

Herty introduced the basic concept about 1920 [26]. He introduced the so-called V-Ratio. He used a simple molecular theory to propose the concentration ratio.

$\text{V-Ratio} = \%CaO / \%SiO_2$

The method is an indicator for the depolymerisation of the melt. It also indicates the trend in changes oxide activities with composition.

Reaction number 4 is used, when the importance of slag basicity has to be demonstrated for dephosphoration.

$$[P] + 5/2\,[O] + 3/2\,(O^{2-}) \rightarrow (PO_4^{3-}) \qquad \ldots(4)$$

High basicity allows phosphate ions to be readily accepted into the slag.

CaF_2 is or was often used to lower the melting point of the slag and its viscosity. Studies have shown that in a wide range of CaF_2 no changes of basicity are expected. One to four % of CaF_2 can increase the phosphate capacity by the factor 3 [16].

CaF_2 is increasing the activity coefficient of FeO. The CaF_2 addition has various negative effects, investigated in different medical reports [50]. Too much CaF_2 addition can lower the viscosity of the slag. This can lead to an increase of CaO disownment.

The major components of steelmaking slag are CaO, MgO, SiO_2 and FeO.

The refractories often contain a high percentage of MgO. If no enough MgO is added to the slag, the slag gets its MgO out of the refractories. It is already explained in “Oxidation in

Electric Arc Furnace" on page 40. The solubility limit of MgO in the slag decreases during oxygen blow. Because of this the dissolved lime concentration in slag increases.

For a slag V-Ratio of less than 2, the (MgO) solubility limit is greater than 8 wt% meaning that a large mass of MgO must be added to the furnace as flux to avoid excessive refractory wear [16].

The phosphorus distribution ratio between CaO-SiO_2-Fe_tO slag and liquid iron was found to increase by increasing (%FeO) concentration in the slag to a maximum, after which it decreases [16]. The maximum of FeO in slag is seen in **Figure 4-1**. The maximum is at 20% of the processing time.

4.3 Oxygen Supply

Two types of oxygen providers exist in Electric Arc Furnaces. The first one is the oxygen lance, which is used for steel grades with low contents of elements, which are able to oxidise. The real distribution of oxygen between lance and metal-slag phase is not easily determined. It is a complicated function of various variables like lance high, oxygen flow [16], viscosity of the metal-slag phase, …

The second way of providing oxygen in the metal-slag phase is the addition of oxygen containing alloying elements. Oxygen is reducing the elements, which have a higher oxygen attraction. Al_2O_3 is such an alloying element. But is has to be taken with care. Too much of it and it can change the basicity of the slag and can have negative effects on the dephosphoration process [16].

The major element, which provides the necessary oxygen for the dephosphoration, is FeO.

$FeO_{Liquid} \rightarrow Fe_{Liquid} + [O]$ …(8)

The (%FeO) concentration in the slag is linked with the dissolved phosphorus concentration in the metal through the availability of [O] for dephosphorisation. The concentration of (%FeO) and [%O] are related.

The impact of decreasing the available dissolved oxygen in the metal phase can be interpreted by applying Le-Chátelier's principle [16].

$2[P] + 5[O] \rightarrow P_2O_5$ …(9)

The evolution of slag and metal composition as a function of processing time is shown in **Figure 4-1** [16, 47].

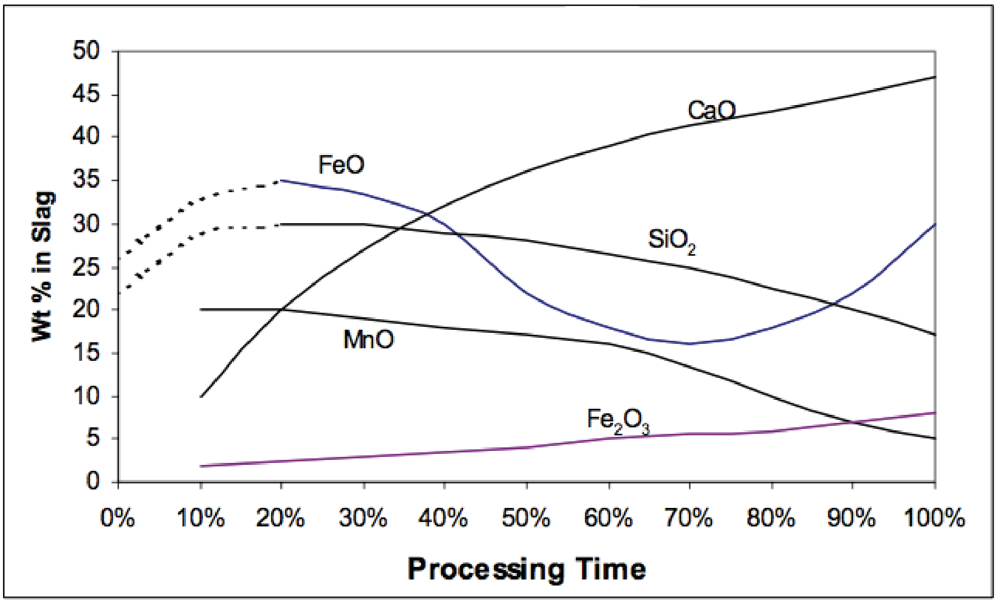

Figure 4-1: Bulk slag composition as a function of processing time [16, 47]

In **Figure 4-1** can be seen, that at the beginning is a fast generation of FeO. This leads to a fast dephosphoration of the metal phase. After some time, FeO concentration decreases and CaO still increases. This leads to a reverse move of the phosphorus into the metal phase. It can be seen in **Figure 4-2** in the region between 40% and 70% of the blowing time.

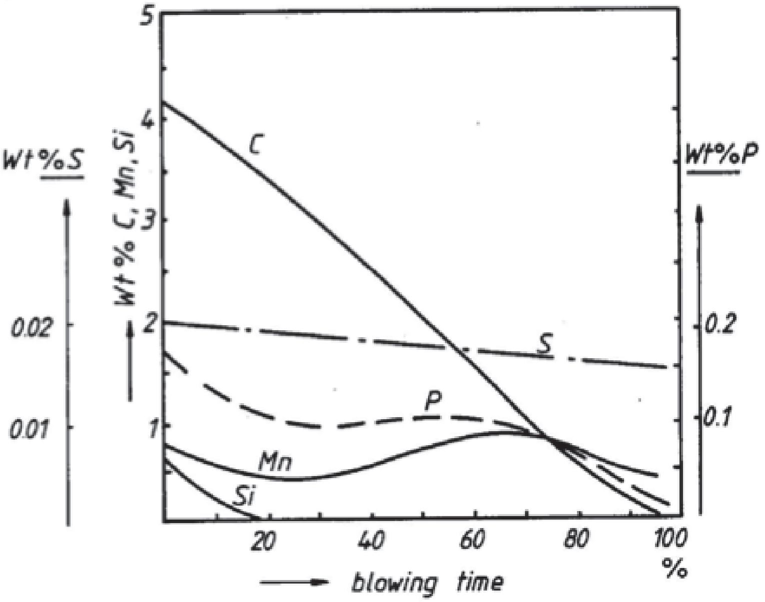

Figure 4-2: The bulk metal composition plotted as a function of blowing time in a 300-ton converter at Corus [16] (formally Hoogovens)

4.4 Kinetics of Dephosphoration

The reaction kinetics is the step, which determines the reaction time. The thermodynamic is just describing under which conditions a reaction can take place perfectly. For the kinetics of dephosphoration, several points are important, that limit the time of reaction [16]:

- *“The rate at which reactants and products move to and from the reaction sites”.*
- *“The rate at which the reagents react at the reaction site”.*
- *“The interfacial area of reaction”.*
- *“The rate of heat transfer to or from the reaction site”.*

These points have to be optimised to speed up the process. But all of this has to be done under the earlier described thermodynamic limits.

Studies made of the kinetics of dephosphoration have shown that the time limiting step is the mass transfer [16]. Similar results are expected at the Electric Arc Furnaces.

Due to the many phases and many reaction interfaces inside the BOF, it is possible for combinations of metal-slag, slag-gas, and metal-gas reactions to occur. A consequence of a reaction occurring through a series of reaction steps is that one or more of those steps must be rate limiting and control the overall rate of the reaction. That is the reason why no single element can be reduced through oxygen blowing. In different areas different oxidising reactions take place [16]. This is why in calculation ”Economic Study of Pre Melts”, no single element is used to get the economic limit of pre melts.

5 Pre melts

5.1 Current Situation

At this time, for some steel grads of Villares Metals, a certain amount of pre-material is melted twice in the Electric Arc Furnace. Especially steel grades with high contents of chromium, nickel and molybdenum and materials with a high alloying content as well as low amount of phosphorus at the same time.

The advantage of this procedure is to avoid unnecessary element losses. The amount of expensive elements, which transform from the liquid phase of the steel into the gas phase and escape or move as oxides into the slag, should be as small as possible.

This is possible by avoiding high contents of phosphorus elements in the scrap or by oxidising these by starting the oxygen blow until the requested phosphorus level is reached (explained in previous chapters).

Villares Metals produces 7 different kinds of pre-melts. The focus there is on one element, and up to three different elements. The aim is to keep the metallurgical adjustment of the material as small as possible.

The material mainly solidifies in conventional casting forms. Some pre melts also solidify at continues casting aggregate, but the metallurgical adjustments at the furnaces have to be much more precise than for conventional casting. Imprecise chemical composition can cause various problems at continuous casting. After the solidification the blocks are moved to the stock. The exact place of storage depends on the chemical composition. All blocks, along with the result of the chemical analysis, are stored in the database of the computer system for assembling the baskets for the Electric Arc Furnace. The pre melts can now be used as an important scrap source.

5.2 Economic Review of Pre Melts

The advantages of the pre melts are:

- saving several elements from oxidation
- a faster final furnace operation, caused by a more precise chemical composition and a better scrap size distribution

The disadvantages of intermediaries are:

- the higher amount of furnace costs for double melting
- the occupancy of the furnace
- increase of working capital caused by added transformation cost
- an additional blooming process to reduce the size of pre melts.

The economical benefit is shown below, Economic Study of Pre Melts is on page number 121. The result clearly shows that the preparation of pre melts is economically reasonable for high alloyed steels with one or two elements to oxidise to low concentrations. For such steels, an additional pre melt in an electric arc furnace is recommendable, even if the furnace is fully occupied. The minimum amount of elements, which have to be saved, is about Cr 0.73 %, V 0.20 %, Si 3.0 %, Mo 0.41 %, Mn 2.36 %. The minimum amount of elements, which have to be saved, depends on many different variables, like:

- Costs of casting
- Costs of rolling
- Price of alloying elements
- Price of current
- Price of power limit
- Tap to tap time → Costs of electric arc furnace
- Costs of electrodes
- And many others ….

If a furnace is not fully occupied and has free capacity, the minimum amount of saved elements, has to be much smaller. The reason is the not existing missed profit generation of the furnace. In this case, materials with low concentrations of easily oxidized alloying elements should be produced by pre melts. The minimum concentration of saved alloying elements, which have to be saved through the preparation of pre melts, is about Cr 0.73 %, V 0.20 %, Si 3.0 %, Mo 0.41 %, Mn 2.36 %. The production process is characterised by high variable amounts and compositions of alloying elements and especially scrap. Because of this, a continous adaption of the economic review of pre melts calculation is recommended [5].

The same results can be used for estimating the benefit of recuperated pre melts. If the difference of chemical concentration (of the first tests samples of recuperated material) to the final taping composition is bigger than the amount of required saved elements, pre melts are highly recommended.

More about this is on page number 61 under “Pre Melt Concept with different Alloying Contents”.

6 Utilization of the EAF

The actual productivity of the two furnaces and their secondary metallurgical aggregates is one of several bottlenecks of the process chain. To increase the productivity, more tonnes have to be produced during the same time. There are only two possible ways of producing more:

- Reduce the tap to tap time
- Find and use unused downtimes

In order to achieve a reduction in tap-to-tap time, a reduction of the duration of the basis stops is imperative. The total amount of the stops in 2012 of Electric Arc Furnace #1 was 1739 hours. For Electric Arc Furnace #2, it was even higher with 1865 hours. These stops have to be divided into stops, caused by absolutely necessary activities such as loading or taping and other stops, which are unforced stops like any damage to the furnace or a lack of energy.

- Unforced stops have to be avoided as much as possible. Different consequential steps for each of the stops have to be taken, in order to avoid the same basis stops occurring again. If such a basis stops happens, a fast solution has to be found to restore operations to normal as soon as possible.
- Stops caused by necessary activities have to be as short as possible. All possible preparations have to be made to do this work quickly.

Also the operation time of the furnace is variable. It depends highly on the loaded material. The size of the material and the density are having big impacts on the melting time of the furnace. Material, which is small in size and has a huge surface area compared to the volume, cannot be melted with a high-energy impact. The arc is much more instable, by only heating up chips with low density. Material of a big size and high density is difficult to melt, because it can easily damage the electrodes. The perfect scrap assemblage for the furnace consists of material that is medium in size and also has smaller chips in the gaps. This material has a high density and can easily build up a stable arc.

Studies have been made on all different reasons of tapping delay, to decrease the tap-to-tap time and generate a higher utilization.

6.1 Reduction of the Analysing Time of Electric Arc Samples

The current procedure of measuring the chemical composition of the melted material in the Electric Arc Furnace is as follows: The sample is pulled out of the furnace with a long ladle and taped into a small cup to solidify. Afterwards it is cut, marked and one part of the sample is sent to the chemical laboratory by airmail. At the chemical laboratory the sample is prepared by hand and analysed with an X-ray spectrometer. The operator checks the results and sends it back to the furnace.

During this process step, the Electric Arc Furnace does not operate. A suggestion has been made to reduce this stoppage by using a portable X-ray analysing tool, which can analyse the material precisely enough to continue operation after some seconds. The average time saving would be 3 to 6 minutes per sample. This would create a total time saving of 3 to 30 minutes per tap-to-tap, depending how many samples are necessary. The exact testing at the laboratory cannot be avoided, but a precise enough overview, to continue the operation till the final result arrives, is possible.

6.2 Reduction of Unforced Stops caused by Power Limit

The energy system in Brazil is very similar to the European energy supplying system. Villares Metals has a fixed contract for the price of the energy per MWh and another contract for the maximum allowed power consumption. By consuming more power than the limit dictates, the company has to pay a multiple of the price they pay normally. Because of this, a short exceeding of the limit is not acceptable and is regulated by sensors and computer software. The software calculates the expected power consumption for each 15 minutes. If the result of the calculation is that the voltage consumption within the 15 minutes will exceed the limit of voltage, then the system shuts down Electric Arc Furnace #2. If the expected voltage still reaches the limit within this 15 minutes, Ladle Furnace #2 shuts down, then Electric Arc Furnace #1 and at least Ladle Furnace #1.

The price per MW is 3474 R$ during the day. Between 6pm and 9pm in summertime and between 7pm and 10pm in wintertime, the price is almost five times higher than the normal price. One MW costs 15822 R$ during this peak time. Because of that, Electric Arc Furnace # 2 is normally turned off during these 3 hours.

The benefit of increasing the limit to avoid the majority of stops is shown by a calculation shown under “Increase of Productivity by higher Power Limit” on page number I. The positive effect of the increased power limit is not enough to produce one more heat per day. Because of this, the positive side effect of an optimum size deviation to reduce the average tap-to-tap time was added to this calculation.

Including all the positive effects on an increased power limit makes it hard to calculate and hard to measure. It can be expected that a positive result of the calculation will be a much higher in reality. Such positive effects are:

- Better cyclization of the production and planning capability (also for the forging department and the blooming mill).
- Less thermal energy loss during melting.
- A continuous operation is better for the consumption of refractories and electrodes.
- Avoiding stops in at secondary metallurgical aggregates.
- Avoiding stops at Electric Arc Furnace #1, which has the same effects as in Electric Arc Furnace #2.

One important boundary condition is that all the other departments are able to handle the additional amount of produced material without generating higher costs than the variable ones. It was also assumed that 100% of the produced material can be sold on the marked at normal prices.

6.2.1 Results of Economical Study to Increasing the Power Limit

The detailed calculation is shown under “Increase of Productivity by higher Power Limit” on page number 114. The result of the calculation with actual data of the year 2013 and statistical data of 2012 shows the advantages of increasing the limit of power.

Increasing the power limit would not lead to an increased production of the Electric Arc Furnace #2, because the average time saving of 4 minutes and 39 seconds is too low to be able to carry out 7 instead of 6 heats in 21 hours. The required reduction would be 10 minutes. Because of this, the calculation was made in combination with the reduction of fusion time, caused by a better distribution of the scrap size.

By increasing the limit from 42MW to 50MW during ordinary daytime hours, it was calculated that 97% of all stops caused by an expected overstep could have been avoided. This would have been about 8407 minutes per year, which is a little bit more than 140 hours per year. This figure already includes the lost production time of up moving and down moving electrodes.

The amount of money required to increase the power limit from 42 MW to 50 MW beside the peak time is 185280 R$ per year. The amount of money, earned with one more heat of low profit product of 0.72 R$ per kg, per day, would generate an extra profit of 1762235 R$/year. The difference between these amounts of R$ can be used to find solutions to decrease the median tap-to-tap time by 5.35 minutes per heat.

The solution to avoiding big parts of scrap will be described in the next chapter and also in the final profit generation.

6.2.2 Profitability of Increasing the Power Limit during Peak Time

Electric Arc Furnace #2 is shut down almost every working day for 3 hours. The reason for this is the lower power limit during this time, which is caused by the five-time higher MW price. The calculation under “Increase of productivity by creating higher capacity by equalizing the power limit during peak time” at page number 117, shows the affordable amount of extra heats per year to be economically efficient by increasing the limit from 30 MW to 50 MW.

The total costs would be 3797280 R$ for this increase. The amount of possible extra heats per year with an average tap-to-tap time of 180 minutes would be about 259 heats. The amount needed to gain profit with this investment is 30 heats.

The real amount of extra heats for a positive result will be a little bit smaller because of positive side effects, which are almost not measurable and vary a lot from month to month. Because of this, it is assumed that the real number of necessary heats to be efficient is about 29 heats.

Positive side effects are:

- Reduced energy loss through decreasing tap to tap time.
- Almost no stops at Electric Arc Furnace #1 because of exceeding the voltage limit.
- No stops of the secondary metallurgical equipment during this time.
- Better planning ability.
- Gain of a continuous production of Electric Arc Furnace #2 would be such that even a short time before peak time heats could get started.
- A continues operation is better for refractory and electrode consumption.
- Better cyclization of production and planning capability.

In this calculation it was also taken for granted that the market is able to pay the regular price for the higher quantity of produced material. The investment should only be made, if the extra quantity of 30 heats per year is absolutely needed.

6.2.3 Reduction of Fusion Time by using optimal Scrap Sizes

The fact that the fusion time is a function depending on many different aspects is very well known at the company. The fact that the size of the scrap can increase or decrease a lot in this time is known too. But except estimations, now serious information about the effect of the size on the time of fusion is known.

The tests at the Electric Arc Furnace were done with the material VSM13A and VMO. VSM13A is a super martensitic stainless steel, which is mainly used in the oil and gas industry and produced in high quantities using Furnace #2. VMO is a low-alloyed steel, used as standard steel for forging dies and extrusion. This material was used for the investigation of the effect of scrap size on the fusion time in furnace #1. The chemical composition of VSM13A can be seen at **Table 6-I**. The chemical composition of VMO is shown in **Table 6-II**. The time of fusion was calculated by the total amount of energy consumption of the heat and the average energy input. In Electric Arc Furnace #2, the investigated material was VSM13A and in Furnace #1 VMO. The three loadings were made with different sizes of scrap. The smallest material was internal scrap in the size of chips. The optimum loading had a lot of different sizes of scrap components, but mainly cut bars of metal of a size of half a meter by 15 cm times 15 cm. Some materials were bigger and some chips were also part of the loading to fill the gaps between the bigger parts. The baskets with the biggest parts were loaded with pre melts with a weight of about 2 tons. To protect the refractories and the electrodes, a specific amount of chips is necessary. 20% of the total weight was made up of chips. The rest were pre melts. Although 20% of chips were used, an electrode broke during the melt down of VMO. Big parts of scrap (about 1 ton) were falling on the electrode from one side of the furnace. These parts were not melted as fast as the material direct under the electrodes.

Table 6-I: Chemical Composition of VSM13A [20]

C	Si	Mn	Cr	Ni	Mo	P
wt%	**wt%**	**wt%**	**wt%**	**wt%**	**wt%**	**wt%**
0.015	0.20	0.45	12.50	5.80	2.10	0.02

Table 6-II: Chemical Composition of VMO [55, 56]

C	Si	Mn	Cr	Ni	Mo	P
wt%	**wt%**	**wt%**	**wt%**	**wt%**	**wt%**	**wt%**
0.05 - 0.06	0.1 - 0.4	0.6 – 0.9	0.8 – 1.2	1.5 – 1.8	0.35 – 0.55	max. 0.03

The investigation was made with material of very extreme sizes. The real loading is far away from the extreme conditions. but out of the collected statistic data of the heats in 2012, it was clear to see that also most of the heats had no perfect size distribution. Also the energy consumption of the heat was measured and compared with the data collected earlier.

As a result of this, an investigation into the economical size reduction of ingots was made.

6.2.4 Economic Results of Pre Melt Size Reduction

The calculation about the increase of the power limit shows, that the amount of minutes for one additional heat per day is 5.35. The results out of the investigations are shown in “Increase of Productivity by higher Power Limit” for VMO in Electric Arc Furnace #1 and in **Figure 7-4** for VSM13A in Electric Arc Furnace #2.

The tap-to-tap time of different heats varies a lot. Between heats with perfect scrap size compositions, heats with very small parts of scrap and heats with very big parts of scrap was a big difference. Electric Arc Furnace #2 had a bigger tap-to-tap time difference than Electric Arc Furnace #1. For the calculation, Electric Arc Furnace #2 is very interesting. A 24-hour production/day is not established at this furnace. Within 21 hours, a predefined amount of heats has to be done. The tap-to-tap time reduction of the furnace #1 is a positive effect, but was not taken into consideration.

The result of “Increase of Productivity by higher Power Limit” and **Figure 7-4** as well as calculation 11.5 on page number 118. This calculation ensures a saving per heat in average of 3.1 minutes at Electric Arc Furnace # 2 and 0.23 minutes at Electric Arc Furnace # 1. This amount of saved time is the result of an average amount of 3.1 wt% of scrap with perfect scrap size distribution, added to all heats. The investment is relatively low with extra costs of 807690 R$ per year, if all 3682 tons (2012) of pre melts get bloomed. It is reasonable to roll the pre melts as long as additional furnace capacity is needed and the market is paying a price with a company profit of 1.06 R$ per kg. If no additional furnace capacity is needed, the material should not be rolled. The saved amount of variable costs of furnaces #1 and #2, would be 453879 R$ per year. This amount is much lower than the extra costs of 807690 R$ for blooming and cutting the material.

At this calculation, many positive effects have not been taken into consideration. These are for example:

- Lower electrode consumption
- Lower risk of an electrode damage
- Lower refractories consumption
- Higher availability for the whole hydraulic equipment (no 2 tons part will fall in the furnace anymore).

Because of these reasons, a little bit lower profit per kg would also gain a profit for Villares Metals.

If the maximum amount of additional heats get sold on the market for a profit mixture of at least 1 R$ per kg, the annual profit of rolled pre melts is 555791 R$.

If it is not possible to sell all 757.49 extra tons, the specific profit has to be more than 1.06 R$/kg. The increase of the specific profit depends on the difference to 757.49 tons. The yield of the Electric Arc Furnace was taken into consideration.

The recommendation for the further production is, to increase the power limit and to cut and press all the materials into pieces, which have a perfect size for a fast melting process 150 mm x 150 mm x 1500 mm to 200 mm x 200 mm x 1500 mm).

If the blooming mill has free capacity and can roll the material for free (no increase of variable costs), the material should be bloomed. The amount of money for oxycut is only 92462 R$ per year and is much lower than the saved variable costs of the furnaces with reduced scrap size.

Several tests on the effect of scrap size were done. The results are shown on page 65 under “Test of Scrap Size Effect on Fusion Time in Electric Arc Furnaces”.

6.2.5 Pre Melt Concept with different Alloying Contents

The idea is to use pre melted materials for a decrease of the melting time.

The expected positive effects would be:

- tap to tap reduction of the final heat
- savings of refractories of the final heat
- more precise in calculating the chemical composition and the final result of composition

The expected negative effects are:

- higher energy consumption for each product
- implementation of a new heating furnace in the process route. This could lower the annual furnace capacity and lead to a higher tap-to-tap time in total.

The optimum material for this procedure is a material, which usually needs very long for the chemical adjustment in an Electric Arc Furnace. Materials, which have a high degree of unknown components, are materials with low target compositions of elements which are difficult to reduce. Villares Metals found a lot of these materials in previous discarded slag of previews years. This material is mainly slag with rest material left on bottoms of ladles and converters. The rest material has often a very high content of iron with a lot of expensive alloying elements.

The used material for the pre melts is more or less a black box of elements roughly sorted by differences in colour size and shape. Because of this, several groups were established. But the content of elements is still unknown.

6.2.6 Economic Review of a Pre Melt Concept

The detailed calculation is added in “Economic Study of Pre Melts” on page number 114. The result of this calculation is the same as for the investigation of economic benefit of existing pre melts. If the chemical composition of scrap and the composition of the final product are not to big, a pre melt is not recommendable. The requested differences of chemical composition is the same as in the investigation of economic benefits of existing pre melts on page number 52.

Nevertheless, the typical amount of oxidised elements are smaller than the amount of requested saved elements. The conclusion is, that for the normal sorted scrap, a pre melt generation does not make sense and is a waste of money, capacity and time.

Materials with an unknown or very imprecise composition are typical materials for a pre melt generation. Villares Metals has such materials and is planning to make double melting processes with this scrap, pulled out of slag and stored at the area during the last 10 to 15 years.

6.2.6.1 Recommended Pre Melts

The mechanism of achieving the final recommended compositions in the Electrical Arc Furnace by using pre melts, is very complex and includes many variables. These all influence each other. That is the reason why the calculation was made out of already existing data. The recommended amount of added pre melts was derived from various pre melts. The average difference between the elements of the pre melts and the composition at tapping were calculated. Out of this, information and the information of the percentage of used pre melts, a mathematical model was built up. The graphical solution as well as the resulting mathematical models is shown in **Figure 11-22** to **Figure 11-38**.

The results were differences of chemical scrap composition and chemical taping composition. With all these differences, the operators were able to produce the correct chemical composition of the final product. All the data is shown in various diagrams, where the achieved chemical difference, versus the added weight percentage of pre melts is drown. Out of these data, EXCEL calculated an exponential regression. The calculation was done for a positive change and a negative change of chemical composition. How to solve a negative or a positive deviation in the composition is a big difference in process. A higher content of an element is only possible through alloying. Changes in the other directions are able through diluting or oxidation in the Electric Arc Furnace or a secondary metallurgical aggregate. Important is, that the calculation has to be done in percentage. The reason is the different size of the two Electric Arc Furnaces.

The database will be more precise the more data will be added. The adjustment of the exponential regression becomes better and better for each element. Out of the used data, a good mathematical model was created, which is a big help in the process of pre melting and melting final heats.

By knowing the mathematical formula of the exponential regression, the maximum amount of added pre melts can be calculated. By fixed amounts of added pre melts, the chemical composition can be calculated.

More about this tool is under “Quantity Estimation of used Pre Melts” on page 73.

7 Experiments Process Engineering

7.1 Test Result of Blooming various Pre Melts

To proof the possibility of reducing the square diameter and enlarging the surface of scrap, the material got bloomed. This was done to speed up the melting process of the Electric Arc Furnace. The total amount of produced pre melts is 3862 tons per year (2012). The blooming aggregate has some free capacity. Pre melts could be bloomed, when the steel plant does not deliver the material on time. This free capacity can be used to heat up the materials and to roll it.

The tests were made to prove the possibility of rolling cheap pre melts. The cheapest pre melts do not have a hot top. A hot top is used to reduce the shrinkage of the material at the top and increase the quality of the blooming process. This shrinkage and the high variation of chemical compositiont can lead to different problems during rolling processes. Typical problems are open tops or ends. Open tops or ends can make it impossible to continue the blooming process or scratch the surface of the rolls.

Beside the hot breakage or an open end of the bar, no limitations about the surface, the exactness of the measurement and the straightness of the bar, were given.

The first test was with two different pre melts. One pre melt with low phosphorus content and the other with high content of nickel and chromium were used. Both of them had no hot top. The final size of the bar was 145 mm to 165 mm with a length of 3 m. The length of 3 m is necessary to continue the cutting and cooling process, without any extra expenditure. The chemical composition of the materials can be seen in **Table 7-I**.

Table 7-I: Alloying Content of Bloomed Material

Heat Nr.	C	Si	Mn	P	S	Co	Cr	Mo	Ni	V
	m%	m%	m%	m%	m%	m%	m%	m%	m%	m%
4845920	0.07	0.18	0.15	0.0029	0.002	0.01	0.25	0.08	0.06	0.01
804612	0.657	0.31	0.48	0.032	0.038	0.20	10.15	1.29	7.98	0.105

7.2 Test of Scrap Size Effect on Fusion Time in Electric Arc Furnaces

To prove the impact size and size distribution on the time of fusion, one material was selected for furnace #1 and other for furnace #2. Furnace # 1 got loaded with typical scrap for Villares Metals and VMO. Both materials are very similar. Because of logistical problems these two materials had to be used. The average tap-to-tap time of VMO in furnace #1 was 141.9 minutes in 2013. These materials are not very different in their chemical composition and are getting produced out of the same scrap types. The diagram of the tap-to-tap time of VMO in Electric Arc Furnace # 1 is shown at **Figure 7-1**. The chemical difference between the different heats is not very important. The chemical adjustment is taking place after the melt down.

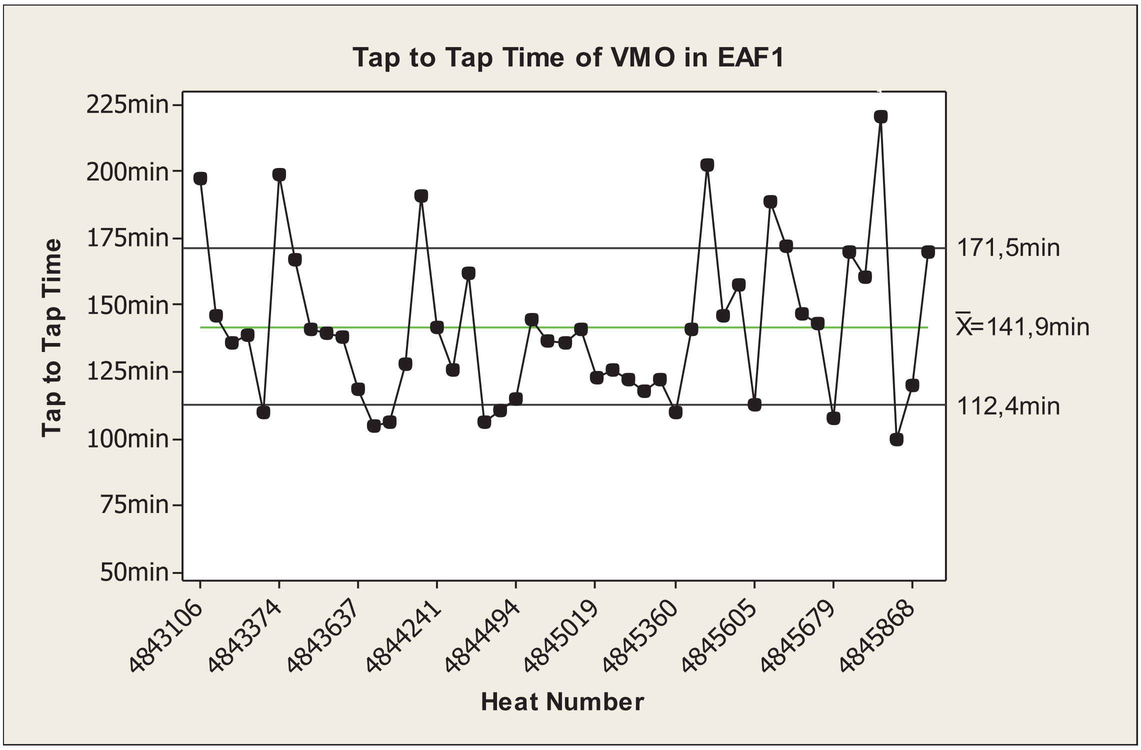

Figure 7-1: Tap to Tap Time of VMO in Electric Arc Furnace #1 in 2013

Three different melts were made in electric Arc Furnace #1, to proof the effect on the fusion.

- The first heat assembling was like every furnace operator would like to have every day. The parts were about 200 mm x 200 mm. A few of them had a smaller square and others were a little bit wider. The lengths of these materials were between 300 mm to one meter. To have an optimum charged baskets, the spaces between the big parts of scrap were filled with small chips. The amount of used chips was 20% of the total charge in weight.
- The scrap for the second were only big parts, which came from the forging department. This scrap was like an internal scrap. To avoid a damage of the electrode, some chips were used too. The amount of used chips was 20%.
- The third heat were baskets with 100% of chips. This scrap with low density needed 5 baskets to fill the furnace with 38 tons.

Furnace # 2 got loaded with a different material. The material was VSM13A. The average time of fusion for this material in this Electric Arc Furnace was 205.6 minutes in 2013. This material was very interesting, because big parts like pre melts with 2 tons and low content of phosphorus were used. For this heat three different charges with three different scrap size distributions were necessary. The diagram of the tap-to-tap time of VSM13A in Electric Arc Furnace # 2 is shown at **Figure 7-2**.

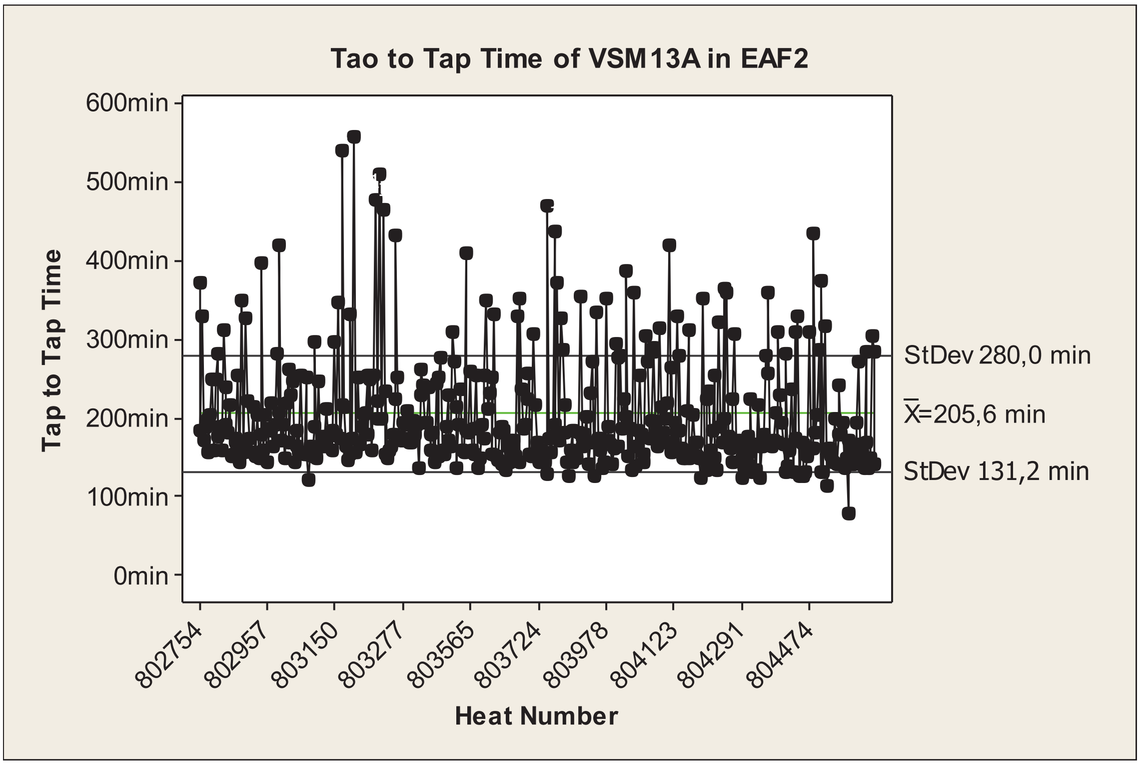

Figure 7-2: Tap to Tap Time of VSM13A in Electric Arc Furnace #2 in 2013

- The first test was done with scrap which had the perfect scrap size distribution for a fast melt down. The material was 150 mm x 150 mm and had an average length of one meter. Many round bars were used, which were left from the conventional casting of different VSM13A heats. Between the big parts were some chips. They were used to fill the space in between the big parts. The charging was done with three baskets.
- The second heat was with big pieces. Pre melts with 1650 kg were used and also big scrap with more than 1000 kg. 20% of chips should protect the electrode from damages, like at Electric Arc Furnace #1.
- The last heat for this test was with 100% chips of VSM13A. 6 baskets were used to load the furnace. The charging of the furnace took some minutes, because the material of the last baskets had to be pushed down into the liquid metal bath. Otherwise a closing of the furnace is not possible.

The result shows, that material with a high weight to surface coefficient need longer to melt than materials with a lower coefficient. But materials, with low weight and big surface, have normally a low-density level. This is negative for a stable arc and a fast melt down.

7.2.1 Example calculation of Weight-Surface Coefficient:

Big parts: 424 mm x 424 mm x 1500 mm

Surface: 2.9 m^2 (**Table 11-V**)

Weight: 2127 kg (**Table 11-V**)

Weight-Surface Coefficient: 733 kg/m^2

Medium parts: 140 mm x 140 mm x 1000mm

Weight Surface Coefficient: 242 kg/m^2

Small parts: 3 mm x 100 mm x 20 mm

Weight Surface Coefficient: 0.12 kg/m^2

The tests in the Electric Arc Furnace #1 were giving some problems, which had an effect on the final result. By melting the big parts of scrap, the material was unstable and felt from the side of one furnace to one electrode. The electrode broke and it took more than 25 minutes to continue with the process. During this time, a big amount of thermal energy got lost. Nevertheless, the results show differences between fusion of the different charges. The fastest one was the material with the perfect size distribution. The time difference was about 3 minutes. The test result is shown in **Table 11-V** on page 104.

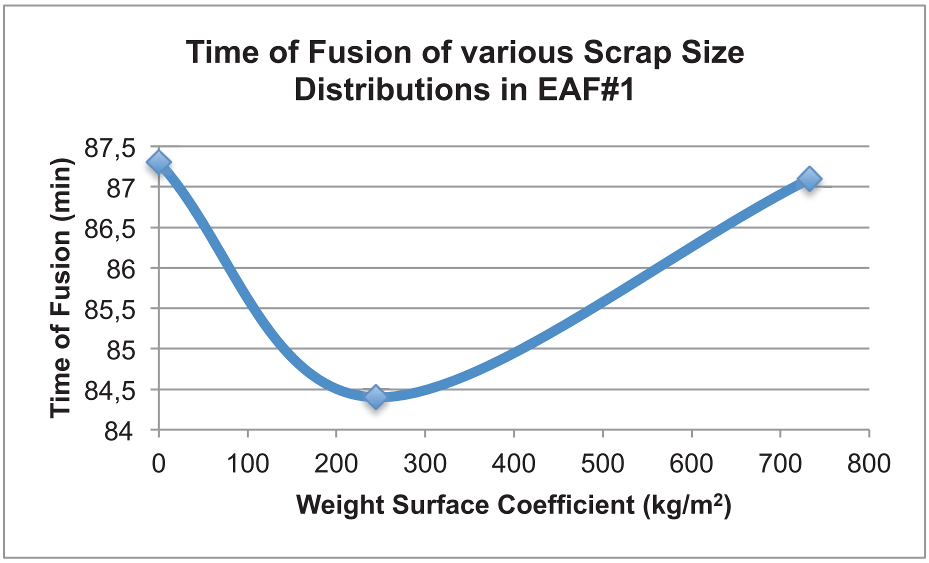

Figure 7-3: Time of Fusion in EAF 1 with various Scraps Size Distributions

The test results of the Electric Arc Furnace #2 are similar. The results are shown in **Figure 7-3** where the graphic interpretation of the tap-to-tap time of all heats of VSM13A in 2013 is drawn. **Figure 7-4** shows the time of fusion result, compared with to the weight-surface parameter of charged material. It is shown the same way as with VMO in Electric Arc Furnace #1 before.

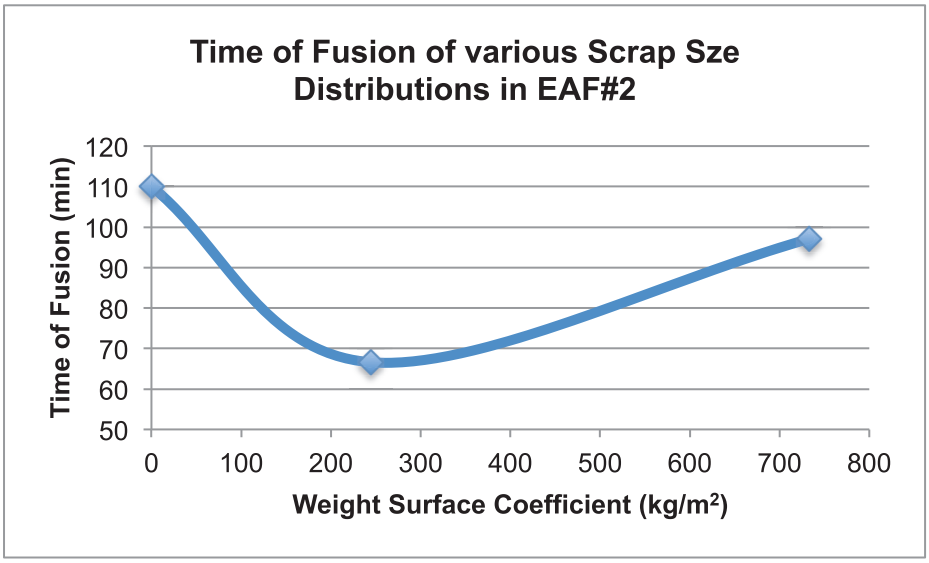

Figure 7-4: Time of Fusion in EAF 2 with various Scraps Size Distributions

The difference between the chips, the optimum charged material and the big parts, were 36 and 43 minutes.

The results of these tests were used for further calculations and investigations concerning the economical aspect of scrap size reduction and power limit increase.

The heat numbers of the tests are shown in **Table 11-V**.

7.3 Pre Test of Recuperated Scrap

To know more about the composition of recuperated scrap, one small samples was prepared. The scrap pieces were collected and melted in an induction furnace. The slag was removed and after solidification, the chemical composition got analysed. **Figure 7-5** and **Figure 7-6** show one type of recuperated scrap.

Figure 7-5: Storage of Recuperated Scrap

Figure 7-6: Recuperated Scrap

Figure 7-7: Recuperated Scrap in Detail

The quality of the recuperated scrap varies a lot. The scrap got stored at the slag area for many years. The product mix of the company was changing many times during this years. Because of this, different areas contain metals with different compositions. By digging down the "mountains of slag", different steel grades appear. That is the reason, why the mixture of scrap is changing frequently.

The test was done to analyse the process of getting scrap samples of the chemical composition. It was important to know more about the complexity and feasibility of this procedure. The results of the chemical composition is shown in **Table 7-II**. In **Table 7-III** is the chemical composition of two heats shown which only contain magnetic recuperated scrap.

Table 7-II: Chemical Composition of Recuperated Material

Heat Nr.	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**	**V**
wt%	**wt%**	**wt%**	**wt%**	**wt%**	**wt%**	**wt%**	**wt%**	**wt%**	**wt%**
1	0.77	0.046	0.13	0.03	0.029	0.92	0.59	0.52	0.03

Table 7-III: Chemical Composition of Recuperated Material

Heat Nr.	**C**	**Si**	**Mn**	**P**	**S**	**Co**	**Cr**	**Mo**	**Ni**	**V**
wt%	**wt%**	**wt%**	**wt%**	**wt%**	**wt%**	**wt%**	**wt%**	**wt%**	**wt%**	**wt%**
803882	1.435	1.59	0.99	0.047	0.025	0.08	11.85	0.77	4.3	0.276
804330	0.434	0.43	0.48	0.053	0.041	0.1	10.55	1.28	5.72	0.244

A preview about the next recuperated scrap material was created. This might be an important procedure to know more about the following scrap quality and to create regular forecasts.

The weight of scrap was 430 g. To melt the material and to create a useful slag, 44 g of CaF_2 and 2 g of Al were added. CaF_2 had to be added to get a specific slag fluidity and Al to reduce some components.

The metallic output of the melted material was 349 g. The yield of the melt down is 81.2%. This is a very low amount of metallic component in recuperated scrap. It even has to be considered, that the material was already separated from parts with a visible lower metallic content.

Figure 7-8: Melted Metallic Content of Recuperated Scrap

Figure 7-9: Melted non-metallic Content of Recuperated Scrap

7.4 Quantity Estimation of used Pre Melts

To ensure a stable process and to assist process engineers, making the right decision, a tool was created. This tool calculates the maximum amount of added pre melts. It can be used in two ways:

- The minimum quantity of pre melts is known and the limits of chemical composition of pre melts can be calculated. This helps to create pre melts composition limits. Prerequisite is the knowledge of the production plan for the following days and a rough overview about the expected chemical composition of recuperated scrap. The more days of known production plan, the better.
- The maximum amount of used pre melts can be calculated. This is important, because of a decrease of possible used pre melt by increasing difference between pre melt composition and chemical composition of the final steel grade.

Several data of earlier pre melts were used to create this tool. The difference of chemical composition of each pre melt, to the final taping composition and the amount of used pre melts, were transferred to diagrams. Two diagrams exist for almost every element. One diagram for a negative deviation (the quantity of the element in the pre melt was lower than the final composition limit of taped steel) and one diagram for a positive deviation (the pre melt had a higher concentration of this element, than the final taping composition) was made. Alloying elements or decreasing the amount of a specific element are two totally different processes. That is the reason why two different diagrams were absolutely necessary for almost every element. The difference in chemical composition of the pre melt composition in comparison to the final taping determines the amount of the used pre melt. There is never a lack of tramp elements. Accordingly diagrams for such elements were not drawn. Furthermore addition of phosphorus or sulphur is never required.

The difference of composition was drown at the abscissa and the amount of added pre melt at the asymptote. Out of the data of 22 pre melts, an exponential regression was drawn. One fixed point of this extrapolation was, at 100% of pre melt. No changes of composition are possible at this point. This boundary condition is not totally correct, but a good approximation. The final chemical composition can change a little bit through oxidation and deslaging.

Figure 7-10 and **Figure 7-11** show the extrapolations of the element molybdenum.

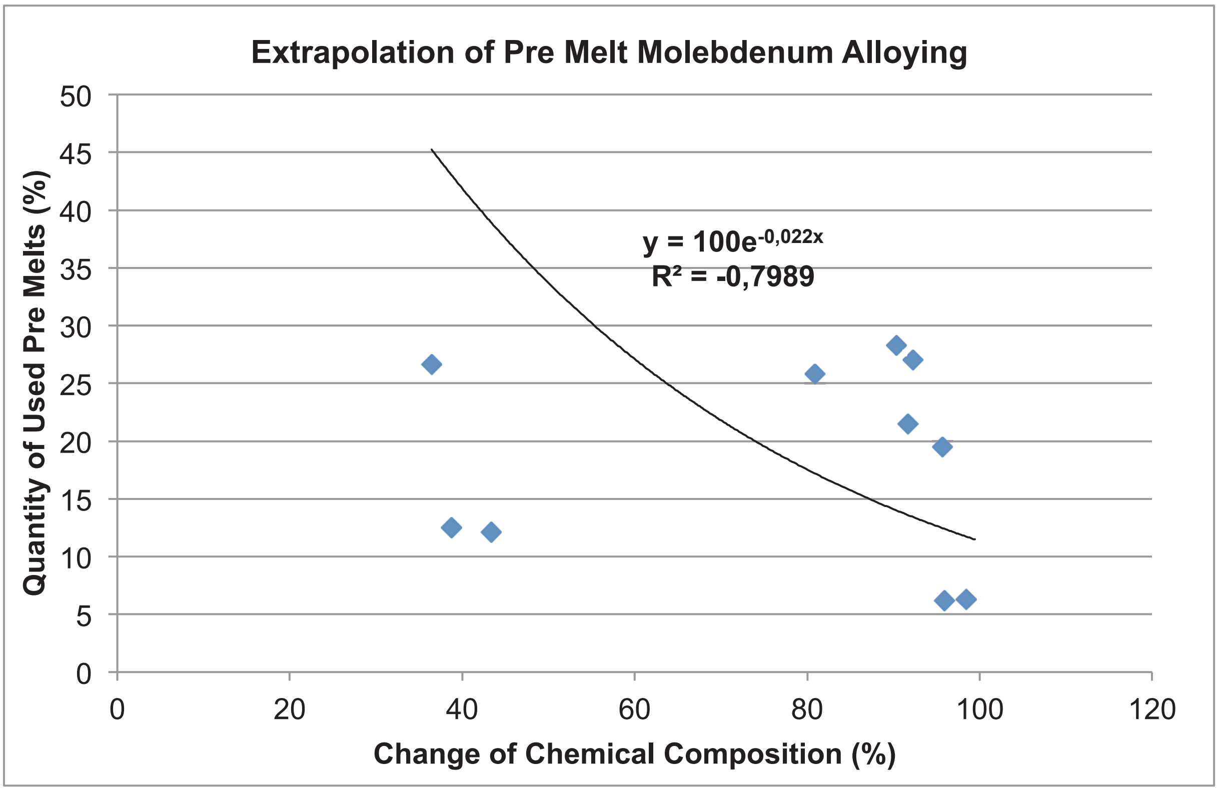

Figure 7-10: Extrapolation of Pre Melt Molybdenum Alloying

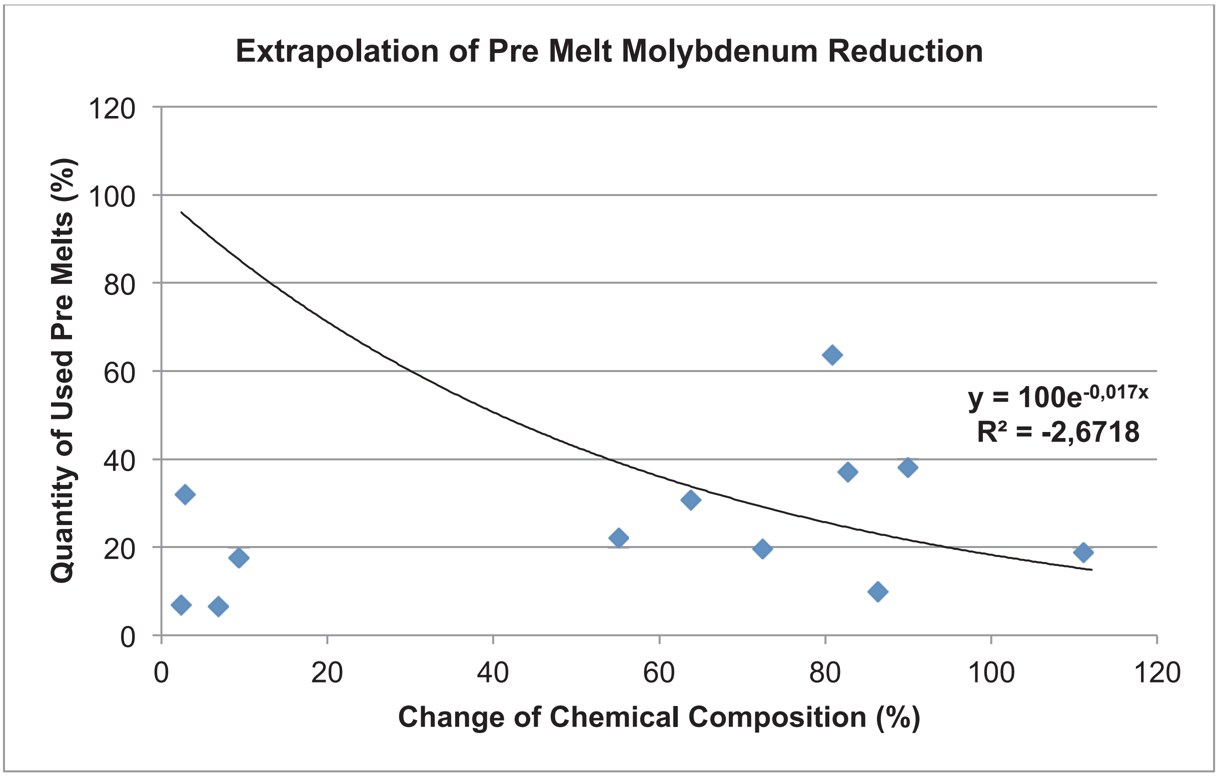

Figure 7-11: Extrapolation of Pre Melt Molybdenum Reduction

The extrapolations of other elements are shown in **Figure 11-22** to **Figure 11-38**.

R^2 is an indicator for the exactness of as extrapolation. If all points are on line, R^2 is 1. The greater the difference to 1, the greater is the inaccuracy of the extrapolation. With more and more data of produced heats, the extrapolation becomes more precise.

8 Experiments Material Science

Several different experiments were made to proof the real feasibility of the material science theories of steels with low and high phosphorus contents.

8.1 Material Selection

VSM13A is the chosen test material. It is a super 13 % Cr martensitic stainless steel for mainly oil and gas industry [20].

The material was chosen because of several reasons:

- It is the material with the highest production volume of Villares Metals (2012 and 2013).
- Electric Arc Furnace #1 and #2 produce this material.
- Most of the material is produced by the production with pre melts as a scrap component.
- Low phosphor content is needed (maximum 0.02 wt%).
- The volume of oil and gas extraction will increase. These and similar steel will be needed [29].

VSM13A is a martensitic stainless steel with improved mechanical properties, weldability and corrosion resistance regarding the normal 13 wt% Cr martensitic steels [20]. These super martensitic families are based on iron, chrome, nickel and molybdenum. They have a low amount of carbon, nitrogen, phosphorus and sulphur [21]. The chemical composition of the VSM13A of Villares Metals is shown in **Table 6-I** [20]:

The requirements are very tough for materials in the oil and gas industry [30]. The main application includes flow-lines transporting produced fluids with high level of CO_2 and low levels of H_2S in the oil and gas industry [20]. These materials are used under conditions where improved corrosion resistance, in relation to carbon steel, is needed and has to be free of coating and inhibitors [19]. An economical aspect is the cheaper production, compared to duplex stainless steels. That is the reason why 13 wt% Cr super martensitic grades are substituting more expensive duplex stainless steels in many applications nowadays. Forged parts, coupling stocks, flanges and rings can be produced with this grade [21].

The Material has a high resistance against corrosion in CO_2 and/or chloride containing environment and low levels of H_2S [20].

The material is designed to keep toughness at low temperatures (customers require high toughness at -10°C). The steel is applied to petroleum extraction offshore and inshore, when showing sufficient toughness at -60°C [20].

Table 8-I: Mechanical Properties at Room Temperature (minimum values) (Quenched and Tempered) [20]

Yield Strength	**Ultimate Tensile Strength**	**Elongation**	**Reduction of Area**	**Hardness**	**Impact Strength**
0.2% Mpa	**Mpa**	**%**	**%**	**HRC**	**J**
655	724	18	40	Max 27 to 32*	**

* according the requires strength level

** Charpy Impact test (ISO V) (at -60°C): min. ave: 40J and min single: 30J

8.2 Thermo-Cal Calculation

A Thermo-Cal calculation was done before the material was tested. Calculations for the expected phases of each sample (explained in the following chapter) and a phase diagram, with variable content of phosphorus, were created.

The phase diagrams with the final parameters of the calculation are attached in the appendix of this theses (**Figure 11-17**, **Figure 11-18**, **Figure 11-19**, **Figure 11-20** and **Figure 11-21**).

The calculation was done with the Thermo-Cal Version 5. The parameters were the chemical composition of each sample and a temperature of 400°C to 1600°C. The expected phases where Liqide, FCC-A1, BCC-A2, Chi-A12, Sigma, M23C6, M7C3 Hcp-A3, FeP, M3P, MnS.

The result of the Thermo-Cal calculation fits very well to the expected microstructure of the material (explained in: “The Effect of Phosphorus on Steel”). The expected laves phase was one of the results of the calculation. The M3P phase, consists of Fe_2Mo and phosphorus. Literature results have shown, that a laves phase contains about 65 at% iron, 26 at% Molybdenum and up to 9 at% Phosphorus. This concentration was obtained in a ferrit with 0.95 wt% of phosphorus. This concentration is almost constant, except at the very early stages of seggregation [22].

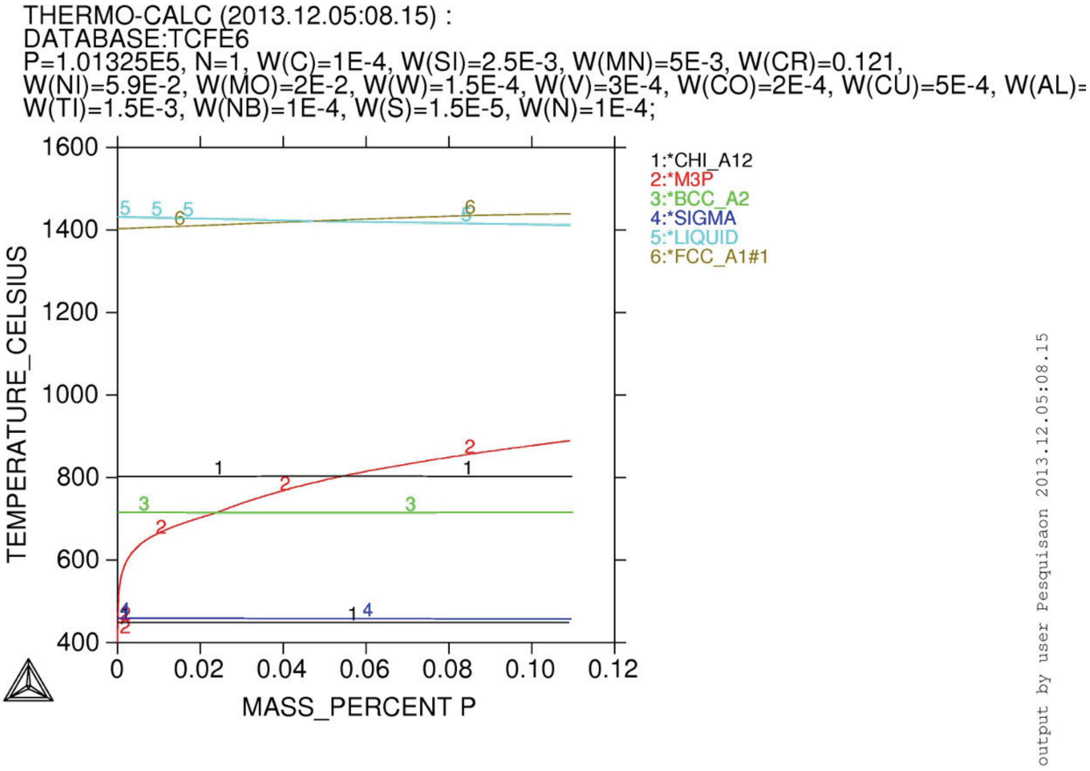

Figure 8-1: Phase Diagram of VSM13A

8.3 Sample Preparation

Table 11-XVII, shows the chemical composition of the prepared samples. The samples were produced in a vacuum induction furnace. Each sample was an ingot with about 55 kg, a medium section width of 140 mm^2 and a length of 300 mm. The logarithmic forming degree per heat was less than that of the rolling process of customers as well as the total forging degree of the customer [11]. The material is ordinary VSM13A steel, produced earlier at Villares Metals. Only the content of phosphorus varies. The phosphorus got adjusted with the alloying material ferro-phosphorus (all materials with a phosphorus content >0.02 wt%), or by oxidising the phosphorus and adjusting all the reduced elements with proper alloying elements (material with phosphorus content of 0.01 wt%). The image of the ingots is shown in **Figure 11-5**.

The ingots got homogenised at 1200 °C for 4 to 6 hours. After this, the material was forged to bars, with a height of 40 mm and a width of 60 mm. The minimal temperature at the forging process was 800 °C. The finished bars are shown in **Figure 11-6** and **Figure 11-7**.

4 Charpy impact samples, two tensile strength samples and one sample for potential corrosion tests were machined. The orientation of the long side was lengthwise to the bar. All the samples were taken out from the middle section of the bar (the area of proved material started about 200 mm from the sharp end of the forged bar).

The samples got heat treated at 950 °C. After this procedure, the material got quenched in water. For the reduction of the thermo mechanical stresses, two tempering stages had to be done. The first one was 30 minutes at 650 °C. At the end was the material water-cooled. The second tempering stage was 30 minutes at 550 °C for 30 min with an air-cooling. These temperatures are very interesting. The industry does similar heat treatments with this material. Out of the literature, the peak of phosphorus segregation is at 500 °C to 600 °C [10,13, 19 to 26].

8.4 Charpy Impact Test at -10°C

The client requires a high toughness at -10°C. The toughness should be higher than 200 J at these temperatures. Gas could escape through a small crack and cool down the material, and cause such low temperatures. At such temperatures, no changes of the physical properties are allowed.

4 samples of each material were produced. This was done to ensure good statistics. Each sample had the notch to create a more multiaxial stress state. The preparation of the sample and the testing was done after ASTM E23. The samples were cooled down to -10 °C in liquid alcohol. The absorbed impact energy was measured analogue and digital. The digital datas were checked with the analogue ones. But for the calculations, just the digital ones were used.

The results of the impact tests are shown in **Figure 8-2**. The measured data and the statistic evaluation are shown in **Table 11-VII** and **Table 11-VI**.

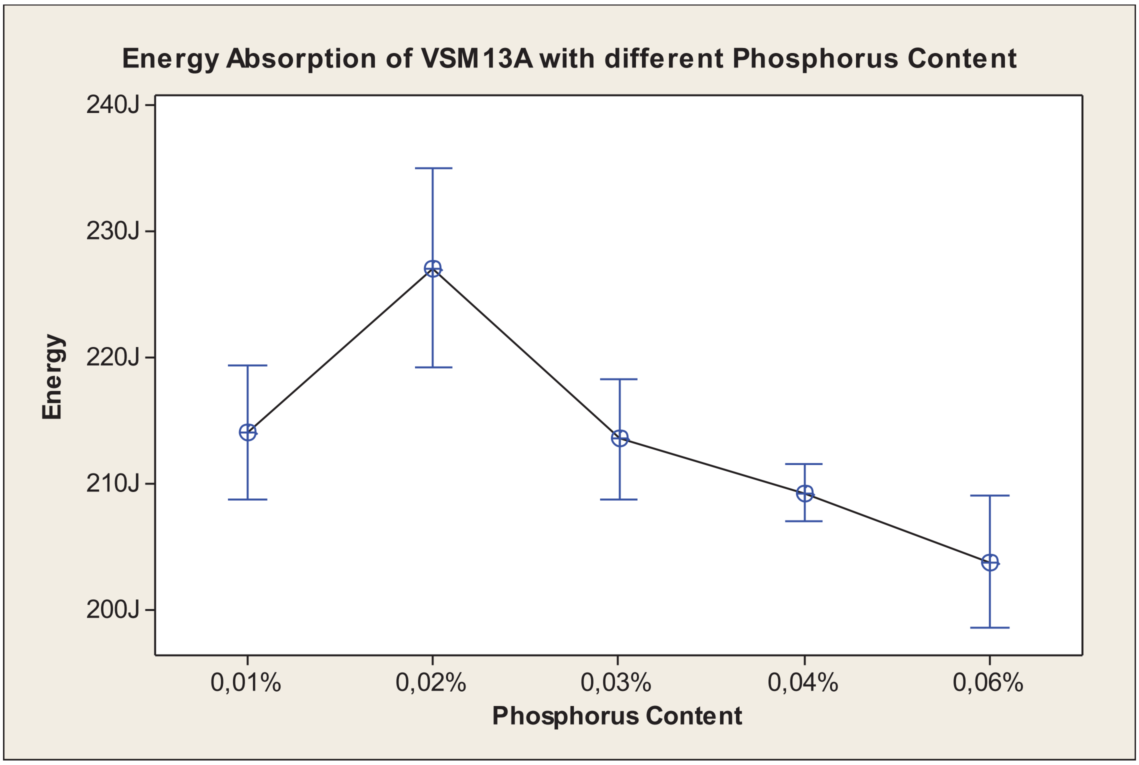

Figure 8-2: Results of the Charpy Impact Test at the VSM13A with different phosphorus content and standard deviation at -10°C

A tendency for decreasing of toughness is apparent, out of the test results. The measured results are still higher than the required limit. Also with the highest phosphorus content of 0.06 wt%, the media toughness is higher than 200J. It seems that molybdenum is almost neutralising all the negative effect of phosphorus. The mechanism was explained in “The Effect of Phosphorus on Steel”. The material with a phosphorus content of 0.02 wt% has the highest toughness of all materials. Including the samples with a content of 0.01 wt% phosphorus. The strange behaviour, of the steel with 0.01 wt% of phosphorus, has to be in perspective. The difference of the medium absorbed energy is a little bit more than 20 J. This is not much and can easily be caused by inhomogenity. A tremendous decrease of absorbed energy, similar to the results of H11 tool steel, is not apparent. The results of phosphorus on H11 tool steel were shown in “Mechanism of Phosphorus in Steel on Material Science Scale” on page 10.

The statistic range of the results is quite different. The standard deviation of the material with 0.04 wt% phosphorus was 4.43 J compared to the material with 0.02% phosphorus content and a standard deviation of 15J. This is more than 3 times smaller. The material with 0.04 wt% of phosphorus had the most precise test results. A big standard deviation is a note for a less accurate test result. All the other materials have a standard deviation of about 10 J.

8.5 Charpy Impact Test at -10°C, -45°C and -80°C

The material was tested at -45 °C and -80 °C too, to ensure a meaningful test temperature.

The samples were prepared the same way than before for the -10 °C tests. To speed up the whole process, only three samples of each material and for each temperature were produced. With three samples proper statistics are possible. The test results are shown in **Figure 8-3**. **Table 11-IV** to **Table 11-X** show the measured data and the statistic evaluation of the tests.

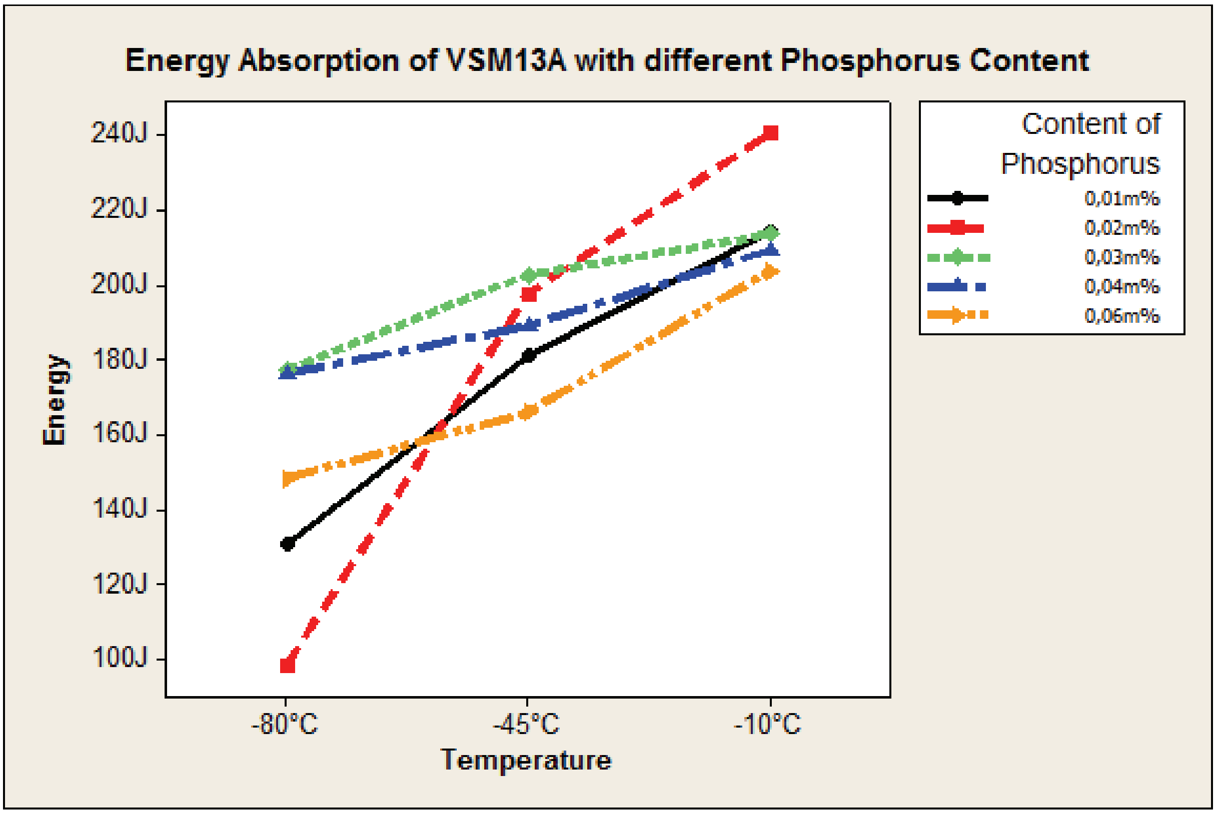

Figure 8-3: Results of the Charpy Impact Test at the VSM13A with different Phosphorus Content

In **Figure 8-4** the standard deviations of the results are shown. For most of the results the standard deviation is smaller than 10 J. Only two results have a significant bigger standard deviation than the others. The biggest standard deviations are about 15 J. These results are more imprecise than the others and must be interpreted accordingly.

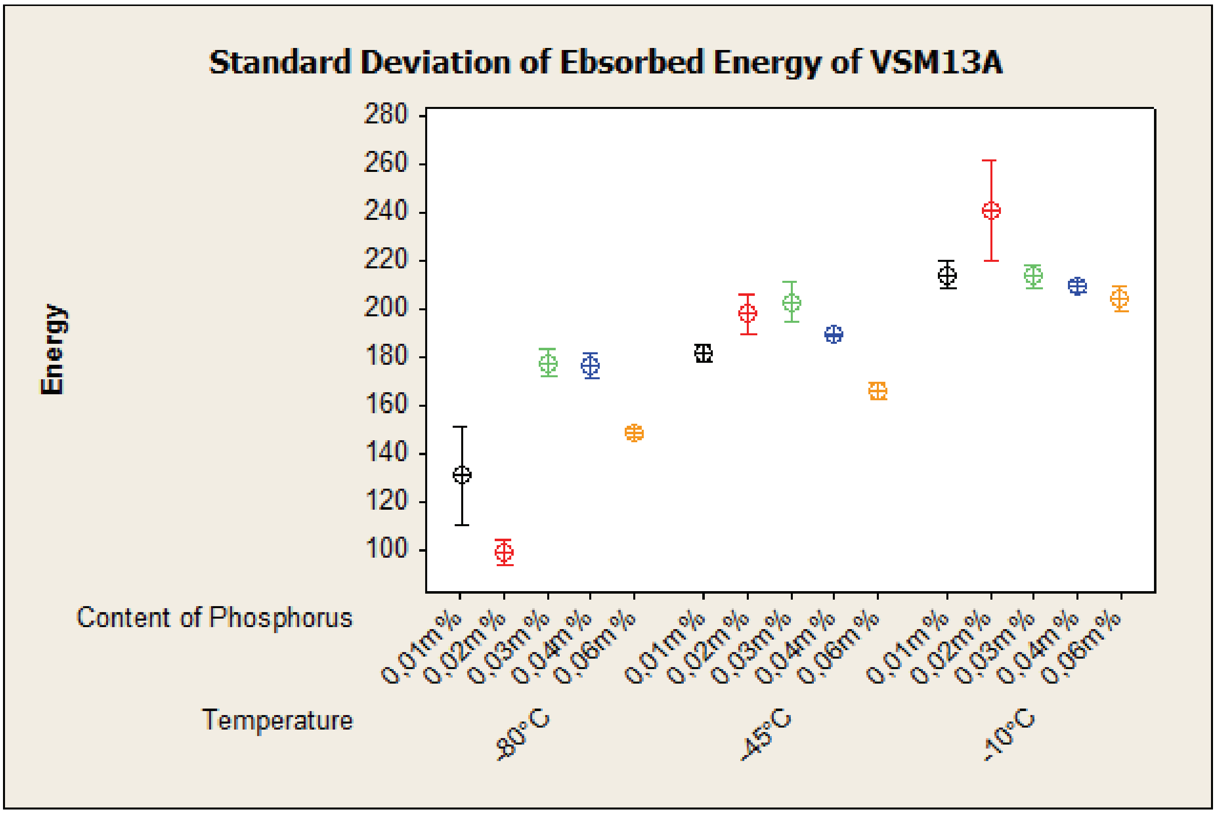

Figure 8-4: Standard Deviation results of the Charpy Impact Test at the VSM13A with different Phosphorus Content and Standard Deviation at -10°C, -45°C and -80°C

The increasing phosphorus content does not have big effects on the toughness. This can be seen in **Figure 8-3** and **Figure 8-4**. The order of toughest material is changing from temperature to temperature. One reason might be the close results. These are in a range of about 40 J at -45 °C and about 80 J at -80 °C. With decreasing temperature, the difference between the materials is getting bigger.

A totally different behaviour is showing the material with 0.02 wt% of phosphorus. The toughness differs a lot from the progressions of other materials. It is the material with the highest toughness at -10 °C and the lowest toughness at -80 °C. The results at -10 °C have the biggest standard deviation of all materials. Phosphorus might not be the only reasons for the different toughness progression. Segregations or different microstructures, caused during forging and heat treatment, are possible. These microstructural changes might cause such differences.

A required minimum average toughness of 40 J at -60 °C can be assured. Even at much lower temperatures and with much higher phosphorus content than 0.02 wt%.

8.6 Grain Refinement

The grain size is decreasing with increasing phosphorus content. This is obvious by comparing the images of VSM13A microstructure with different phosphorus content. The grain size of the super martensitic stainless steel with 0.01 wt% phosphorus is 8. The size was measured after ASTM E112 – 12. The size is constantly decreasing to a final grain size of 10.5 at the material with 0.06 wt% phosphorus.

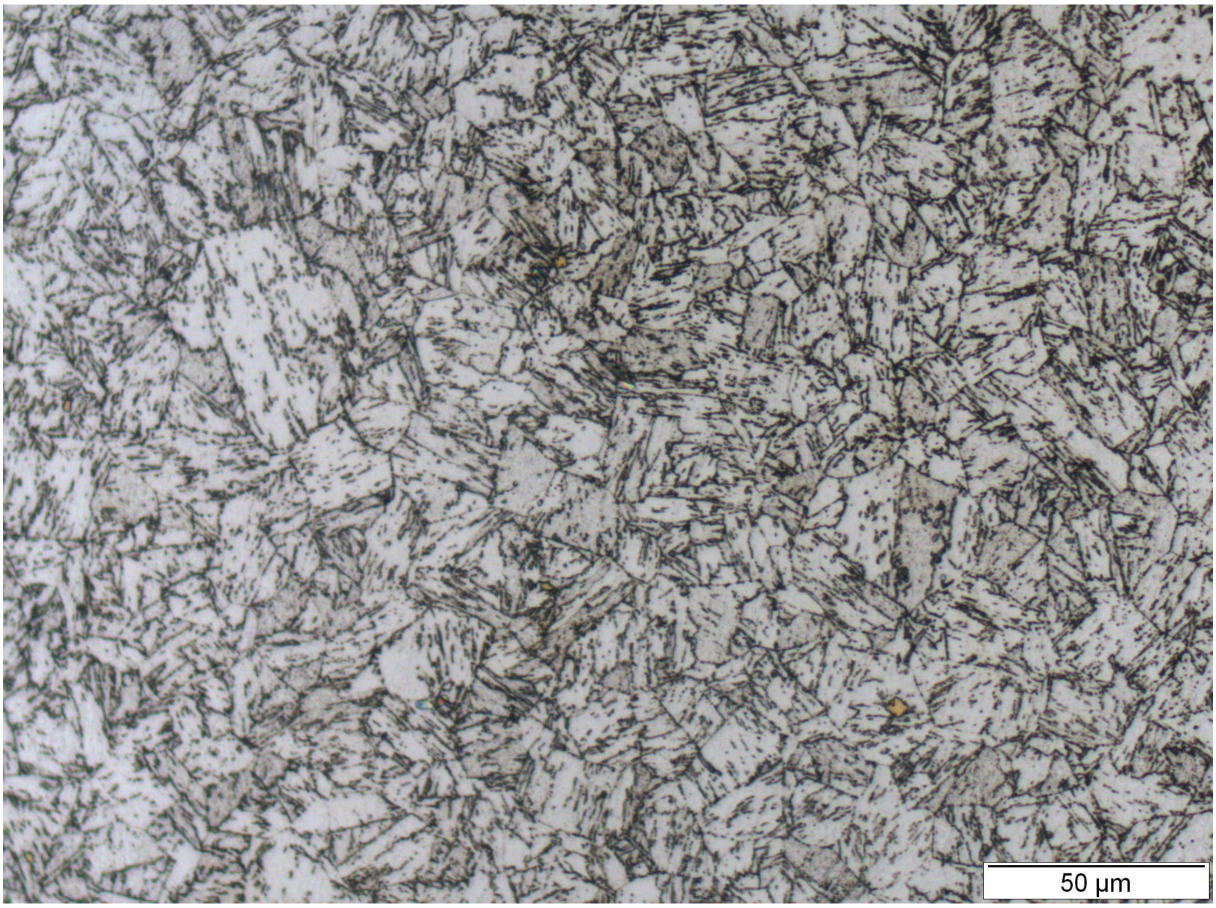

Figure 8-5: VSM13A with 0.1% Phosphorus Content after Corrosion Test with 500X Magnification

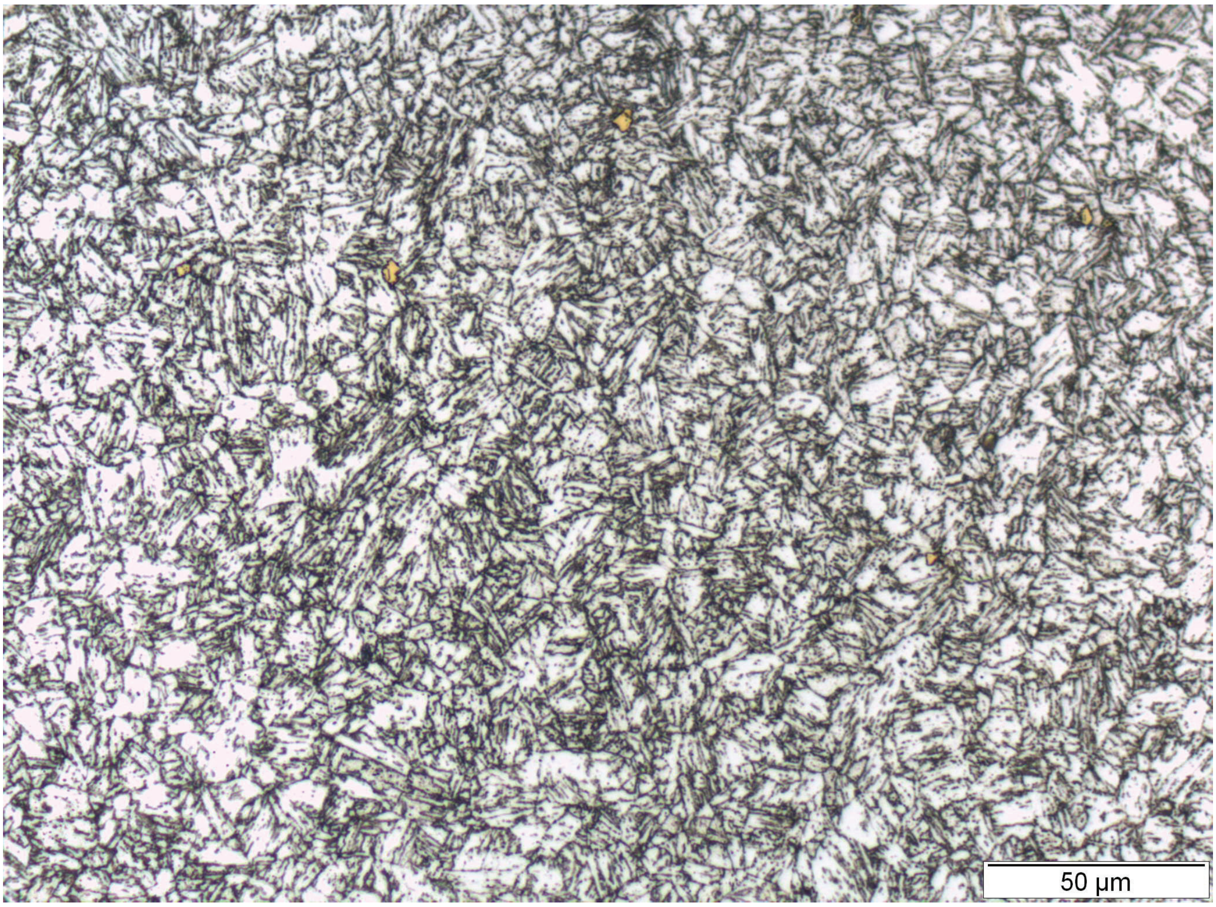

Figure 8-6: VSM13A with 0.06% Phosphorus Content after Corrosion Test with 500X Magnification

Pictures of all the other microstructures are shown in the **Figure 11-8** to **Figure 11-16**.

It was not possible to find similar investigations or investigations where similar grain refaining effects appeared in literature. In steels with a molybdenum content of 2 wt%, the molybdenum atoms segregate with the iron atoms to a so called laves phase (described in “The Effect of Phosphorus on Steel” on page 9). This phase is stable up to a temperature of 850°C [8]. It is assumed by the author that laves phases are pinning or at least hindering the grain boundary. The grain cannot grow as it does in steels with laves phases with lower phosphorus content. The laves phase is a phase, which has a higher concentration close to the grain boundaries. During grain growth, the grain boundary has to tier itself away from the fine particles it wants to grow. Laves phases with phosphorus content of 9 wt% have a higher surface energy (binding energy of the molybdenum and the phosphorus is calculated as 8 kJ per mol, up to 35 kJ per mol [22]) and are bigger than phases with less phosphorus content. These phases might hinder the grain more than ordinary laves phases consisting only of iron and molybdenum.

A finer grain size distribution with increasing phosphorus content is reasonable with this theory.

8.7 Testing of Yield Strength

The yield strength was tested with 2 samples of each material. The tests were performed after ASTM E8M. The first measurement went wrong. It was not possible to use the sample again. Because of that, only one result of the 0.01 wt% phosphorus sample exists.

The results show increasing yield strength with increasing phosphorus content. This is caused by the solid solution hardening effect of phosphorus. Phosphorus is the strongest hardening element in ferrit, except carbon [22]. Beside that, a grain refining mechanism was obtained. 0.05 wt% of phosphorus increases the average yield strength for more than 11 %. Except the material with 0.04% phosphorus, all the other materials show almost a linear increasing strength.

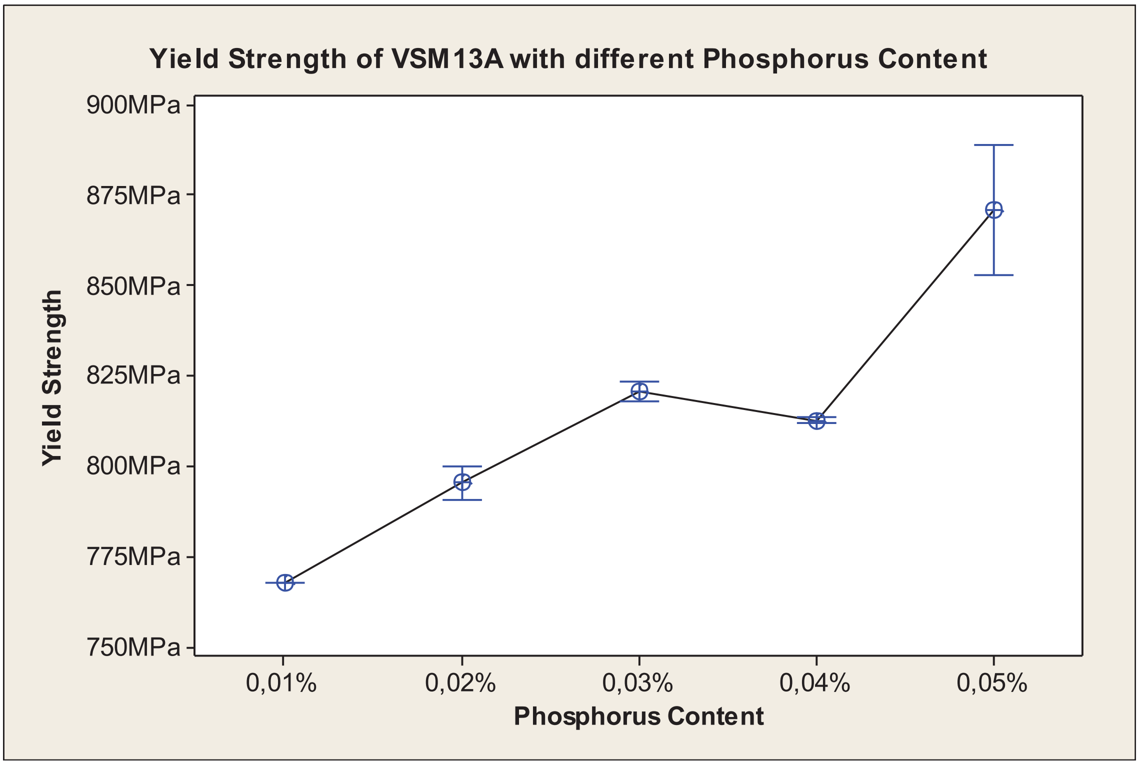

Figure 8-7: Yield Strength of VSM13A with different Phosphorus Content

As elongation measurement the A50 standard was used.

The elongation is declining with increasing phosphorus content. This is also caused by the strong phosphorus hardening effect.

The sample with 0.01 wt% of phosphorus has the lowest elongation of all materials. The medium elongation of this material was calculated, with only one figure. That is why the medium figure is the same as the measured data. This material showed an expected strengthening effect but a strange behaviour at elongation. Because of this, a mistake with the automatic elongation measurement equipment is obvious.

The standard deviation of the yield strength results is very small. The testing process and the equipment are a stable process with reliable results. The standard deviation of the elongation measurement is becoming smaller with increasing phosphorus content. The 0.02 wt% and 0.03 wt% materials have a big standard deviation but a decreasing tendency of elongation.

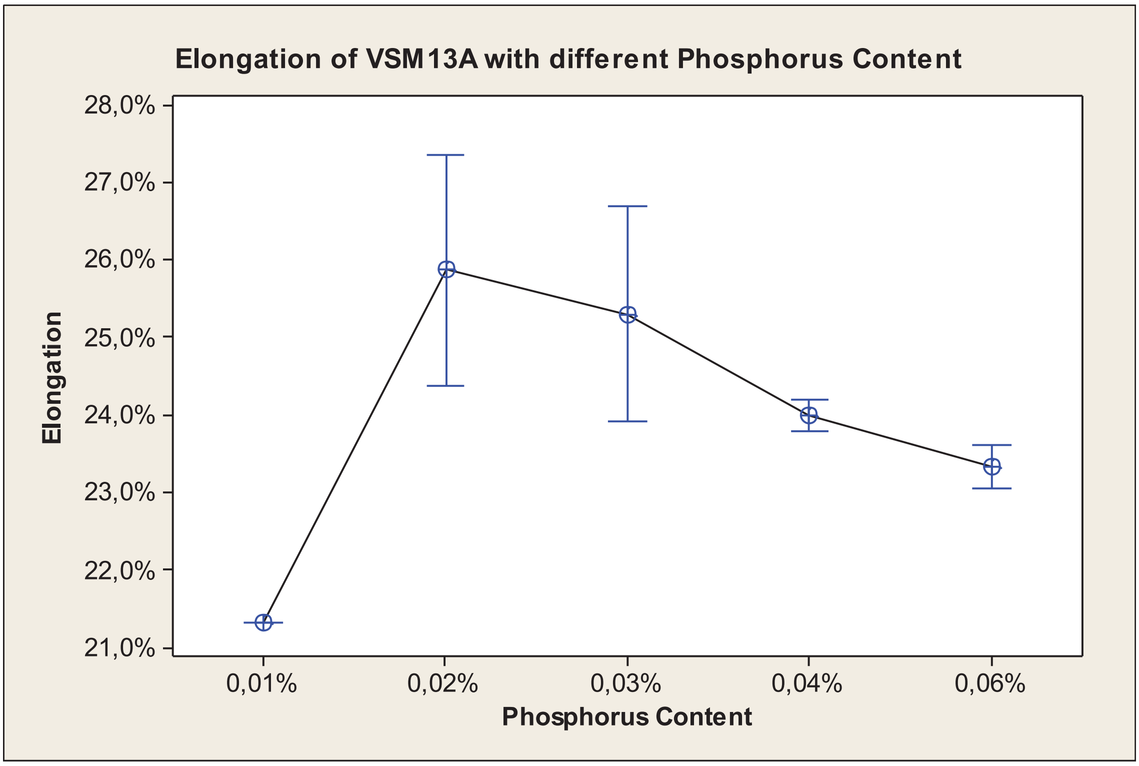

Figure 8-8: Elongation of VSM13A with different Phosphorus Content

The detailed test results and the statistics are shown in **Table 11-XVI**.

The decrease of elongation is a result of the solid solution hardening effect of phosphorus, which is mainly caused by the shear module effect of this element [20]. The grain refraining effect causes an increasing toughness which is the opposite to the embrittlement of the solid solution hardening. Out of the result, a stronger embrittlement of solid solution hardening than a toughness increase, caused by grain refining, is apparent.

8.8 Corrosion Resistance

The detrimental negative effects of the phosphorus on stress corrosion cracking of austenitic steel, were shown in previous articles [19, 20, 23, 24, 25]. Different articles are published, about the effect of phosphorus on the stress corrosion cracking. Especially about the effect on welded super martensitic steel [23, 24, 25]. The negative effect of phosphorus on welded materials is very well understood. For the VSM13A is it not very important. The main applications of VSM13A are tubes for the oil and gas industry, which are screwed together.

Stress corrosion cracking is a very interesting topic. Materials, used in the oil and gas industry are facing such problems. Other interesting topic is the pitting corrosion in chloride solutions. The effect of phosphorus on pitting resistance of VSM13A was investigated.

The whole test was made after ASTM 108. It was a DC electrochemical measurement. The machine, used for the measurement, was a AUTOLAB® potentiostat model PGSTAT302. The reference electrode was Ag. The electrochemical potential of the samples in a 2000 ppm NaCl and in a 20000 ppm NaCl solution got measured. The pH was 3.5 acetic acid and the measurement took place at room temperature for about 20 minutes. Tests in the 2000 ppm NaCl solution were performed two times. The first results were strange and the tests were performed again, clarify all doubts.

To ensure the reproducibility, all tests were performed three times. N_2 was used to degas the solution over night.

It is well known that the tests are intrinsically irreproducible with this technique. The pitting howls are changing the surface every time. The new created surface has an effect on following test results. Because of this fact and doubts about the correctness of the first tests, the series of tests got repeated. The difference of the two test series of 2000 ppm NaCl solution and the result of the tests made with the 20000 ppm NaCl solution, show very well, that phosphorus has hardly any effect on the pitting corrosion resistance. Molybdenum is the element with the highest effect on pitting resistance. This element increases the PRE number a factor by 3.3 [33]. The combination of phosphorus with molybdenum and iron, combined in a laves phase, seems to have no effect. The molybdenum content of more than 2000 ppm is much higher than the content of phosphorus. By assuming the chemical composition of such a laves phase with 39 wt% of molybdenum and about 4.4 wt% phosphorus, the amount of molybdenum free from phosphorus is 1.46 wt% by a phosphorus concentration of 0.06 wt% in total. This is a decrease of 0.53 wt% of molybdenum, which is not segregated with phosphorus. The PREN number would decrease for 1.75 points. This would have a measurable effect on the pitting resistance.

Because of these results, it seems that the phosphorus is not neutralising the pitting resistance performance of molybdenum and is not decreasing the pitting resistance.

A smaller potential difference between the open circuit potential and the electrode potential is a hint for a better pitting resistance.

The variable chemical concentrations of different elements, clusters, segregations of atoms and different numbers of exposed grain boundaries at the testing surface, seems to have a bigger effect on the pitting resistance, than the variety of the phosphorus concentration.

The potential difference between the electrode potential and the open circuit potential is shown in **Figure 8-9**.

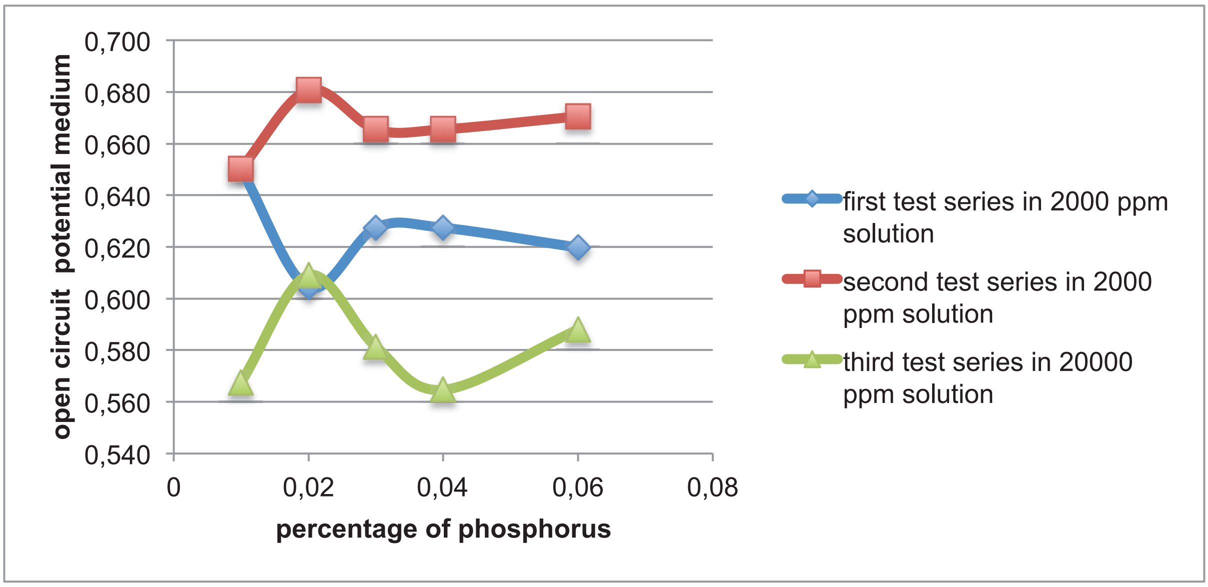

Figure 8-9: Potential Difference of the Open Circuit Voltage and the Electrode Potential

The detailed results of the measurement, the curves of the electrode potentials and the open circuit potential can be seen in “Results of Corrosion Test, Open Circuit and Electrode Potential”.

Table 11-XVII: Chemical Composition of VSM13A Samples with variable Phosphorus Content

Heat Nr.	C	Si	Mn	P	S	Co	Cr	Mo	Ni	V
	m%	m%	m%	m%	m%	m%	m%	m%	m%	m%
1106853	0.012	0.27	0.50	0.010	0.0021	0.01	12.12	2.00	5.89	<0.010
1106854	0.010	0.26	0.50	0.022	0.0019	0.01	11.70	1.80	5.92	<0.010
1106855	0.008	0.26	0.49	0.031	0.018	0.01	12.12	1.99	5.92	<0.010
1106856	0.009	0.25	0.49	0.039	0.0011	0.01	12.17	1.99	5.94	<0.010
1106857	0.012	0.26	0.50	0.063	0.0015	0.01	12.10	1.99	5.89	<0.010

Table 11-XVIII: Chemical Composition of Magnetic Pre Melt of Recuperated Material

Heat Nr.	C	Si	Mn	P	S	Co	Cr	Mo	Ni	V
m%	m%	m%	m%	m%	m%	m%	m%	m%	m%	m%
803882	1.435	1.59	0.99	0.047	0.025	0.08	11.85	0.77	4.3	0.276
804330	0.434	0.43	0.48	0.053	0.041	0.1	10.55	1.28	5.72	0.244

Table 11-XIX: Chemical Composition of various Pre Melts

Heat Nr.	C	Si	Mn	P	S	Co	Cr	Mo	Ni	V
m%	m%	m%	m%	m%	m%	m%	m%	m%	m%	m%
804419	5.1	-246.7	3.7	64.3	68.3	0.0	90.1	80.9	73.9	13.0
804439	-17.2	-158.3	9.7	68.5	58.3	33.3	95.0	91.7	97.0	52.4
804437	98.1	25.9	-59.4	-7.7	72.9	0.0	-4.0	-9.3	-22.0	-20.0
804431	59.4	-233.3	60.0	83.8	60.0	50.0	76.6	95.7	81.6	58.3
804430	25.1	-392.3	77.8	68.8	88.9	0.0	97.8	-72.5	63.6	68.8
804422	7.1	0.0	-21.7	74.4	51.6	33.3	95.0	92.3	95.0	44.4
804421	-10.3	-138.5	15.2	72.7	41.2	33.3	94.9	90.3	96.8	50.0
804420	5.3	-61.9	27.0	18.5	-185.7	12.5	29.1	-80.9	67.2	-65.7
804418	10.2	-33.3	50.7	20.0	-108.3	45.5	-19.1	-82.7	29.7	-31.1
804417	-0.9	23.8	55.7	20.0	-56.3	53.8	-12.3	-90.0	33.5	-33.3
804416	-7.7	27.3	37.5	7.7	-56.3	25.0	-11.9	-111.1	28.4	-27.0
804397	-48.1	42.9	44.4	11.1	-56.3	25.0	-16.1	-63.8	39.5	-33.3
4843590	-30.8	-271.4	-1.4	4.0	-400.0	-84.6	14.6	43.3	4.4	-96.7
4843589	12.5	0.0	0.0	17.2	-566.7	-140.0	11.4	38.7	-2.7	-172.7
803162	32.0	0.0	0.0	68.8	-708.3	33.3	96.9	-2.9	77.1	77.3
803162	26.6	0.0	0.0	0.0	-8.3	0.0	16.1	36.4	33.0	15.9
804106	59.8	-300.0	30.6	78.3	-233.3	40.0	76.8	-2.4	86.0	67.7
803063	-49.4	-57.9	67.9	68.0	-140.7	78.6	95.6	95.9	79.7	83.6
802922	85.5	88.9	72.9	61.5	-221.9	28.6	97.5	-6.9	82.8	82.8
804351	92.1	-9.1	68.4	90.8	-57.9	91.7	99.6	98.4	97.4	87.7
804283	29.9	-221.9	72.0	26.7	-1625.0	53.3	53.9	-55.1	29.7	-12.1
803959	99.4	-142.9	60.3	18.8	-260.0	50.0	37.1	-86.4	35.1	-9.3

Results of Corrosion Test, Open Circuit and Electrode Potential” on page 111.

The pictures of the pitting resistance show howls are much bigger than the average grain sizes. It is impossible to see, if the pitting started intergranular or transgranular.

Figure 8-10: VSM13A with 0.06% Phosphorus Content after Corrosion Test with 50X Magnification

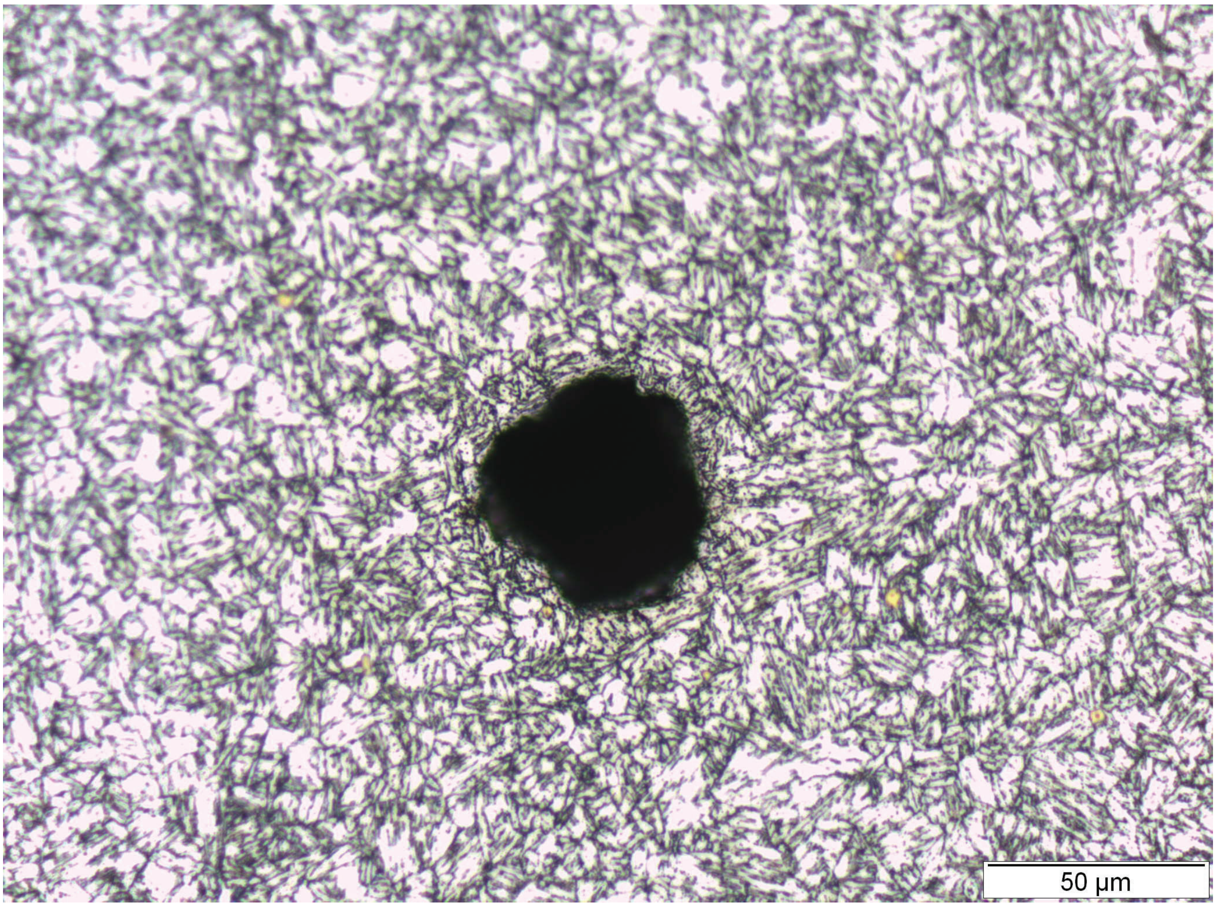

Figure 8-11: VSM13A with 0.06% Phosphorus Content after Corrosion Test with 500X Magnification

9 Conclusion

Some key points for the increase of the utilisation and the profit of the Electric Arc Furnaces were found, by the investigations and achieved results of this master thesis.

The order of key points is not ranked in order of importance. They are ordered occuring the production flow.

- To avoid unpleasant surprises during the melting process, the process of scrap specification, sorting and handling has to be done as precisely as possible. A 40% investigation rate of internal scrap is not enough. Even the way of testing is not as efficient as it has to be. The testing of just a few pieces in a box is not meaningful for the material which is at the bottom of the box and hard to see and to reach. More people have to be employed and more scrap-boxes have to be bought for testing the material.
- To improve the scrap handling, a totally new system has to be established. Fewer scrap shifts and clearer scrap separations have to be introduced. This will hopefully be realized by the new scrap year, which will be finished within the next month.
- A periodically performed check with melted recuperated scrap has to be established. This increases the forecast accuracy of operators. The planning accuracy would increase significantly too.
- The positive effect of “Semana Kaizen” was proved. “Semana Kaizen” has to be a regular tool for the continuous improvement of the operating process at the furnaces and at many other areas too. LEAN management must be used wisely and continuously in all areas of the steel mill. But it must be remembered, that in this areas processes are limited through chemical and physical reaction times, which do not always allow the comparison with a supermarket shelf.

- The calculations about the increase of the power limit have shown two different results.
    - As long as the Electric Arc Furnace is fully occupied, an increase of 7 MW is recommended. The new power limit would be at 50 MW. This limit applies to the time beside the peak time, which has incredible high power prices.
    - The second calculation shows, that an increase of the power limit during peak time is only recommendable if an average profit of 0.543 R$ per kg additional production with 7614.6 additional produced tons is achievable. By an increase of profit per kg a decrease of additional production is possible and count avers.
- The calculations about the size reduction of pre melts have shown that a size reduction through blooming and oxy cut is always advisable, as long as the blooming mill has free capacity. If the blooming mill is occupied, the gained profit of extra produced material has to be higher than 0.59 R$ per kg. The extra amount of produced material has to be produced during the time saved in Electric Arc Furnace through pre melt size reduction.
- Calculations about the economic efficiency of pre melts have clearly shown the limit of chemical differences between scrap and the final product. If this amount of elements is bigger than the calculated difference, no pre melt is recommended. If the amount is definitely smaller than the amount of elements in scrap and alloying elements, the possibility of pre melt-manufacturing route has to be discussed.
- The mathematical model of the maximum amount of added pre melts can help all the scrap assembler and furnace operators to work more precisely. It might be a big help for all the new operators and scrap assemblers who do not have years of experience. It is the first time, that this important procedure is not part of the operator's experience anymore. It is written down for everyone, to use and to check the actual procedure. The actual results are close to the results of the past. This is a sign for the correctness of the method. By increasing the amount of added data to the database, the accuracy of the formulas will be increased.
- Tests have shown that the decrease of tap-to-tap time through an optimisation of scrap size can be huge. Electric Arc Furnace #1 had a much smaller difference than Electric Arc Furnace #2. Two test series with only six tests were not much. Considering the costs and the time expenses of the tests, no more tests were possible. The test accuracy would increase with more tests. But out of the collected data one important statement can be made. Scrap size optimisation has a positive effect on tap-to-tap time. The average time reduction might be in between the tests

of VSM13A and VMO. It is assumed that it might be closer to VSM13A in Electric Arc Furnace #2.

- To operate such a complicated and expensive process like the Electric Arc Furnace as precisely as possible, as many parameters as possible have to be provided and considered. One of the essential parameters for a meaningful mass balance is the slag composition. The slag, depending on its composition, can assist the process or ruin the total melting process. It can even cause horrible and dangerous accidents. Because of this, it is incomprehensible why still not every slag gets tested. Even if the process of analysing the slag is too slow for any slag changes during operation, it is an immense gain of knowledge. This knowledge might be important for many operators in many different departments. These departments are for example the department of refractory, the furnace operators and the maintenance department. If they could decrease the costs for slag removal, they could decrease the alloying content of slag. It has to be stated that the actual slag handling and testing process is pure negligence.
- The tap-to-tap time has to be reduced to make the whole process economically more efficient. An easy step can be the usage of X-ray spectroscopes, to measure the chemical content of the Electric Arc Furnace samples. This can decrease the tap-to-tap time for some minutes. The operators can get a rough overview about the chemical content of the heat and can do the appropriate actions.
- The mechanical and microscopic analysis of VSM13A have shown,
    - that the pitting resistance is not affected by the phosphorus content. A stress corrosion resistance test in H_2S solution is recommended for the future.
    - that the grain size is decreasing. The created laves phases may cause this grain refining. The grain boundaries may not move as freely as in materials with laves phases with a lower content of phosphorus. Phosphorus is increasing the size and the volume of these phases, which might cause the hindering of grain boundaries.
    - The yield strength is increasing through the refined grain size and the solid solution hardening effect of phosphorus, which is one of the strongest in ferrite.
    - The impact tests have shown that all samples with increased phosphorus content fulfil the required limits. The toughness of all materials was sophisticated. And even at very low temperatures (-80°C) and high

phosphorus contents (0.06 wt%) there was no tremendous decrease of toughness visible.

Out of these results, an increase of phosphorus content can be discussed. The discussion will not be easy, because of several regulations and norms for the oil and gas industry. A phosphorus increase of about 50% to 0.03 wt% could avoid the pre melt route and lead to a tremendous production cost reduction. Even if this customer is not sophisticated with an increase of the phosphorus content, others could be. The same material with higher phosphorus content could be sold to other customers who request the same properties of VSM13A with a higher yield strength and finer grain size with a little decrease of elongation.

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11 Appendix

Table 11-I: Statistic Data Tap to Tap Time of VSM13A in EAF2

N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3	Maximum
min		min	min	min	min	min	min	min	min
420	0	205.62	3.63	74.38	78.00	157.00	180.00	233.25	559.00

Table 11-II: Statistic Data Tap to Tap Time of VSM13A in EAF1

N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3	Maximum
min		min	min	min	min	min	min	min	min
32	0	129.59	6.54	36.98	72.00	97.25	124.00	169.00	199.00

Table 11-III: Statistic Data Tap to Tap Time before “Semana Kaizen” in EAF1

N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3	Maximum
min		min	min	min	min	min	min	min	min
224	0	148.52	3.11	46.60	93.00	126.00	137.50	156.50	607.00

Table 11-IV: Statistic Data Tap to Tap Time after “Semana Kaizen” in EAF1

N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3	Maximum
min		min	min	min	min	min	min	min	min
247	0	145.09	2.54	39.87	98.00	124.00	136.00	153.00	380.00

Table 11-V: Scrap Surface Effect on Melting Time of Electric Arc Furnace #1 and #2

Heat Number	Material	Scrap Size	Average Weight per piece	Average Scrap Surface	Time
			kg	mm^2	min
4846227	VMO	small	0.00015	900	87.3
4846070	VMO	optimum	154	46200	84.4
4846159	VMO	big	2087	2872800	87.1
0804503	VSM13A	small	0.00015	900	110.0
0804430	VSM13A	optimum	154	46200	66.6
0804445	VSM13A	big	2087	2872800	97.0

Table 11-XVII: Chemical Composition of VSM13A Samples with variable Phosphorus Content

Heat Nr.	**C**	**Si**	**Mn**	**P**	**S**	**Co**	**Cr**	**Mo**	**Ni**	**V**
	m%	m%	m%	m%	m%	m%	m%	m%	m%	m%
1106853	0.012	0.27	0.50	0.010	0.0021	0.01	12.12	2.00	5.89	<0.010
1106854	0.010	0.26	0.50	0.022	0.0019	0.01	11.70	1.80	5.92	<0.010
1106855	0.008	0.26	0.49	0.031	0.018	0.01	12.12	1.99	5.92	<0.010
1106856	0.009	0.25	0.49	0.039	0.0011	0.01	12.17	1.99	5.94	<0.010
1106857	0.012	0.26	0.50	0.063	0.0015	0.01	12.10	1.99	5.89	<0.010

Table 11-XVIII: Chemical Composition of Magnetic Pre Melt of Recuperated Material

Heat Nr.	**C**	**Si**	**Mn**	**P**	**S**	**Co**	**Cr**	**Mo**	**Ni**	**V**
m%	m%	m%	m%	m%	m%	m%	m%	m%	m%	m%
803882	1.435	1.59	0.99	0.047	0.025	0.08	11.85	0.77	4.3	0.276
804330	0.434	0.43	0.48	0.053	0.041	0.1	10.55	1.28	5.72	0.244

Table 11-XIX: Chemical Composition of various Intermediarios

Heat Nr.	C	Si	Mn	P	S	Co	Cr	Mo	Ni	V
m%	m%	m%	m%	m%	m%	m%	m%	m%	m%	m%
804419	5.1	-246.7	3.7	64.3	68.3	0.0	90.1	80.9	73.9	13.0
804439	-17.2	-158.3	9.7	68.5	58.3	33.3	95.0	91.7	97.0	52.4
804437	98.1	25.9	-59.4	-7.7	72.9	0.0	-4.0	-9.3	-22.0	-20.0
804431	59.4	-233.3	60.0	83.8	60.0	50.0	76.6	95.7	81.6	58.3
804430	25.1	-392.3	77.8	68.8	88.9	0.0	97.8	-72.5	63.6	68.8
804422	7.1	0.0	-21.7	74.4	51.6	33.3	95.0	92.3	95.0	44.4
804421	-10.3	-138.5	15.2	72.7	41.2	33.3	94.9	90.3	96.8	50.0
804420	5.3	-61.9	27.0	18.5	-185.7	12.5	29.1	-80.9	67.2	-65.7
804418	10.2	-33.3	50.7	20.0	-108.3	45.5	-19.1	-82.7	29.7	-31.1
804417	-0.9	23.8	55.7	20.0	-56.3	53.8	-12.3	-90.0	33.5	-33.3
804416	-7.7	27.3	37.5	7.7	-56.3	25.0	-11.9	-111.1	28.4	-27.0
804397	-48.1	42.9	44.4	11.1	-56.3	25.0	-16.1	-63.8	39.5	-33.3
4843590	-30.8	-271.4	-1.4	4.0	-400.0	-84.6	14.6	43.3	4.4	-96.7
4843589	12.5	0.0	0.0	17.2	-566.7	-140.0	11.4	38.7	-2.7	-172.7
803162	32.0	0.0	0.0	68.8	-708.3	33.3	96.9	-2.9	77.1	77.3
803162	26.6	0.0	0.0	0.0	-8.3	0.0	16.1	36.4	33.0	15.9
804106	59.8	-300.0	30.6	78.3	-233.3	40.0	76.8	-2.4	86.0	67.7
803063	-49.4	-57.9	67.9	68.0	-140.7	78.6	95.6	95.9	79.7	83.6
802922	85.5	88.9	72.9	61.5	-221.9	28.6	97.5	-6.9	82.8	82.8
804351	92.1	-9.1	68.4	90.8	-57.9	91.7	99.6	98.4	97.4	87.7
804283	29.9	-221.9	72.0	26.7	-1625.0	53.3	53.9	-55.1	29.7	-12.1
803959	99.4	-142.9	60.3	18.8	-260.0	50.0	37.1	-86.4	35.1	-9.3

11.1 Results

Table 11-VI: Absorbed Energy of VSM13A with variable Phosphorus Content at -10°C

Content of P	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3	Maximum
wt%			J	J	J	J	J	J	J	J
0.01%	4	0	214.00	5.34	10.68	199.00	202.75	217.00	222.25	223.00
0.02%	4	0	227.00	7.91	15.81	213.00	213.50	224.50	243.00	246.00
0.03%	4	0	213.50	4.72	9.43	207.00	207.00	210.00	223.50	227.00
0.04%	4	0	209.25	2.21	4.43	205.00	205.25	209.00	213.50	214.00
0.06%	4	0	203.75	5.20	10.40	189.00	192.75	207.00	211.50	212.00

Table 11-VII: Absorbed Energy of VSM13A with variable Phosphorus Content at -10°C

Content of P	Absorbed Energy S1	Absorbed Energy S2	Absorbed Energy S3	Absorbed Energy S4
wt%	J	J	J	J
0.01	199	214	220	223
0.02	215	232	242	213
0.03	227	207	213	207
0.04	214	205	212	206
0.06	204	212	210	189

Table 11-VIII: Absorbed Energy of VSM13A with 0.01 wt% Phosphorus Content at variable Temperatures

Temperature	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3	Maximum
°C			J	J	J	J	J	J	J	J
-80	3	0	130.70	20.6	35.6	91.00	91.00	141.00	160.00	160.00
-45	3	0	181.33	3.76	6.51	175.00	175.00	181.00	188.00	188.00
-10	3	0	214.00	5.34	10.68	199.00	202.75	222.25	222.25	223.00

Table 11-IX: Absorbed Energy of VSM13A with 0.02 wt% Phosphorus Content at variable Temperatures

Temperature	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3	Maximum
°C			J	J	J	J	J	J	J	J
-80	3	0	98.33	5.24	9.07	90.00	90.00	97.00	108.00	108.00
-45	3	0	197.67	8.35	14.47	181.00	181.00	205.00	207.00	207.00
-10	3	0	240.5	20.9	41.9	213.00	213.5	223.50	284.50	302.00

Table 11-X: Absorbed Energy of VSM13A with 0.03 wt% Phosphorus Content at variable Temperatures

Temperature	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3	Maximum
°C			J	J	J	J	J	J	J	J
-80	3	0	177.33	5.81	10.07	168.00	168.00	176.00	188.00	188.00
-45	3	0	202.67	7.97	13.80	187.00	187.00	208.00	213.00	213.00
-10	3	0	213.50	4.72	9.43	207.00	207.00	210.00	223.50	227.00

Table 11-XI: Absorbed Energy of VSM13A with 0.04 wt% Phosphorus Content at variable Temperatures

Temperature	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3	Maximum
°C			J	J	J	J	J	J	J	J
-80	3	0	176.33	5.21	9.02	167.00	167.00	177.00	185.00	185.00
-45	3	0	189.00	0.58	1.00	188.00	188.00	189.00	190.00	190.00
-10	3	0	209.25	2.21	4.43	205.00	105.00	209.00	213.50	214.00

Table 11-XII: Absorbed Energy of VSM13A with 0.06 wt% Phosphorus Content at variable Temperatures

Temperature	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3	Maximum
°C			J	J	J	J	J	J	J	J
-80	3	0	148.33	1.45	2.52	146.00	146.00	148.00	151.00	151.00
-45	3	0	166.00	3.61	6.24	161.00	161.00	164.00	173.00	173.00
-10	3	0	203.75	5.20	10.40	189.00	192.75	207.00	211.50	212.00

Table 11-XIII: Absorbed Energy of VSM13A with variable Phosphorus Content at -80°C

Content of P	Absorbed Energy S1	Absorbed Energy S2	Absorbed Energy S3
wt%	J	J	J
0.01	160	141	91
0.02	108	97	90
0.03	168	188	176
0.04	185	167	177
0.06	151	146	148

Table 11-XIV: Absorbed Energy of VSM13A with variable Phosphorus Content at -45°C

Content of P	Absorbed Energy S1	Absorbed Energy S2	Absorbed Energy S3
wt%	J	J	J
0.01	181	188	175
0.02	207	205	181
0.03	187	208	213
0.04	190	188	189
0.06	164	162	173

Table 11-XV: Absorbed Energy of VSM13A with variable Phosphorus Content at -10°C

Content of P	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3	Maximum
m%			MPa	MPa	MPa	MPa	MPa	MPa	MPa	MPa
0.01%	1	0	767.84	X	X	767.84	X	767.84	X	767.84
0.02%	2	0	795.38	4.71	6.66	790.67	X	795.38	X	800.10
0.03%	2	0	820.80	2.64	3.74	818.15	X	820.80	X	823.44
0.04%	2	0	812.63	0.830	1.17	811.80	X	812.63	X	813.46
0.06%	2	0	870.9	17.9	25.3	853.0	X	870.9	X	888.8

Table 11-XVI: Elongation of VSM13A with variable Phosphorus Content

Content of P	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3	Maximum
m%										
0.01%	1	0	0.21311	X	X	0.21311	X	0.21311	X	0.21311
0.02%	2	0	0.2587	0.0150	0.0212	0.2437	X	0.2587	X	0.2736
0.03%	2	0	0.2530	0.0139	0.0196	0.2391	X	0.2530	X	0.2668
0.04%	2	0	0.23989	0.00207	0.00293	0.23782	X	0.23989	X	0.24196
0.06%	2	0	0.23321	0.00287	0.00405	0.23035	X	0.23321	X	0.23608

Table 11-XVII: Chemical Composition of VSM13A Samples with variable Phosphorus Content

Heat Nr.	C	Si	Mn	P	S	Co	Cr	Mo	Ni	V
	m%	m%	m%	m%	m%	m%	m%	m%	m%	m%
1106853	0.012	0.27	0.50	0.010	0.0021	0.01	12.12	2.00	5.89	<0.010
1106854	0.010	0.26	0.50	0.022	0.0019	0.01	11.70	1.80	5.92	<0.010
1106855	0.008	0.26	0.49	0.031	0.018	0.01	12.12	1.99	5.92	<0.010
1106856	0.009	0.25	0.49	0.039	0.0011	0.01	12.17	1.99	5.94	<0.010
1106857	0.012	0.26	0.50	0.063	0.0015	0.01	12.10	1.99	5.89	<0.010

Table 11-XVIII: Chemical Composition of Magnetic Pre Melt of Recuperated Material

Heat Nr.	C	Si	Mn	P	S	Co	Cr	Mo	Ni	V
m%	m%	m%	m%	m%	m%	m%	m%	m%	m%	m%
803882	1.435	1.59	0.99	0.047	0.025	0.08	11.85	0.77	4.3	0.276
804330	0.434	0.43	0.48	0.053	0.041	0.1	10.55	1.28	5.72	0.244

Table 11-XIX: Chemical Composition of various Pre Melts

Heat Nr.	C	Si	Mn	P	S	Co	Cr	Mo	Ni	V
m%	m%	m%	m%	m%	m%	m%	m%	m%	m%	m%
804419	5.1	-246.7	3.7	64.3	68.3	0.0	90.1	80.9	73.9	13.0
804439	-17.2	-158.3	9.7	68.5	58.3	33.3	95.0	91.7	97.0	52.4
804437	98.1	25.9	-59.4	-7.7	72.9	0.0	-4.0	-9.3	-22.0	-20.0
804431	59.4	-233.3	60.0	83.8	60.0	50.0	76.6	95.7	81.6	58.3
804430	25.1	-392.3	77.8	68.8	88.9	0.0	97.8	-72.5	63.6	68.8
804422	7.1	0.0	-21.7	74.4	51.6	33.3	95.0	92.3	95.0	44.4
804421	-10.3	-138.5	15.2	72.7	41.2	33.3	94.9	90.3	96.8	50.0
804420	5.3	-61.9	27.0	18.5	-185.7	12.5	29.1	-80.9	67.2	-65.7
804418	10.2	-33.3	50.7	20.0	-108.3	45.5	-19.1	-82.7	29.7	-31.1
804417	-0.9	23.8	55.7	20.0	-56.3	53.8	-12.3	-90.0	33.5	-33.3
804416	-7.7	27.3	37.5	7.7	-56.3	25.0	-11.9	-111.1	28.4	-27.0
804397	-48.1	42.9	44.4	11.1	-56.3	25.0	-16.1	-63.8	39.5	-33.3
4843590	-30.8	-271.4	-1.4	4.0	-400.0	-84.6	14.6	43.3	4.4	-96.7
4843589	12.5	0.0	0.0	17.2	-566.7	-140.0	11.4	38.7	-2.7	-172.7
803162	32.0	0.0	0.0	68.8	-708.3	33.3	96.9	-2.9	77.1	77.3
803162	26.6	0.0	0.0	0.0	-8.3	0.0	16.1	36.4	33.0	15.9
804106	59.8	-300.0	30.6	78.3	-233.3	40.0	76.8	-2.4	86.0	67.7
803063	-49.4	-57.9	67.9	68.0	-140.7	78.6	95.6	95.9	79.7	83.6
802922	85.5	88.9	72.9	61.5	-221.9	28.6	97.5	-6.9	82.8	82.8
804351	92.1	-9.1	68.4	90.8	-57.9	91.7	99.6	98.4	97.4	87.7
804283	29.9	-221.9	72.0	26.7	-1625.0	53.3	53.9	-55.1	29.7	-12.1
803959	99.4	-142.9	60.3	18.8	-260.0	50.0	37.1	-86.4	35.1	-9.3

11.2 Results of Corrosion Test, Open Circuit and Electrode Potential

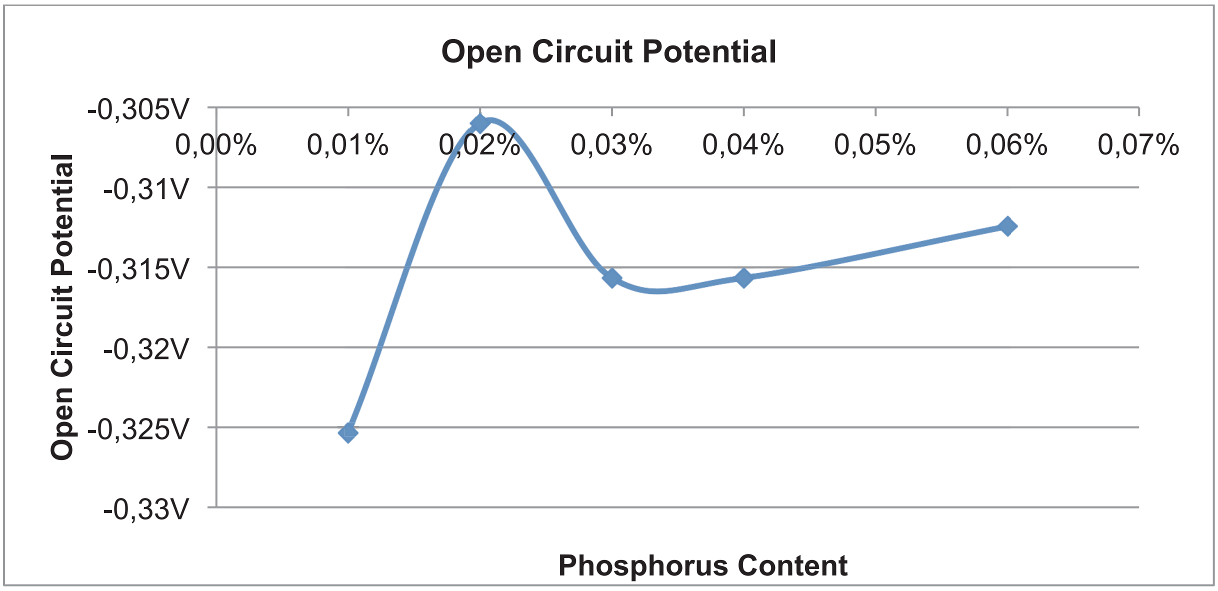

Figure 11-1: Open Circuit Potential of VSM13A with variable Phosphorus Content

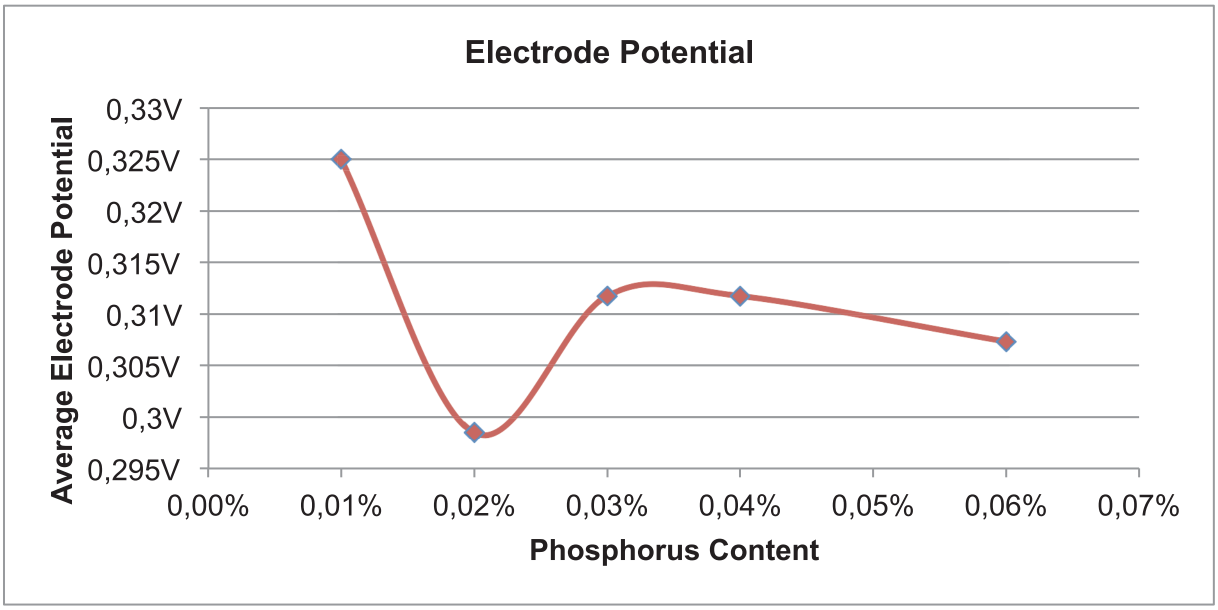

Figure 11-2: Electrode Potential of VSM13A with variable Phosphorus Content

11.3 Increase of Productivity by higher Power Limit

Working days 2012: 259 days/year

Saturdays with full working EAF 2: *259 days / 365 days * 52 Saturdays = 37 Saturdays*

Working days with 3 hours of not working EAF 2: *259 days – 37 Saturdays = 222 days*

Production time per day except Saturdays: 21 h

Production time of one day in minutes: *21 h * 60 min/h = 1260 min*

Average tap to tap time of EAF 1 (2012 – 2013): 145 min

Average tap to tap time of EAF 2 (2012 – 2013): 190 min

Average possible heats per day of EAF 2: *1260 min / 190 min = 6.63157 heats*

Average produced heats per day of EAF 2: 7

Time of production during peak time: *7 heats – 6.63157heats = 0.36843 heats*

*0.36843 heats * 190 min/heat = 70 min*

Avoidable stops through increase of voltage limit at EAF 1(04.2012 – 04.2013): 6835

Medium time of stops: 0.93 min

Time of up moving electrodes: 0.15 min

Time of down moving electrodes: 0.15 min

Total time of average stop: *0.93 min + 0.15 min + 0.15 min = 1.23 min*

Total time of stops caused by exceeding voltage limit: *1.23 min * 6835 = 8407 min/year*

Average time of stops of voltage limit per working day: *8407 min / 259 days = 32.5 min/day*

Left time during peak time after increasing power limit: *70 min – 32.5 min = 37.5 min*

Average amount of time per heat during peak time after higher power limit:

37.5 min / 7 heats = 5.35 min / heat

Out of the test results, an average saved time of 5.35 minutes by optimizing the size of pre melts and pre melts is realistic.

Economical study:

Total saved time: 70 min/day

Fixed costs EAF 1 per ton: 3929 R$/h

Fixed costs EAF 1 per minute: 3929 R$/h = 64.8 R$/min

Amount of produced pre melts in EAF 1 (2012): *1665 t*

Amount of produced pre melts in EAF 2 (2012): *2197 t*

Total amount of produced pre melts (21012): 3862 t

Capacity of blooming: 30 t/h

Amount of hours for rolling all pre melts: 129 h

Variable costs of blooming (2012): 5860 R$/h

Total variable costs for blooming all pre melts: *128 h * 5680 R$/h = 754480 R$*

Variable costs for oxycut: 90 R$/t

Total amount of variable costs for cutting all pre melts: *90 R$/t * 3862 t = 347580 R$*

Costs to increase the current limit for 1 MW beside the peak time: 3474 R$/MW and month

Actual power limit beside peak time: 42 MW

New limit of power beside peak time: 50 MW

Extra MW: *50 MW – 42 MW = 8 MW*

Extra costs for power: *8 MW * 3474 R$/MW and month * 12 month/year = 333504 R$/year*

Total amount of extra costs: *4754481 R$ + 347580 R$ + 333360 R$ = 5435421 R$*

Profit of production mix of rolled product: 3.024 R$/kg

Yield of rolled materials from taping to the final product 72 % of taped material

Gained profit of rolled materials for the EAF 1 per minute:

3.024 R$/kg * 1000 kg/t * 34 t/heat / 145 min/heat *72 % = 509 R$/min

Total amount of saved costs per minute of EAF 1: *64 R$/min + 509 R$/min = 573 R$/min*

Requested amount of saved time of not working EAF 1:

1435564 R$ / 580 R$/min / 222 days/year = 11.16 min

11.15 min is a realistic time of shut downs of EAF 1 every day. It is more economically to increase the power limit than to produce 7 heats per day in EAF 2 and shut down EAF 1 for some time, when the heats are not finished after 21 hours.

11.4 Increase of productivity by creating higher capacity by equalizing the power limit during peak time

Time of shut down: 3 h/day

Saturdays with full working EAF 2: *259 days / 365 days * 52 Saturdays = 37 Saturdays*

Working days with 3 hours of not working EAF 2: *259 days – 37 Saturdays = 222 days*

Total of unproductive time of EAF 2 on working days: *222 days * 3 h = 666 h*

Average tap to tap time of EAF 2 (2012 – 2013): 190 min

Actual voltage limit during peak time: 30 MW

Equalizing limit of voltage with limit beside peak time: *50 MW – 30 MW = 20 MW*

Price per MW per month during peak time: 15822 R$/MW and month

Total extra costs: *15822 R$/MW and month * 12 month/year * 20MW = 3797280 R$*

Yield of rolled material from taping to the final product 72 % of taped material

Maximum amount of extra heats per year with reduced tap to tap time:
666 h / 180 min / 60 min/h = 222 heats

Minimum amount of gained profit per kg by maximum of furnace utilisation:
3797280 R$ / 222 heats / 24.3 t/heat / 1000 kg/t / 72 % = 0.9774 R$/kg

By gaining a higher profit per kg, the minimum utilisation for an economical production during the peak time, will reduce.

11.5 Production Increase through Pre Melt Rolling

Total amount of taped material (2012):	122936 t
Total amount of taped material (Electric Arc Furnace #1, 2012):	83396 t
Total amount of taped material (Electric Arc Furnace #2, 2012):	39540 t
Amount of produced pre melts (2012):	3662 t
Yield of Electric Arc Furnace #1:	92 %
Yield of Electric Arc Furnace #2:	91 %

Total amount of taped material without pre melts (2012):	122936 t – 3662 t = 119274 t
Amount of pre melts scrap (2012):	3662 t / 119274 t = 3.1 %

Known time reduction with optimal scrap size for Electric Arc Furnace #2 (results are shown in "Test Result of Blooming various Pre Melts" on page 64):

80 % scrap with perfect size distribution (Weight-Surface coefficient = 733 kg/m^2)	2.5 min
50 % scrap with perfect size distribution (Weight-Surface coefficient = 548 kg/m^2)	2.3 min
25 % scrap with perfect size distribution (Weight-Surface coefficient = 395 kg/m^2)	2 min
10 % scrap with perfect size distribution (Weight-Surface coefficient = 303 kg/m^2)	1.5 min
0 % scrap with perfect size distribution (Weight-Surface coefficient = 242 kg/m^2)	0 min

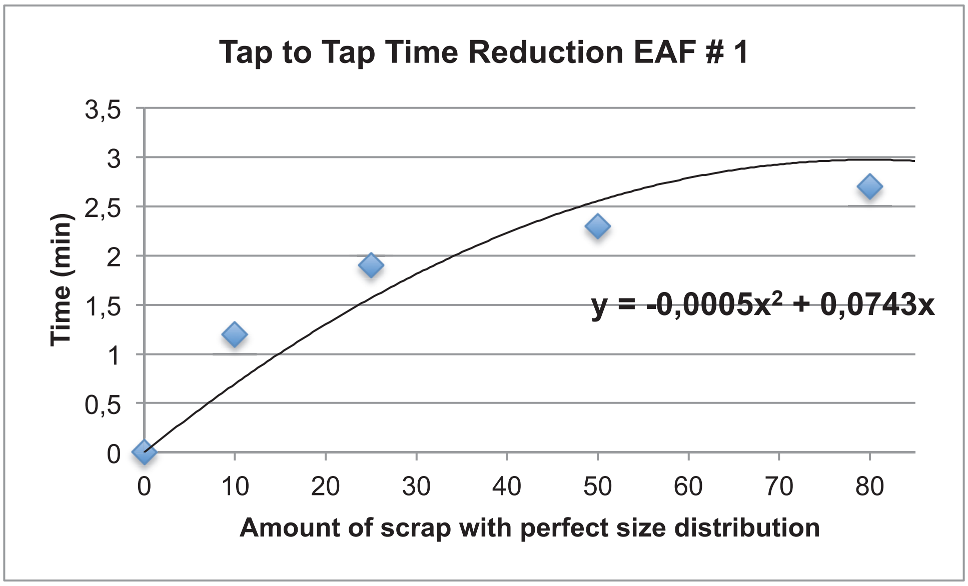

Figure 11-3: Tap to tap time Reduction depending on weight surface coefficient in EAF # 1

Tap to tap time reduction with 3.1 % of scrap with prefect size distribution in Electric Arc Furnace # 2: $-0.0005 * 3.1^2 + 0.0743 * 3.1 = 0.23$ Minutes

Known time reduction with optimal scrap size for Electric Arc furnace #2 (results are shown in "Test Result of Blooming various Pre Melts" on page 64):

80 % scrap with perfect size distribution (Weight-Surface coefficient = 733 kg/m^2)	33 min
25 % scrap with perfect size distribution (Weight-Surface coefficient = 395 kg/m^2)	20 min
10 % scrap with perfect size distribution (Weight-Surface coefficient = 303 kg/m^2)	9 min
0 % scrap with perfect size distribution (Weight-Surface coefficient = 242 kg/m^2)	0 min

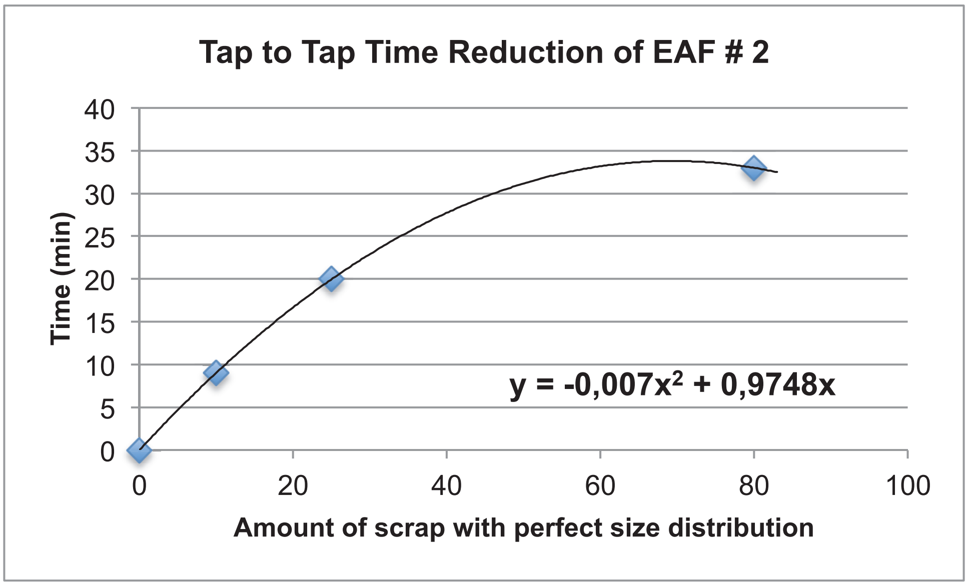

Figure 11-4: Tap to tap time Reduction depending on weight surface coefficient in EAF # 2

Tap to tap time reduction with 3.1 % of scrap with prefect size distribution in Electric Arc Furnace # 2: $-0.007 * 3.1^2 + 0.9748 * 3.1 = 3$ Minutes

Heats in Electric Arc Furnace # 1 without pre melt heats (2012):	2354
Heats in Electric arc Furnace # 1 without pre melt heats (2012):	1576

Total time save with 3.1% pre melts with optimum scrap size distribution:
2354 * 0.23 min 34.3 t/heat / 140 min/heat + 1576 * 3.1 min * 24.3 t/heat / 190 min/heat = 757.49 t

Variable costs of blooming (2012): 5861 R$/h

Capacity of blooming pre melts: 30 t/h

Total variable costs for blooming all pre melts: *3662 t / 30t/h * 5879 R$/h = 715408 R$*

Variable costs for oxycut: 90 R$/t

Total amount of variable costs for cutting all pre melts: *90 R$/t * 3662 t = 347580 R$*

Total costs: 715408 R$ + 92282 R$ = 807690 R$

Requested amount of profit per kg: 807690 R$ / 757490 kg = 1.062 R$

11.6 Economic Study of Pre Melts

Average profit per kg (12.2013): 3.024 R$/kg

Energy costs (03.2013): 0.225 R$/kWh

Product yield from taping to final product of all materials: 72 %

Variable costs EAF 1 (12.2013): 5842 R$/h

Variable costs EAF 2 (12.2013): 4926 R$/h

Average tap to tap time after increasing voltage limit: _190 min – 4.7 min = 185.3 min_

Average power consumption in EAF 2 (04.2012 – 04.2013): 15587 kWh/heat

Tapping: 24.3 t

Energy costs EAF 2:

Average energy costs per EAF 2 heat: _15587 kWh/heat * 0.225 R$/kWh = 3506 R$/heat_

Missed profit generation:

Missed profit generation in EAF 2 per tap: _24.3t * 1000 kg/t * 3.024 R$/kg * 72% = 52907 R$_

Casting:

Variable costs of conventional casting per hour (12.2013): 357 R$/h

Variable costs of conventional casting per minute (12.2013): 5.95 R$/min

Variable costs conventional casting per EAF 2 heat:

5.95 R$/min * 180 min/heat = 1072 R$/heat

Blooming

Variable costs of blooming per hour (12.2013): 5860 R$/h

Variable costs of blooming per minute (12.2013): 97.7 R$/min

Variable costs of blooming per heat: *97.7 R$/min * 180 min/heat = 17593 R$/heat*

Oxycut

Variable costs oxycut 90 R$/t

Variable costs oxycut per heat of EAF 2 *90 R$/t * 24.3 t/heat = 109350 R$/heat*

Total costs:

3506 R$/heat + 52907 R$/heat + 1072 R$ + 17582 R$ + 2187 R$ = 77255 R$/heat

Used quantity of pre melts in second heat: 60 %

Additional costs for EAF 2 production: 77255 R$/heat * 60% = 46353 R$/heat

Time reduction per heat to average tap to tap time (15 min adjusting composition): 15 min

Profit generation because of lower utilisation of EAF 2:

*24.3 t/heat * 15 min/190 min * 3.024 R$/kg *1000 kg/t = 5801 R$/heat*

Total saved costs for pre melt processing per EAF 2 heat without having free furnace capacity:

Profit generation because of utilisation: 5801 R$/heat

Additional costs for pre melt: 77255 R$/heat

Saved elements: X R$

Total: *77254 R$/heat – 5799 R$/heat = X R$*

X = 71453 R$

Costs of elements:

FeCr AC nac: 10.584 R$/kg

Content of Cr:	50 %
Cr:	10.584 R$/kg / 50% = 5.29 R$/kg

FEV80:	50.454 R$/kg
Content of V:	65 %
V:	77.58 R$/kg

FeSi75:	5.238 R$/kg

MoO3	38.124 R$/kg
Content of Mo:	62 %

FeMn AC	6.57 R$/kg

C	0 R$/kg

X must be for each specific element:

Cr	14.0 %
V	3.8 %
Si	56.8 %
Mo	7.8 %
Mn	45.0 %

Cr 2.8%, V 0.76%, Si 11.36%, Mo 1.56%, Mn 9%

Total saved costs for pre melt processing per EAF 2 heat without having free furnace capacity:

Profit generation because of utilisation: 5801 R$/heat

Additional costs for pre melt: 24348 R$/heat

Saved elements: X R$

Total: *24348 R$/heat – 5801 R$/heat = X R$*

X = 18547 R$

X must be for each specific element:

Cr	3.64%
V	0.99 %
Si	14.77 %
Mo	2.02 %
Mn	11.7 %

Cr 0.73 %, V 0.20 %, Si 3.0 %, Mo 0.41 %, Mn 2.36 %

Figure 11-5: Ingots of VSM13A Samples

Figure 11-6: Forged Ingots of VSM13A Samples

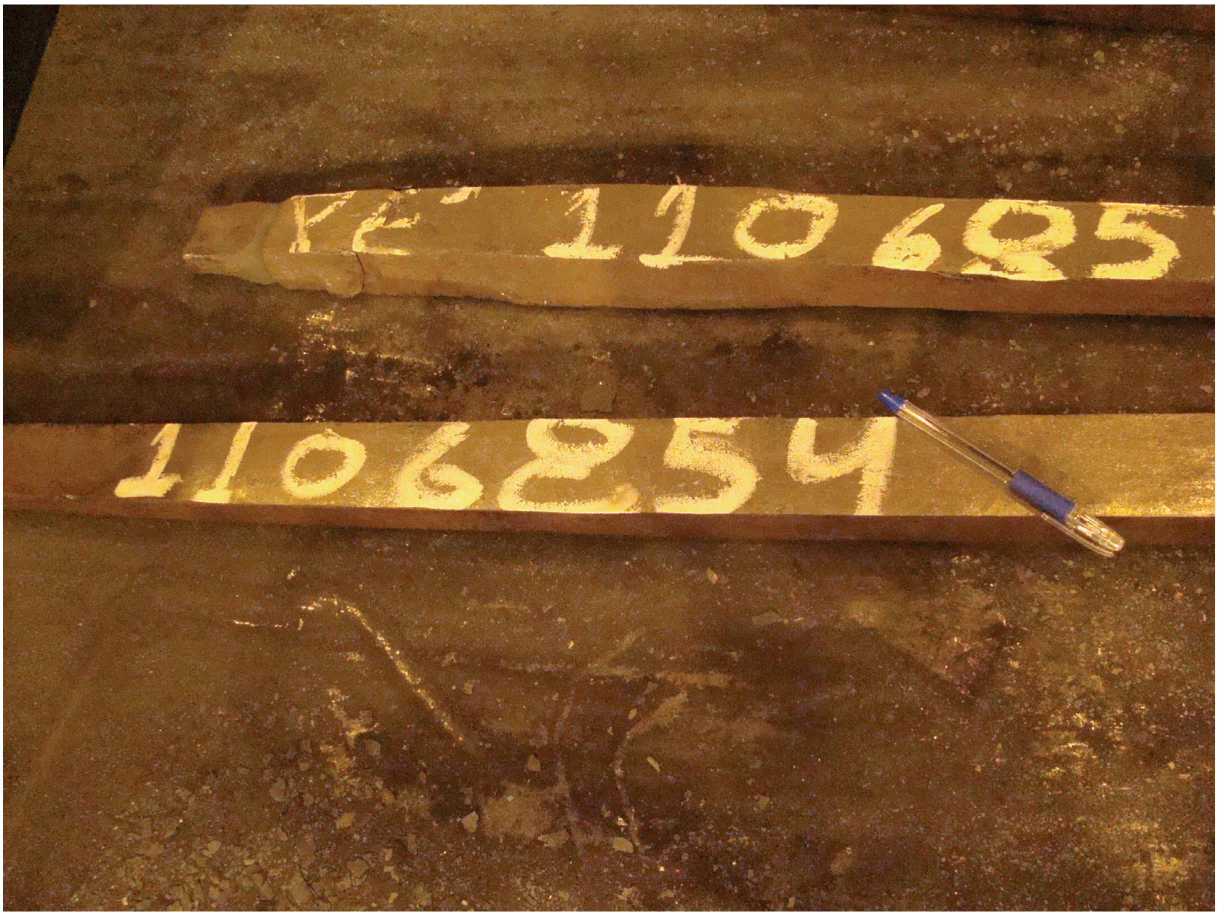

Figure 11-7: Forged Ingots of VSM13A Samples close

11.6.1 Images of VSM13A after Corrosion Test

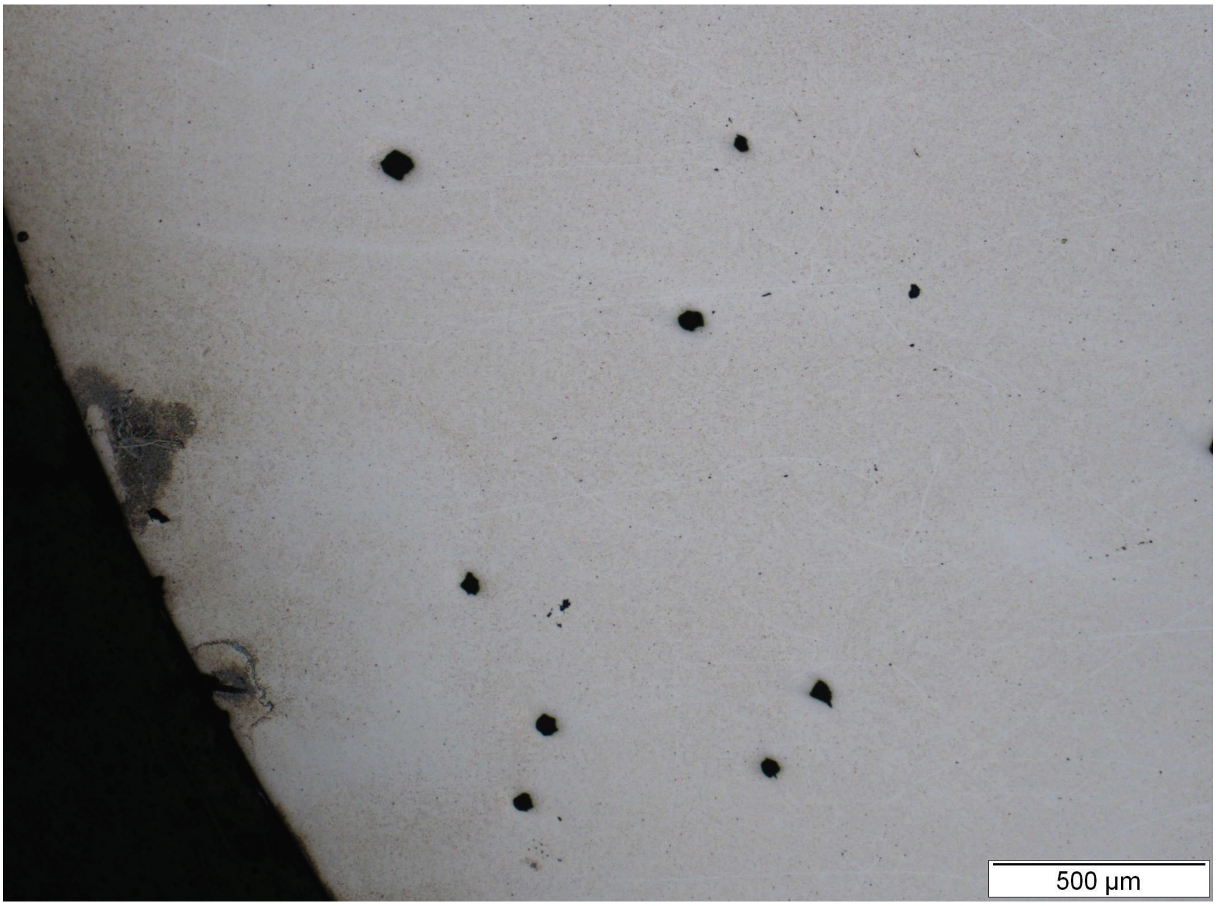

Figure 11-8: VSM13A with 0.01% Phosphorus Content after Corrosion Test with 50X Magnification

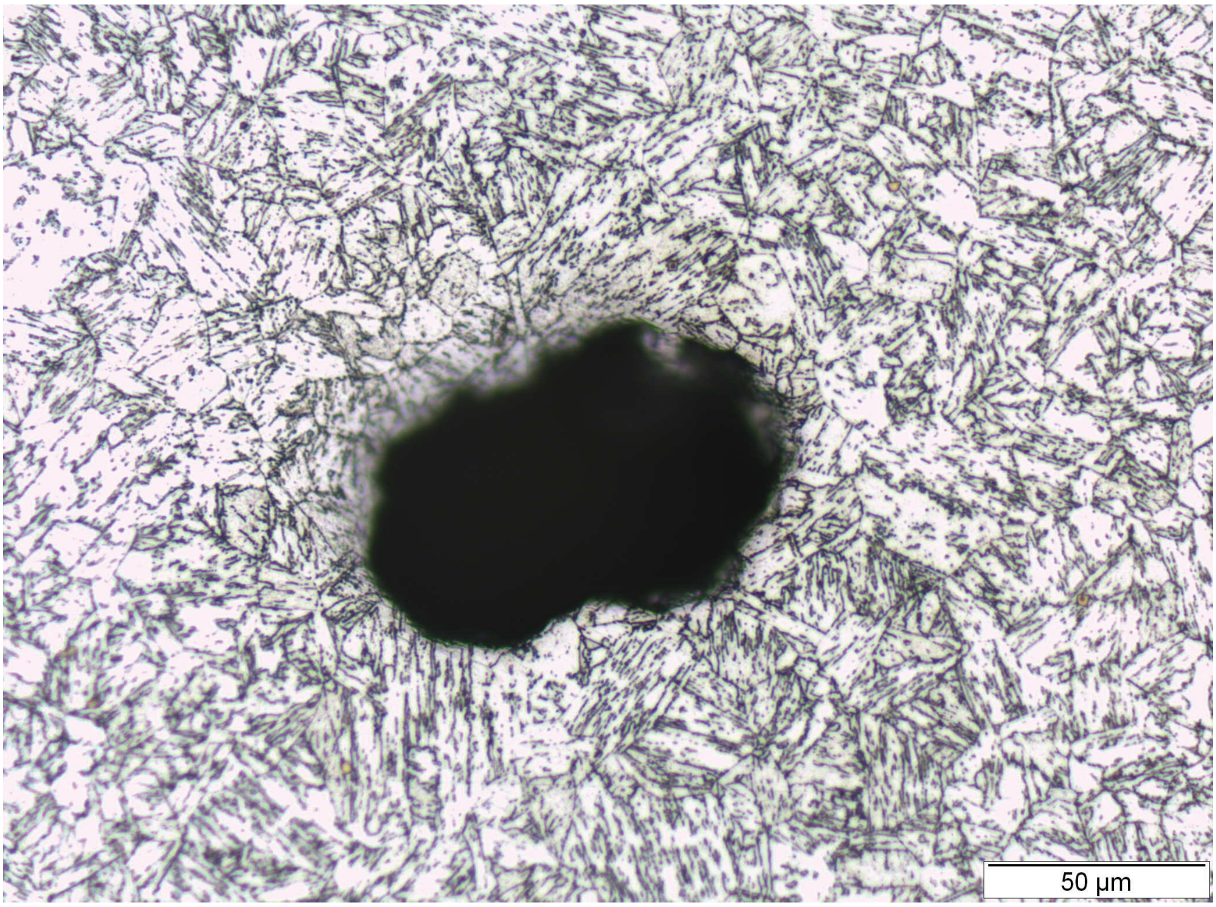

Figure 11-9: VSM13A with 0.01% Phosphorus Content after Corrosion Test with 500X Magnification

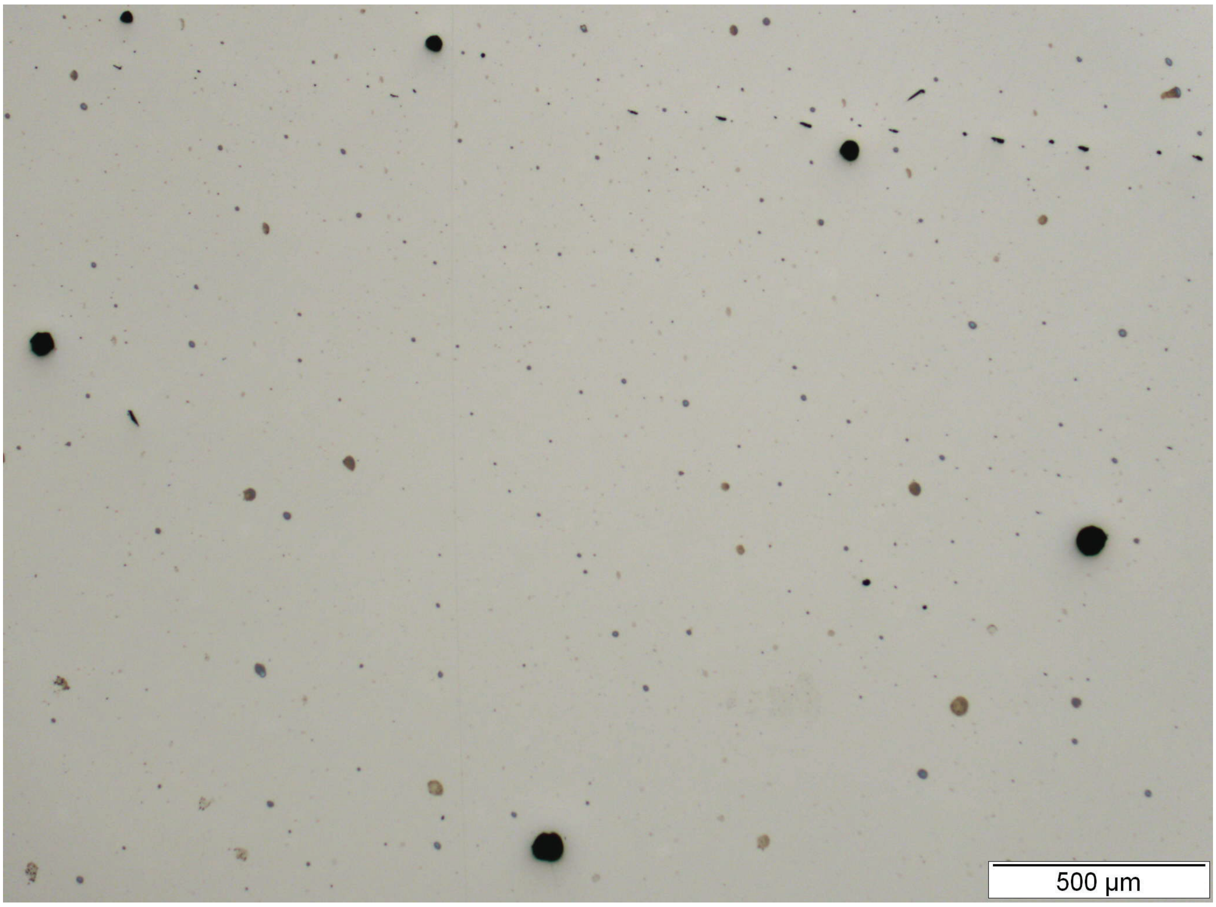

Figure 11-10: VSM13A with 0.02% Phosphorus Content after Corrosion Test with 50X Magnification

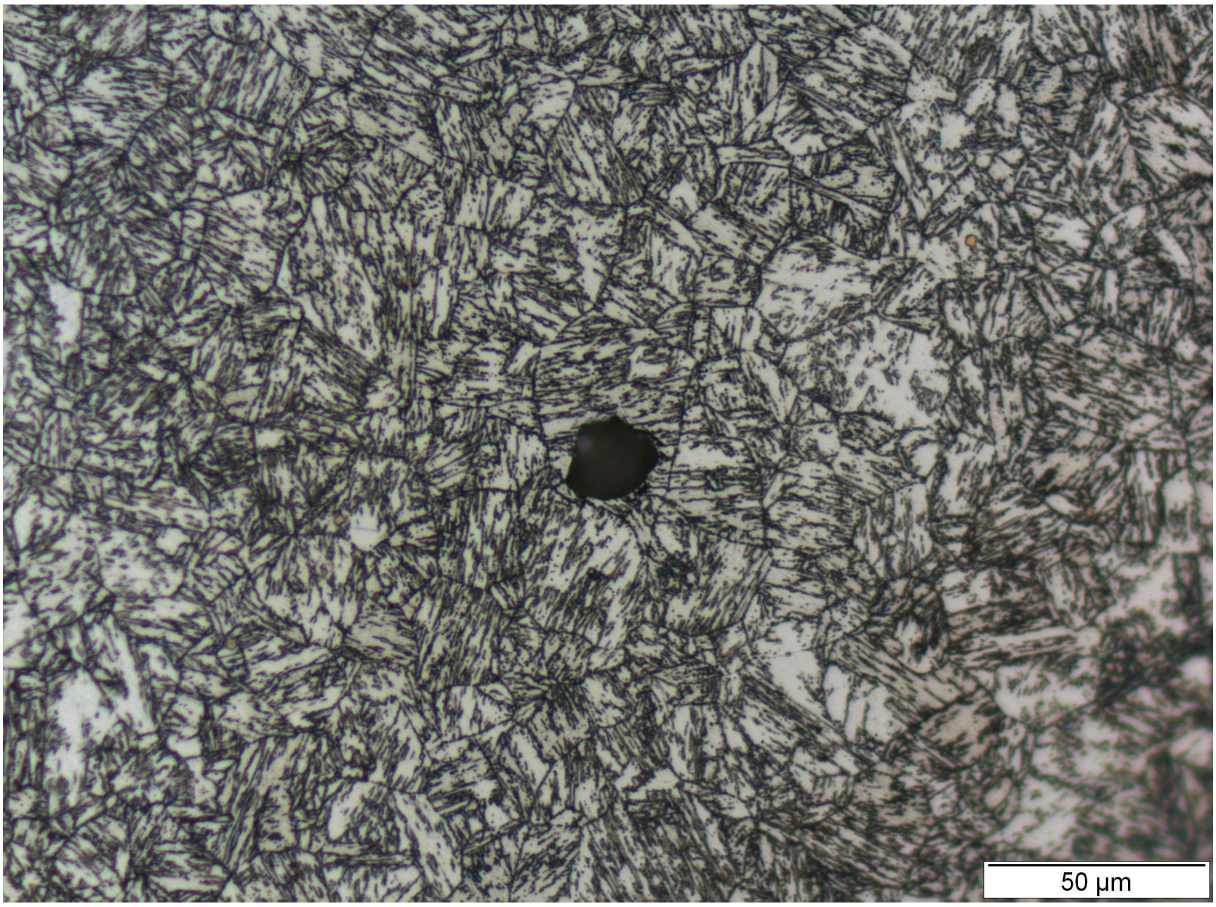

Figure 11-11: VSM13A with 0.02% Phosphorus Content after Corrosion Test with 500X Magnification

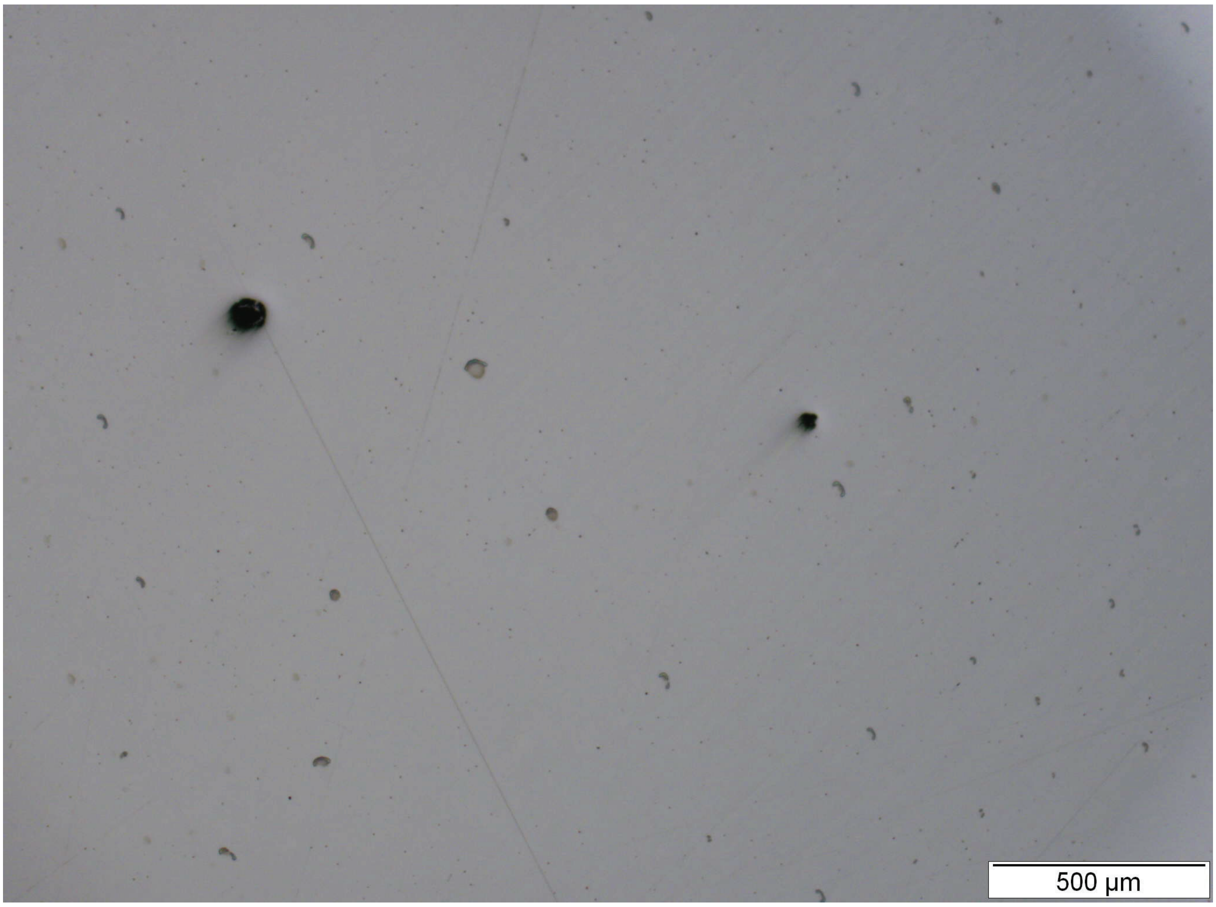

Figure 11-12: VSM13A with 0.04% Phosphorus Content after Corrosion Test with 50X Magnification

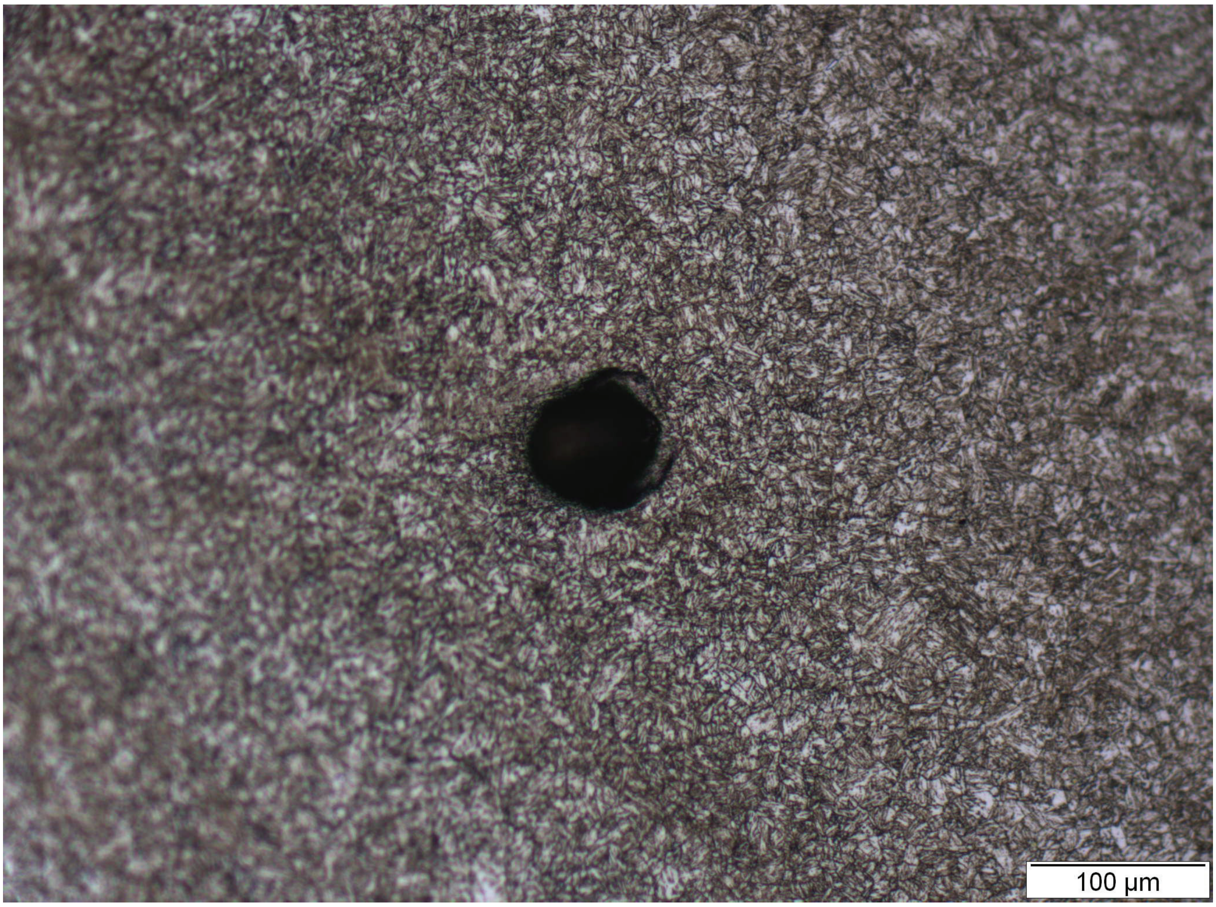

Figure 11-13: VSM13A with 0.04% Phosphorus Content after Corrosion Test with 500X Magnification

11.6.2 Pictures of VSM13A Microstructure

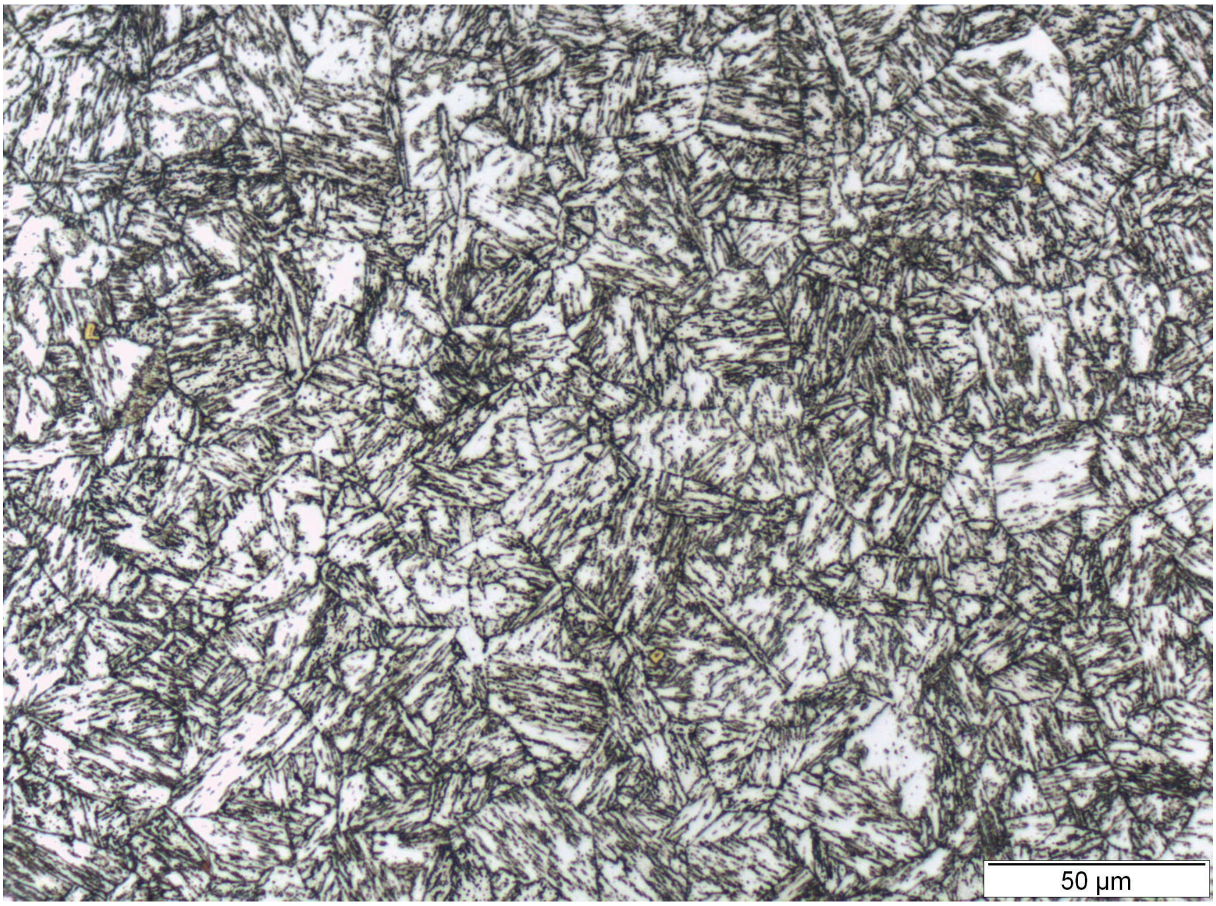

Figure 11-14: VSM13A with 0.02% Phosphorus Content after Corrosion Test with 500X Magnification

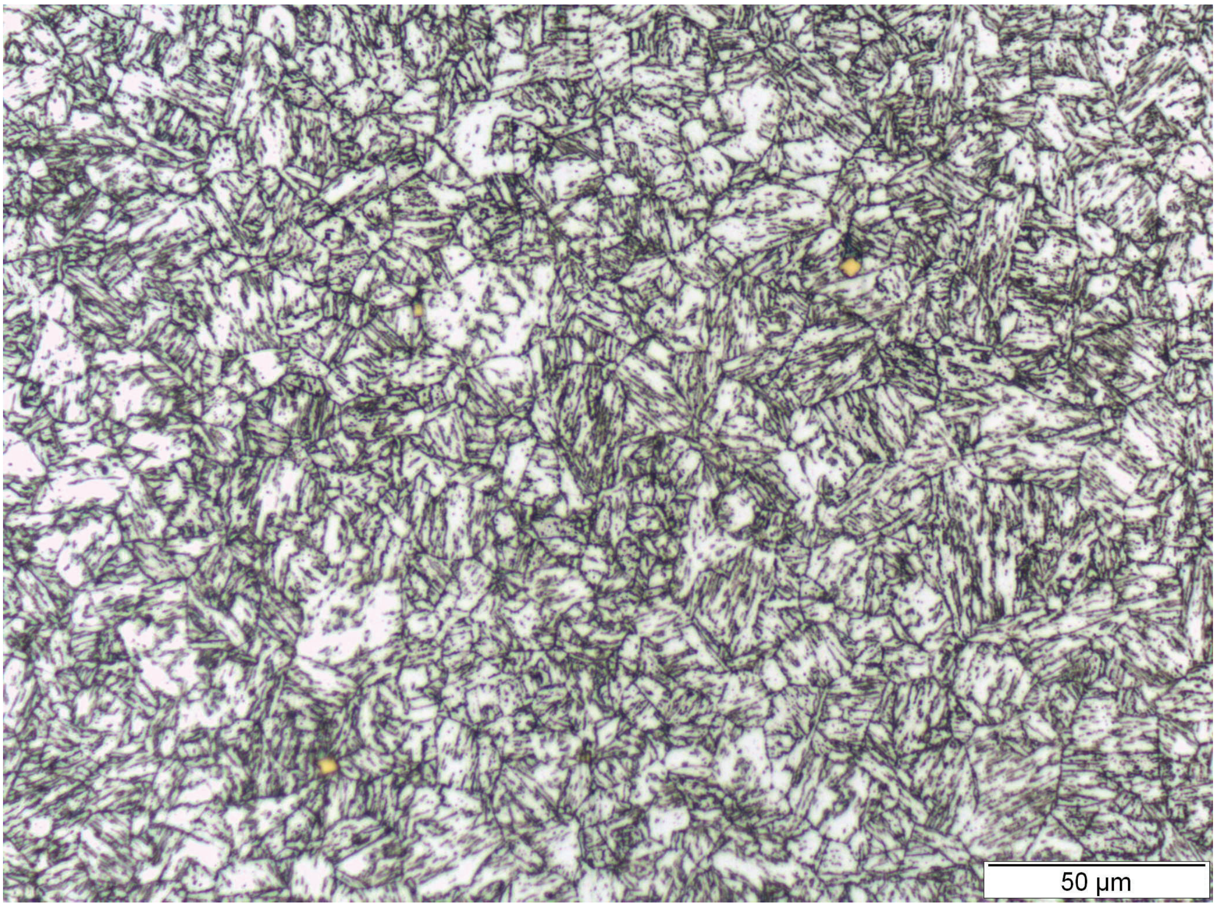

Figure 11-15: VSM13A with 0.03% Phosphorus Content after Corrosion Test with 500X Magnification

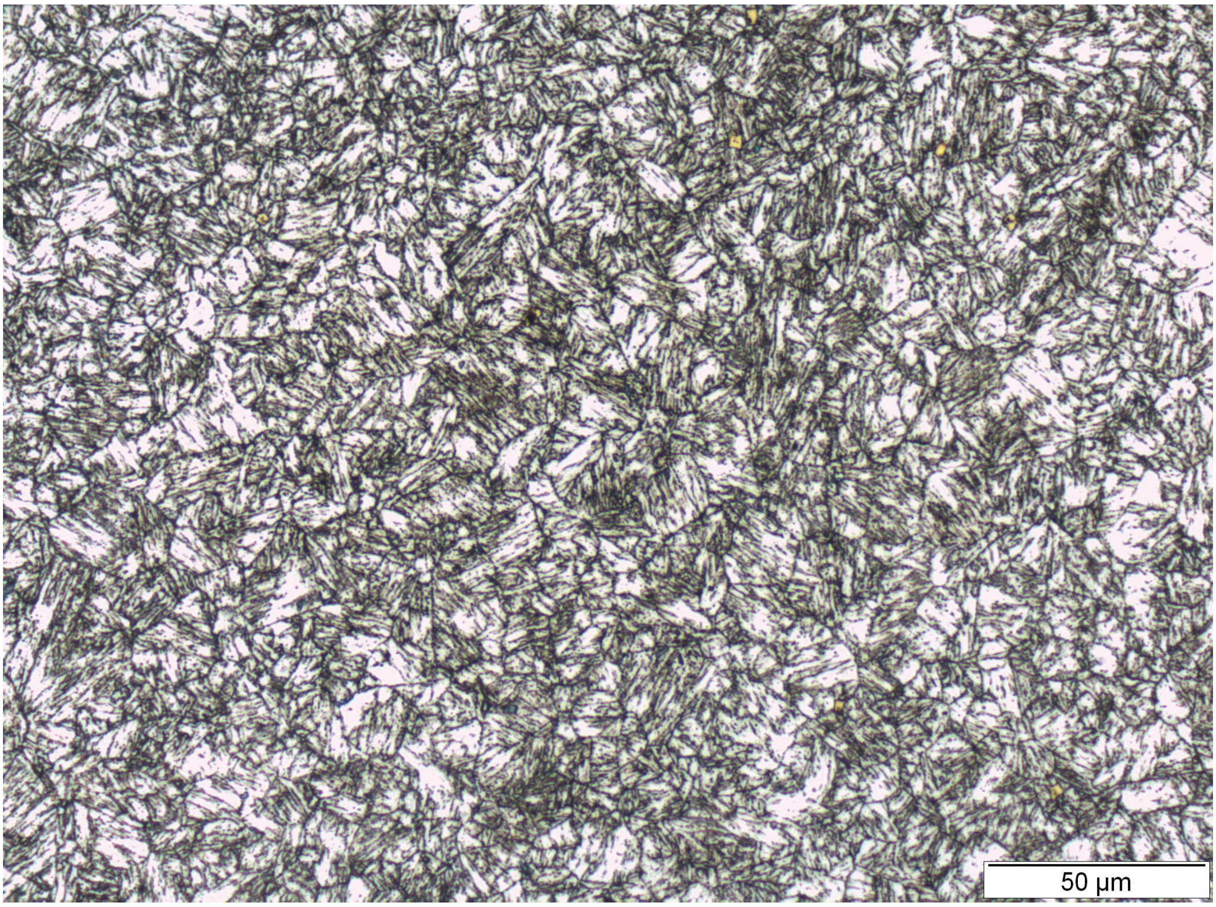

Figure 11-16: VSM13A with 0.04% Phosphorus Content after Corrosion Test with 500X Magnification

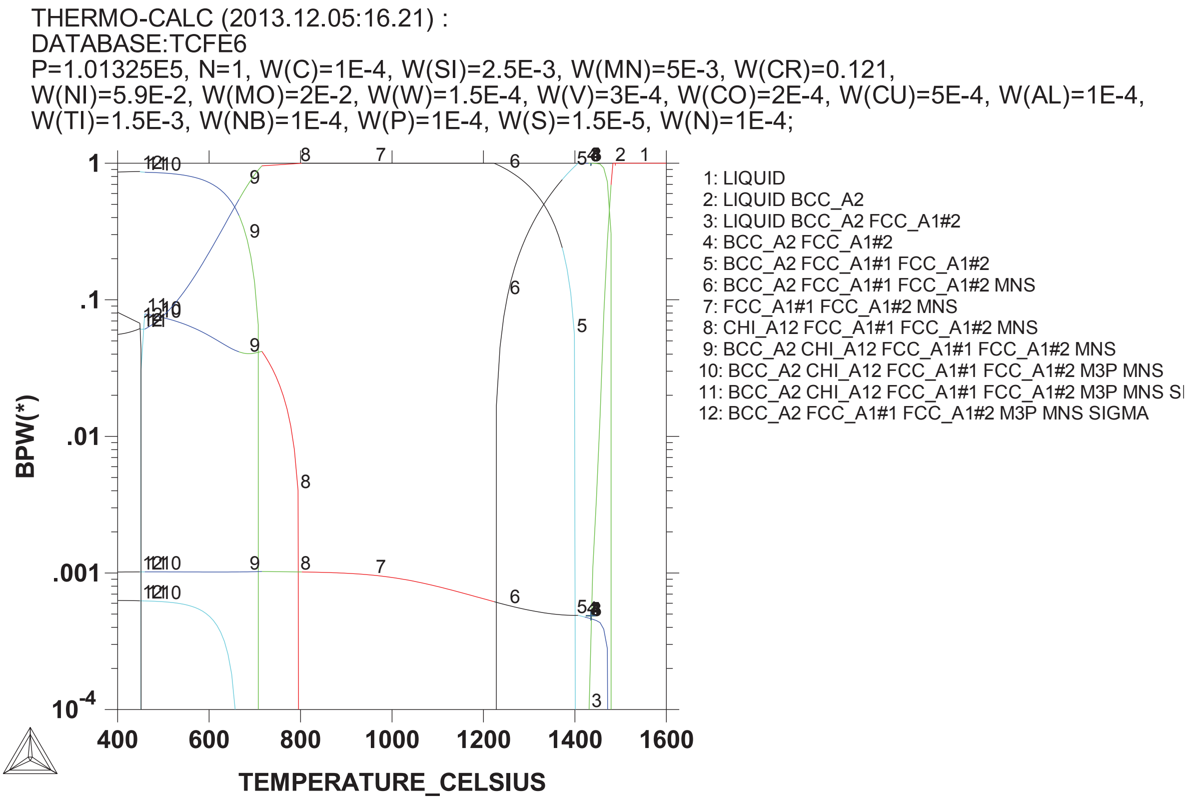

Figure 11-17: Phase Diagram of VSM13A with 0.01 wt% P

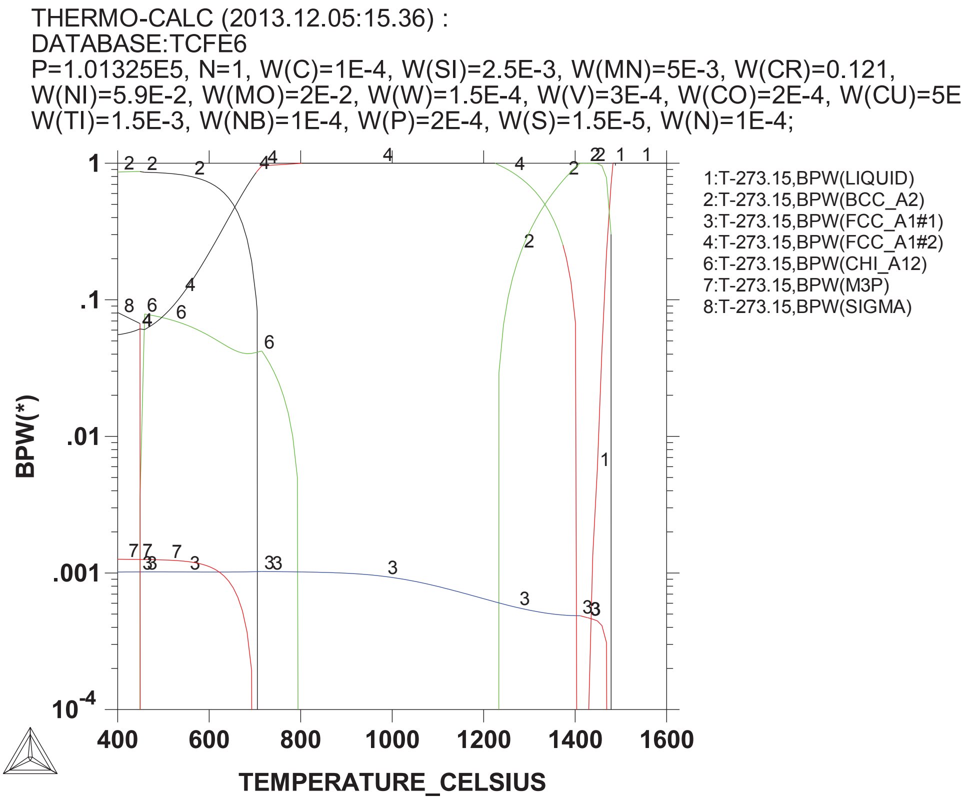

Figure 11-18: Phase Diagram of VSM13A with 0.02 wt% P

THERMO-CALC (2013.12.05:14.52) :
DATABASE:TCFE6
P=1.01325E5, N=1, W(C)=1E-4, W(SI)=2.5E-3, W(MN)=5E-3, W(CR)=0.121,
W(NI)=5.9E-2, W(MO)=2E-2, W(W)=1.5E-4, W(V)=3E-4, W(CO)=2E-4, W(CU)=5E-4, W(AL)=1E-4,
W(TI)=1.5E-3, W(NB)=1E-4, W(P)=3E-4, W(S)=1.5E-5, W(N)=1E-4;

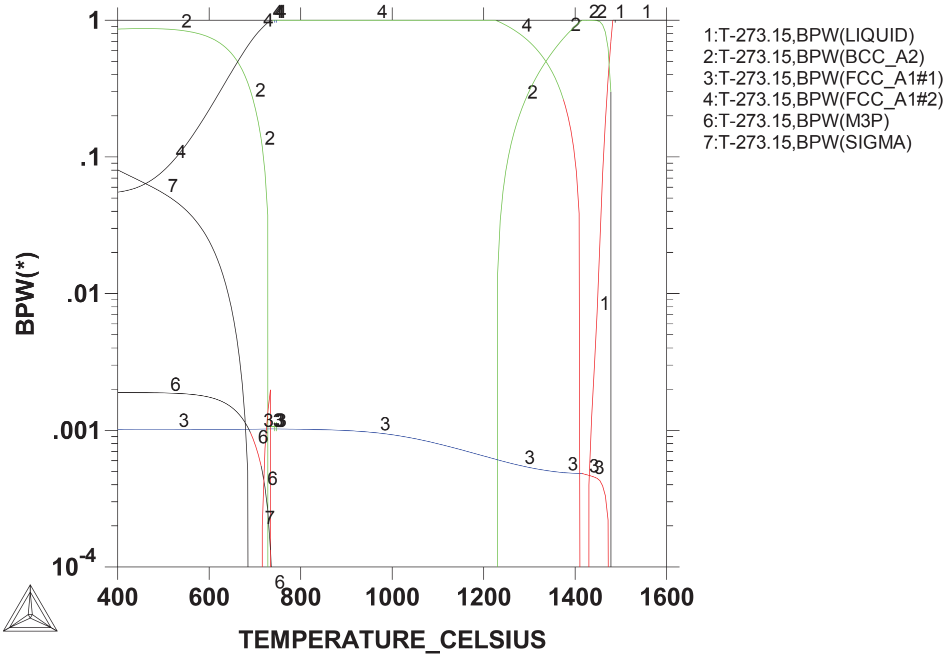

Figure 11-19: Phase Diagram of VSM13A with 0.03 wt% P

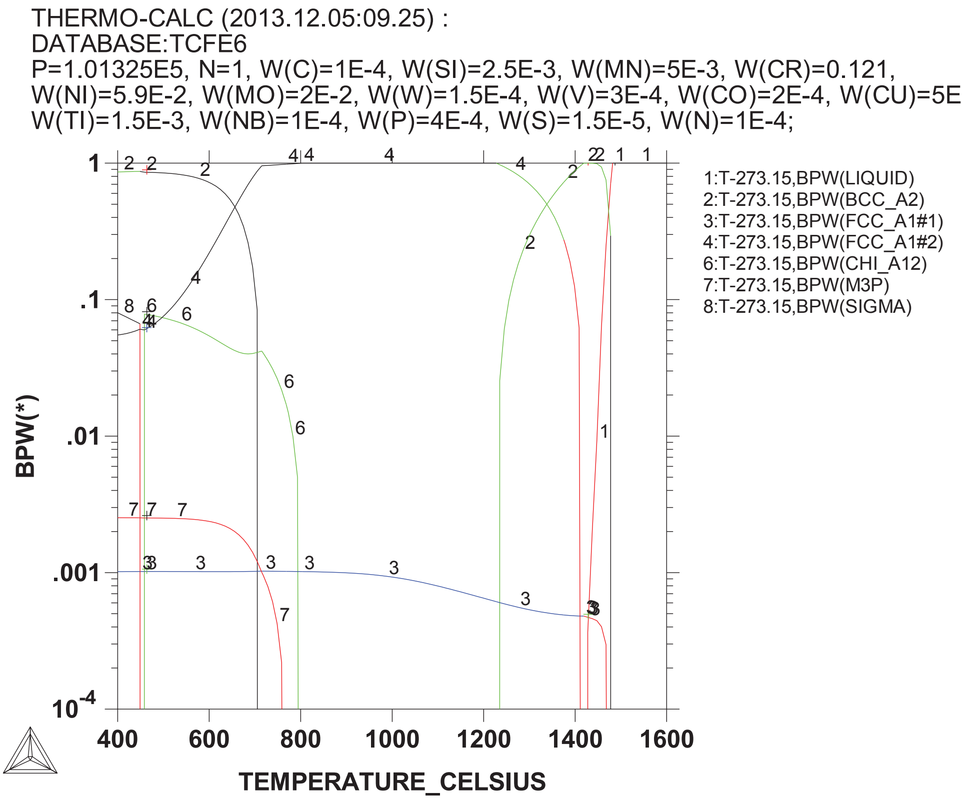

Figure 11-20: Phase Diagram of VSM13A with 0.04 w% P

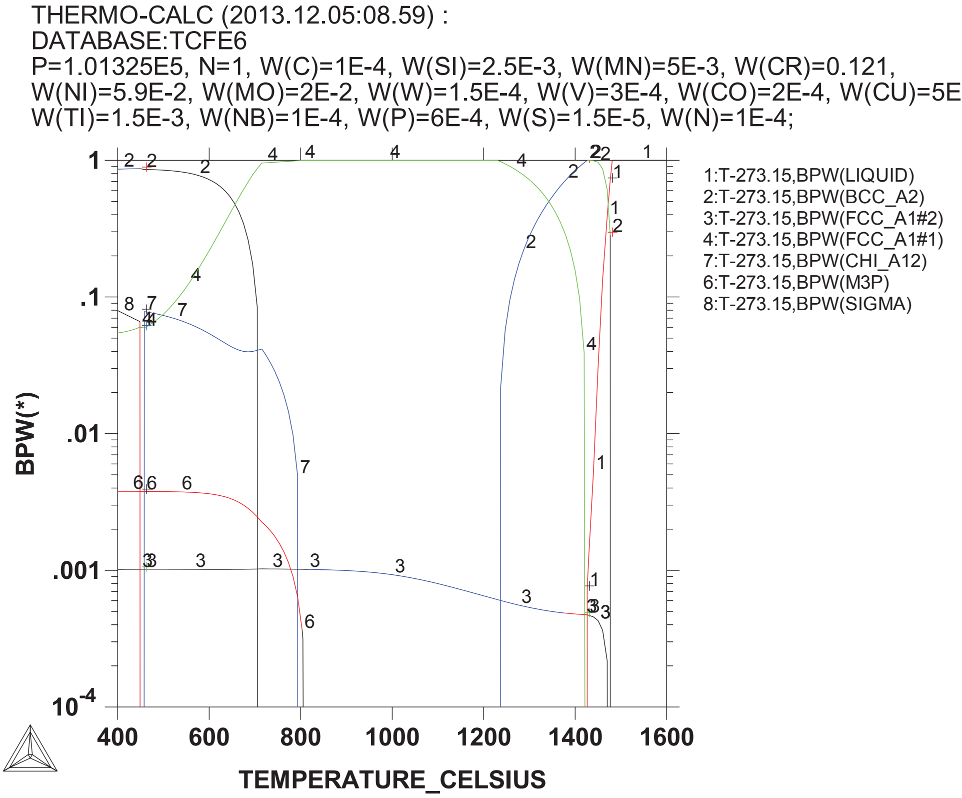

Figure 11-21: Phase Diagram of VSM13A with 0.06 w% P

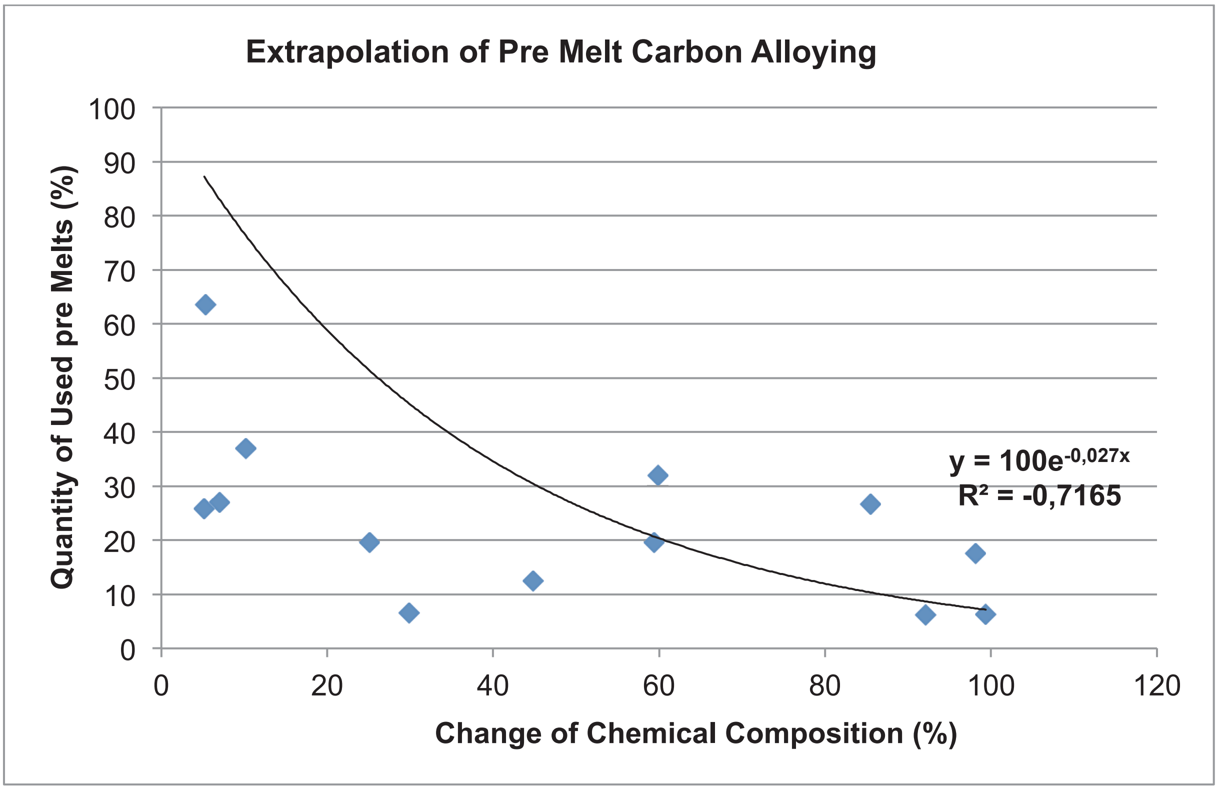

Figure 11-22: Extrapolation of Pre Melt Carbon Alloying

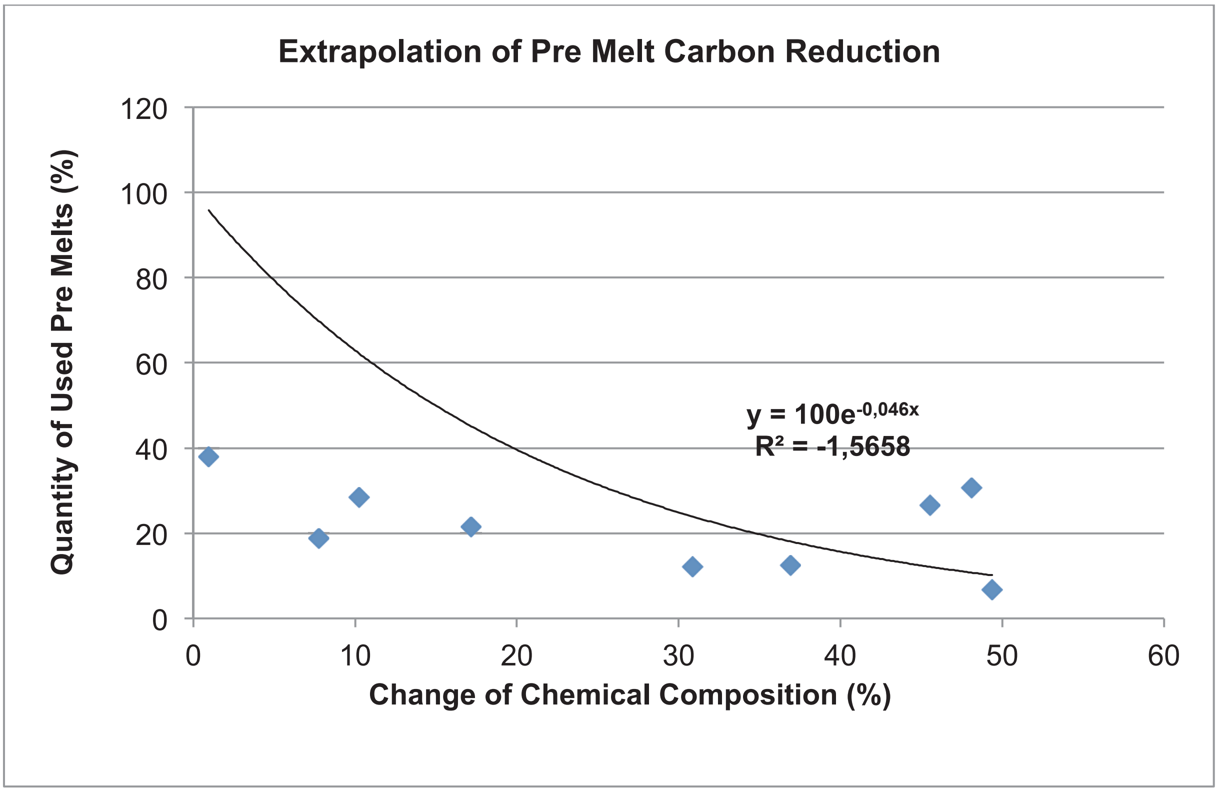

Figure 11-23: Extrapolation of Pre Melt Carbon Reduction

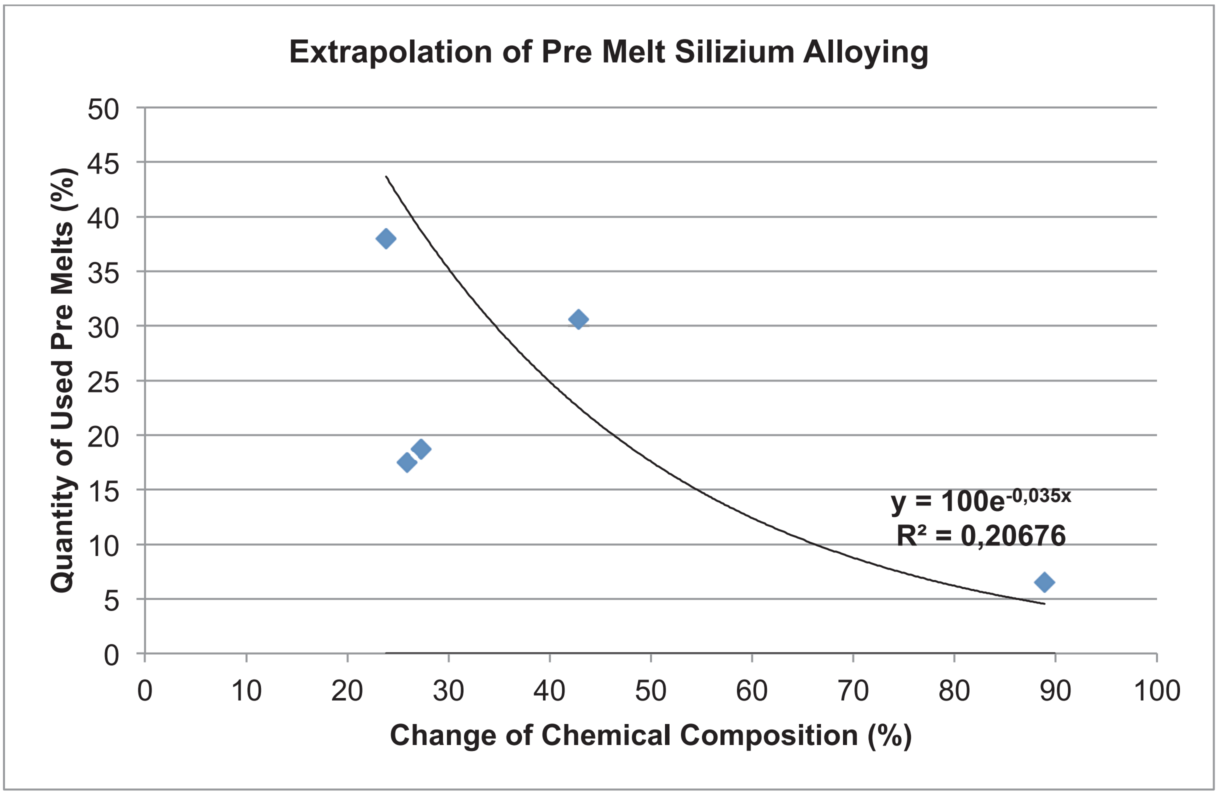

Figure 11-24: Extrapolation of Pre Melt Siloizium Alloying

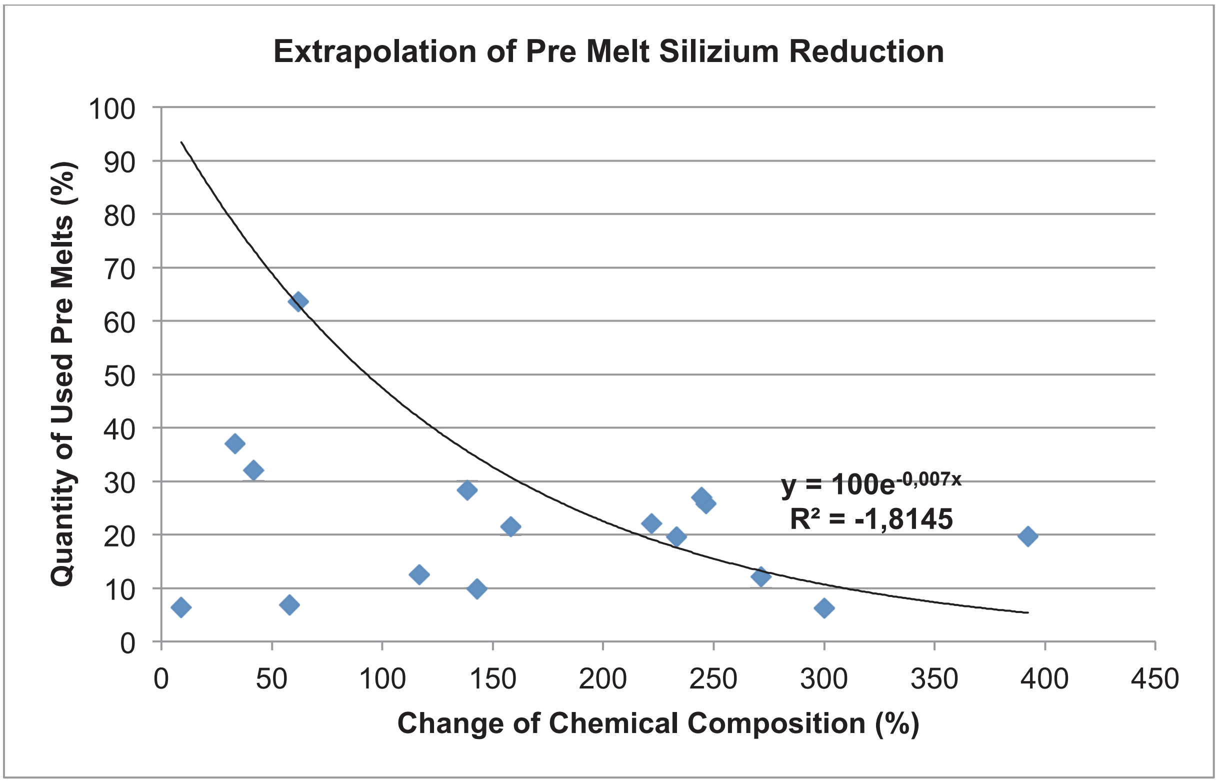

Figure 11-25: Extrapolation of Pre Melt Silizium Reduction

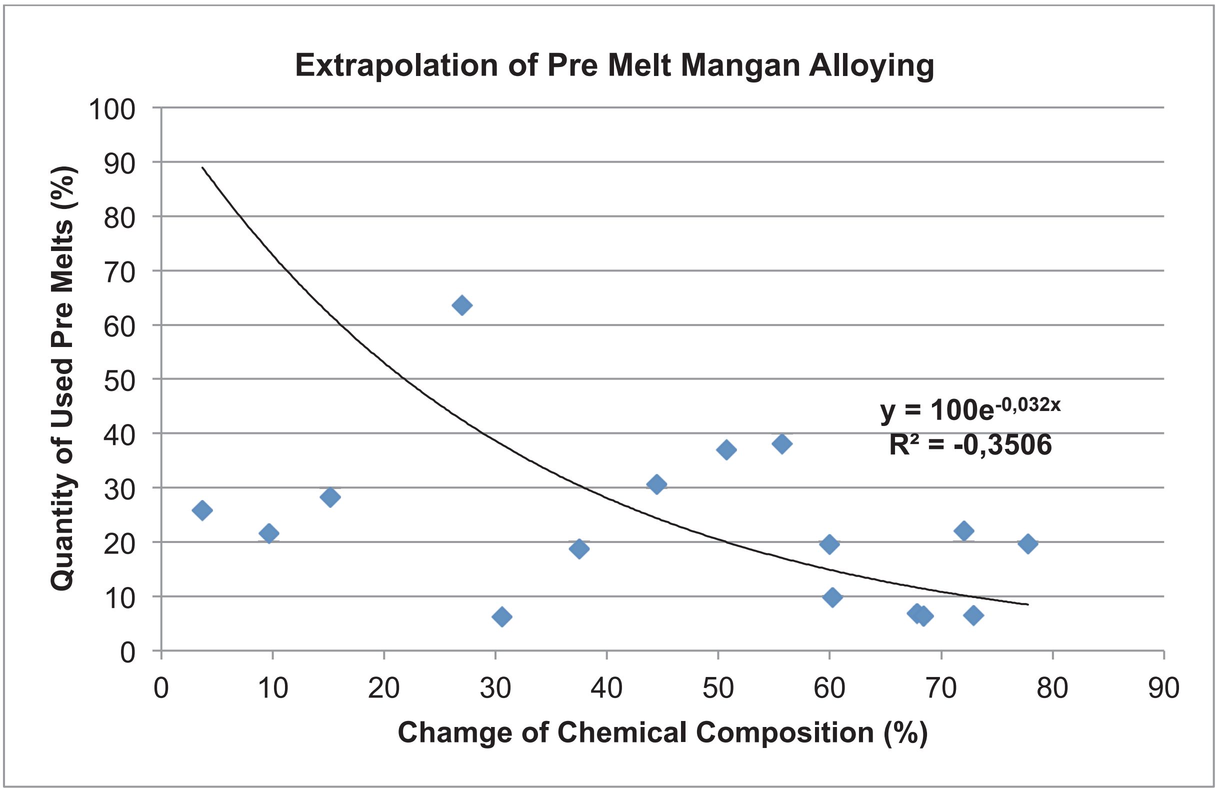

Figure 11-26: Extrapolation of Pre Melt Mangan Alloying

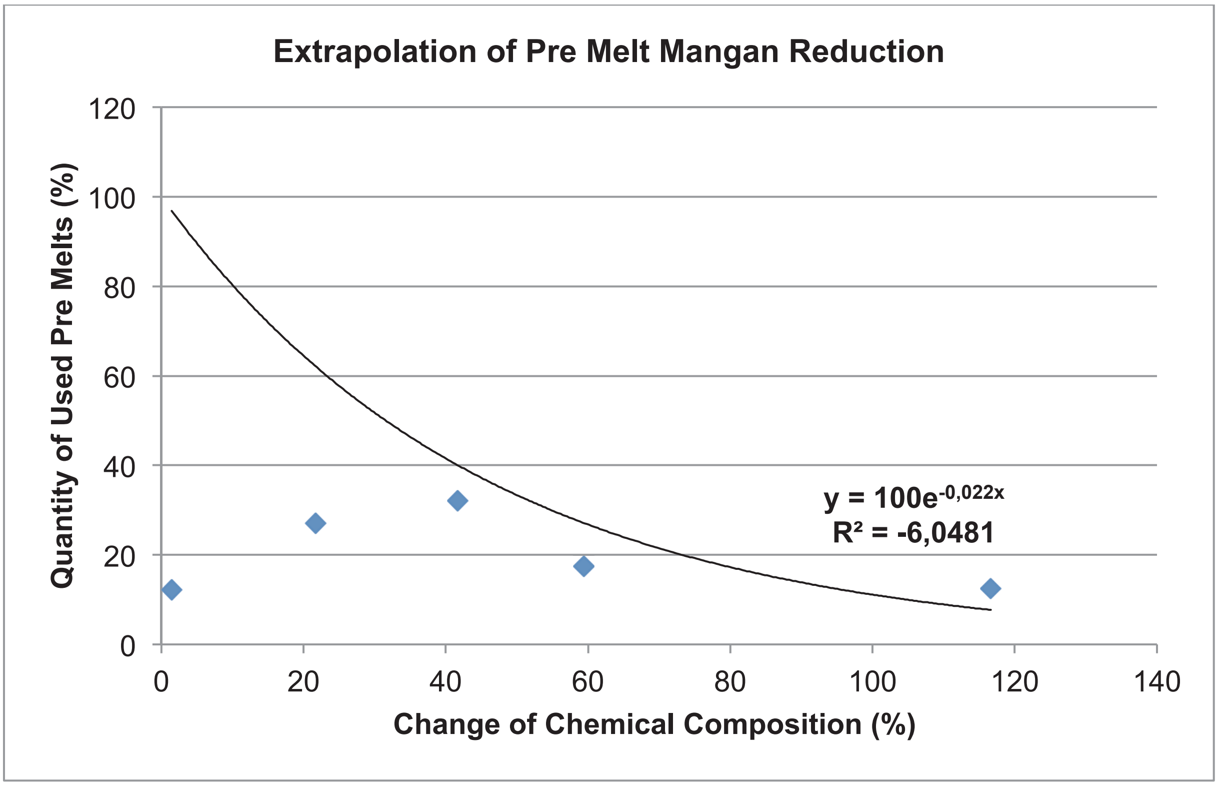

Figure 11-27: Extrapolation of Pre Melt Mangan Reduction

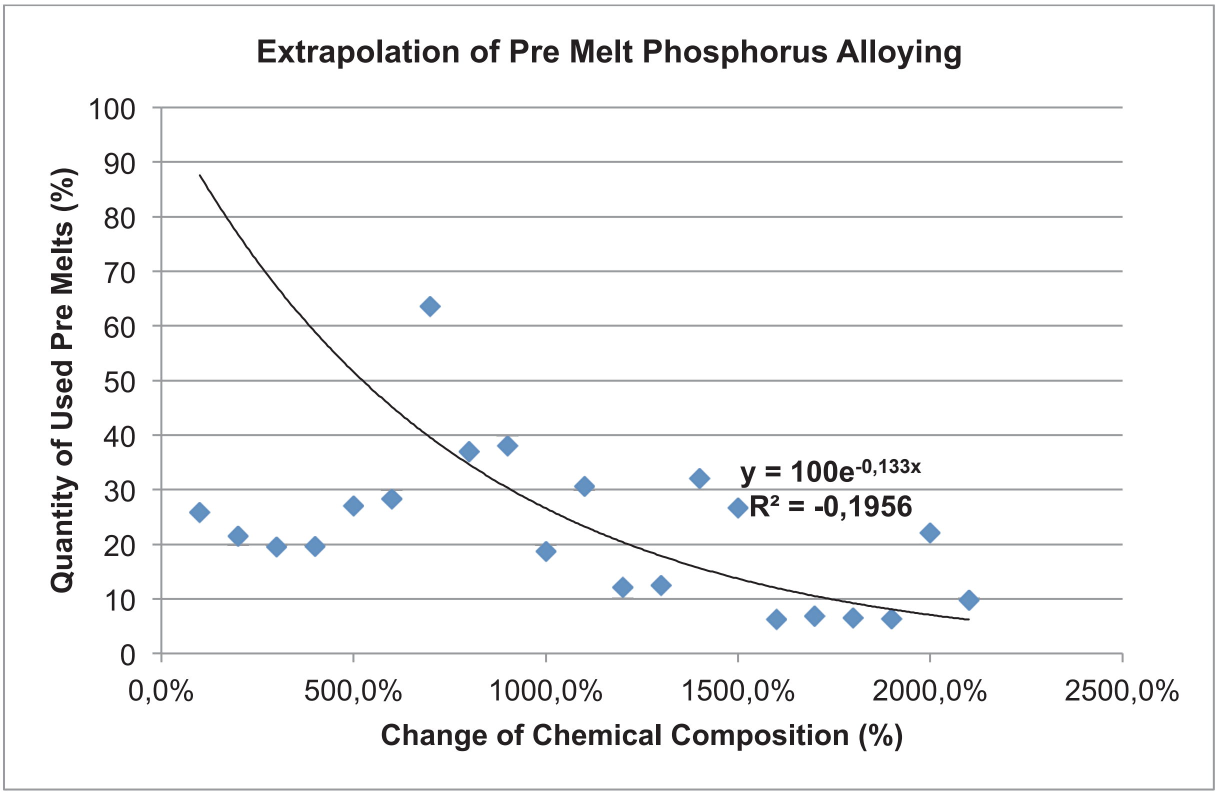

Figure 11-28: Extrapolation of Pre Melt Phosphorus Alloying

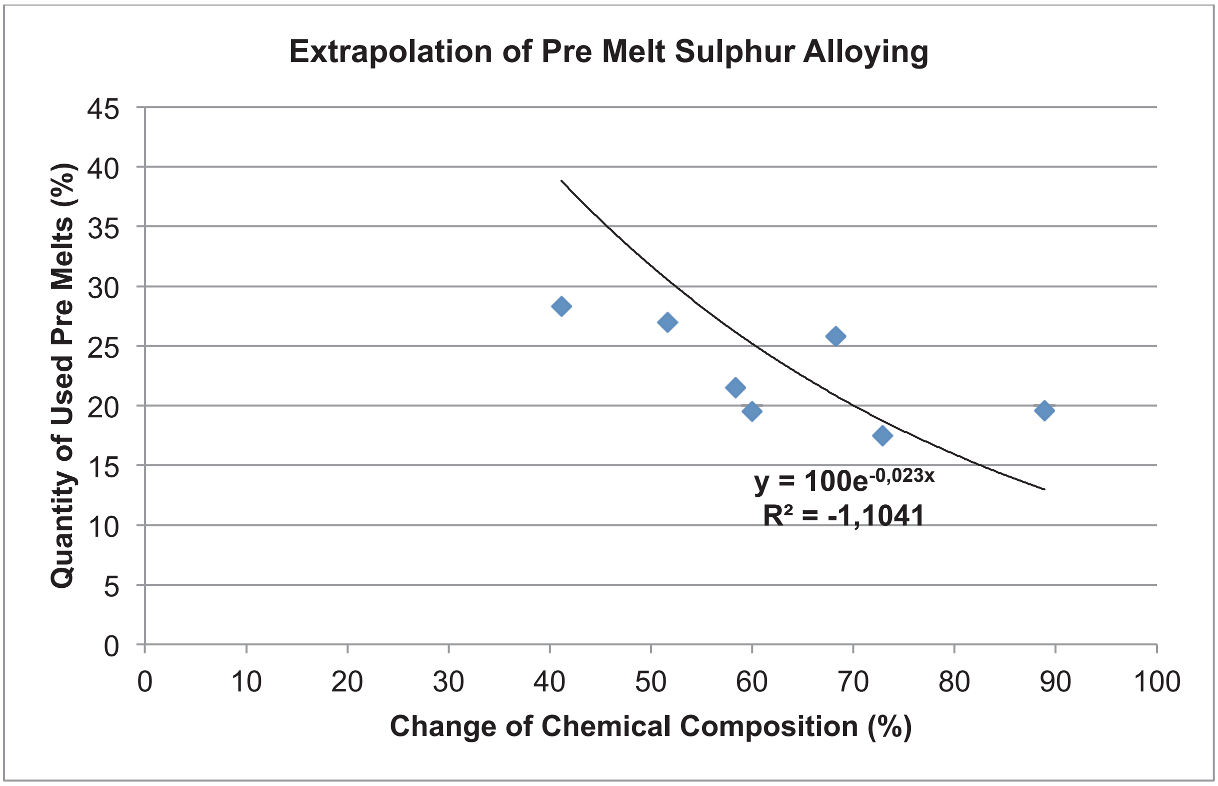

Figure 11-29: Extrapolation of Pre Melt Sulphur Alloying

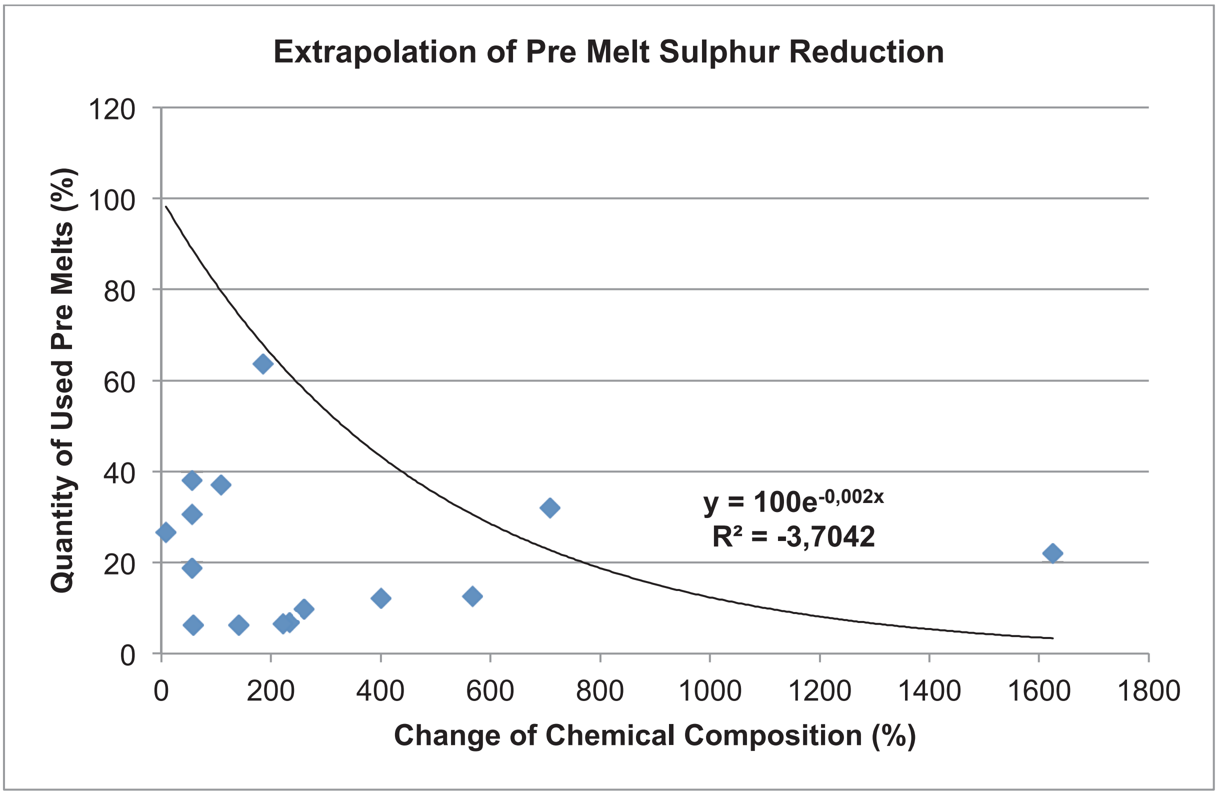

Figure 11-30: Extrapolation of Pre Melt Sulphur Reduction

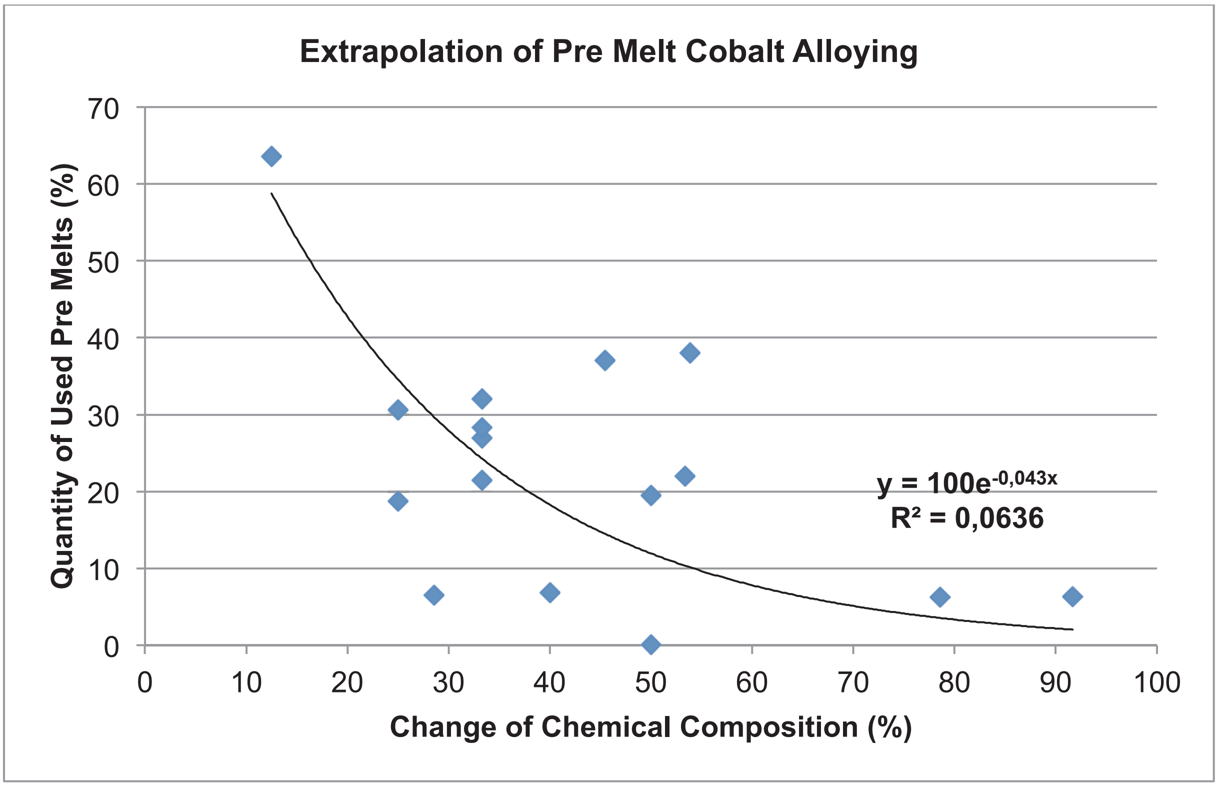

Figure 11-31: Extrapolation of Pre Melt Cobalt Alloying

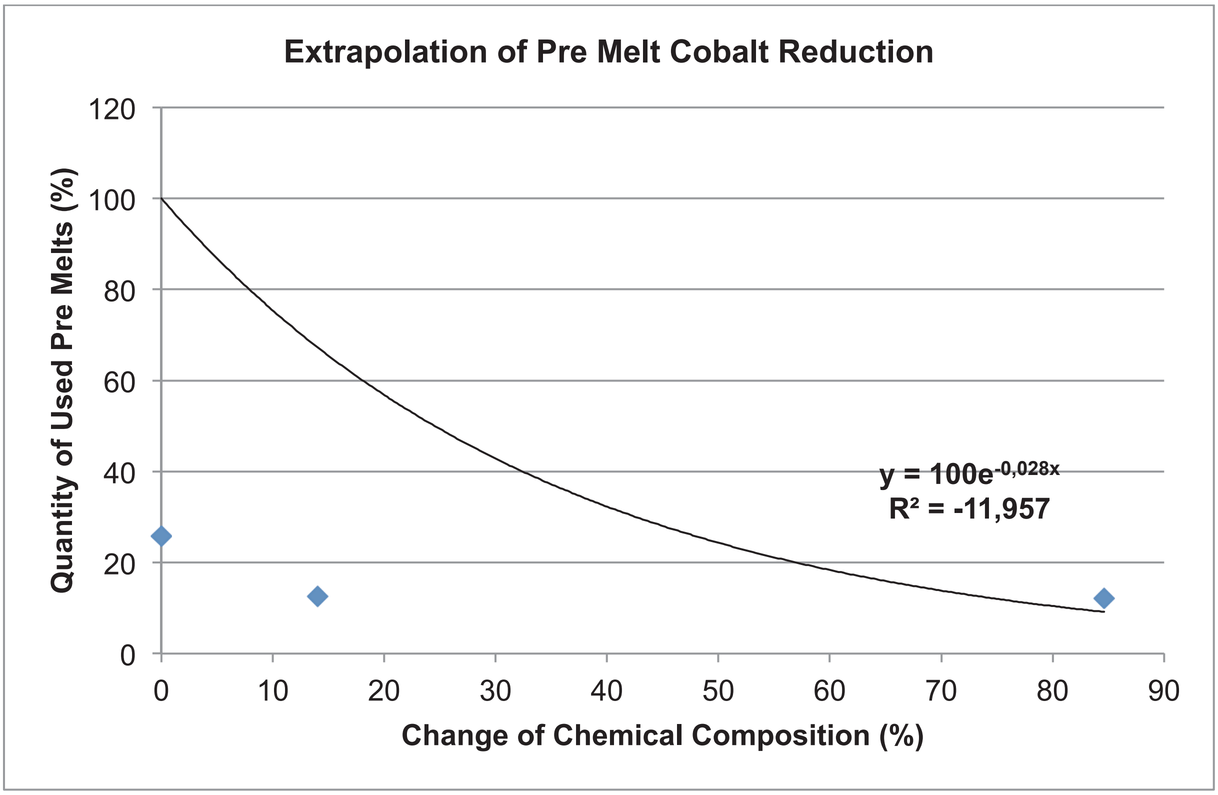

Figure 11-32: Extrapolation of Pre Melt Cobalt Reduction

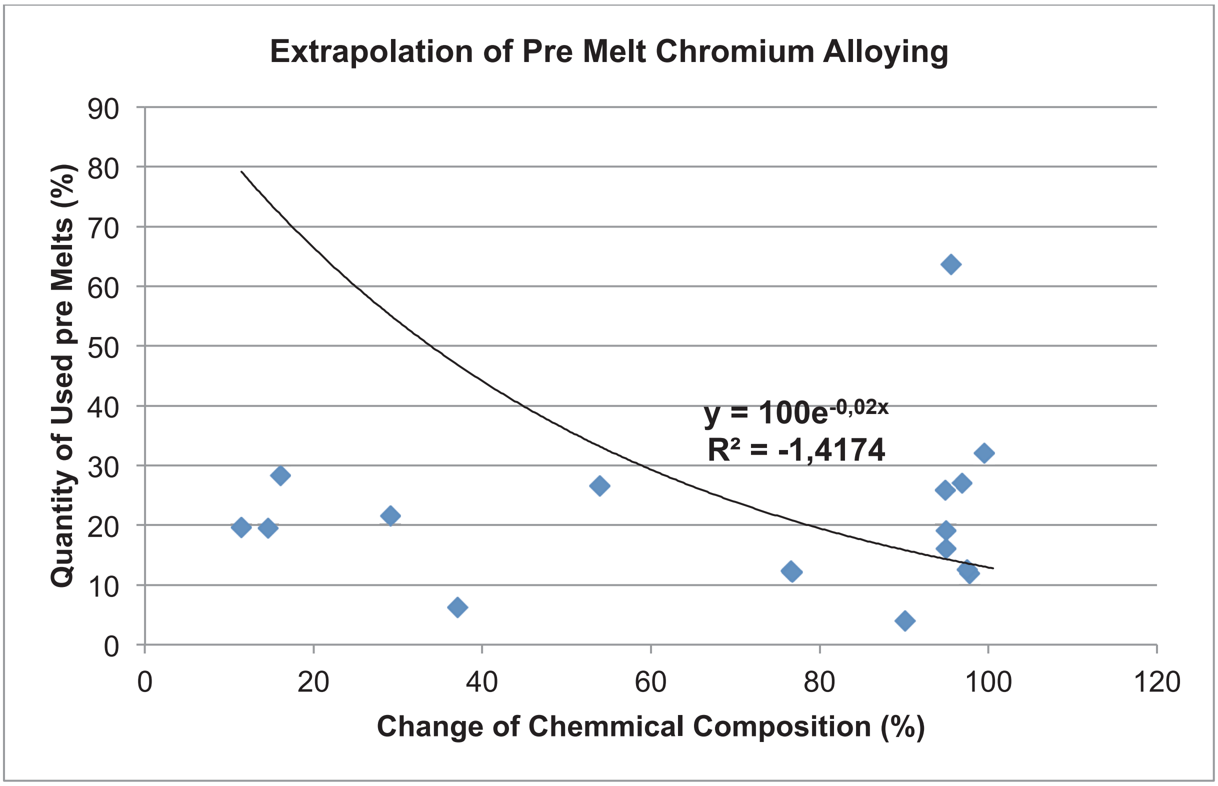

Figure 11-33: Extrapolation of Pre Melt Chromium Alloying

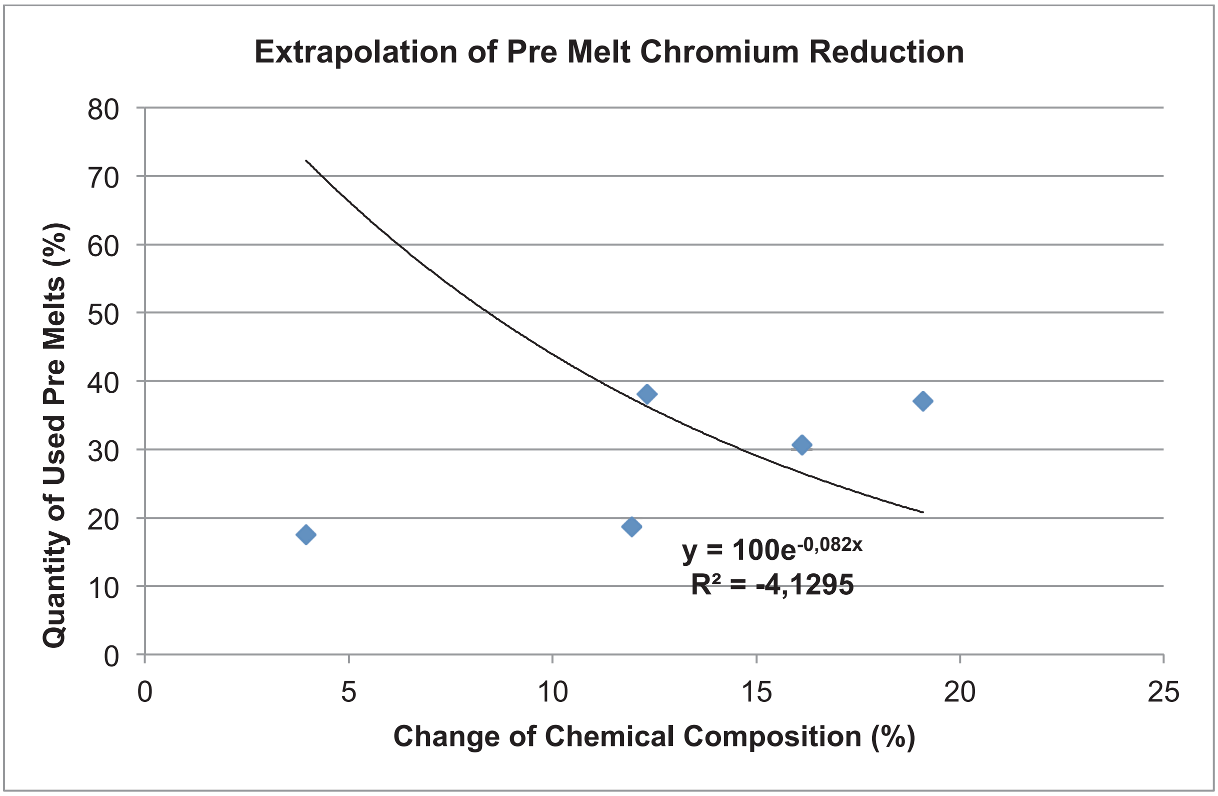

Figure 11-34: Extrapolation of Pre Melt Chromium Reduction

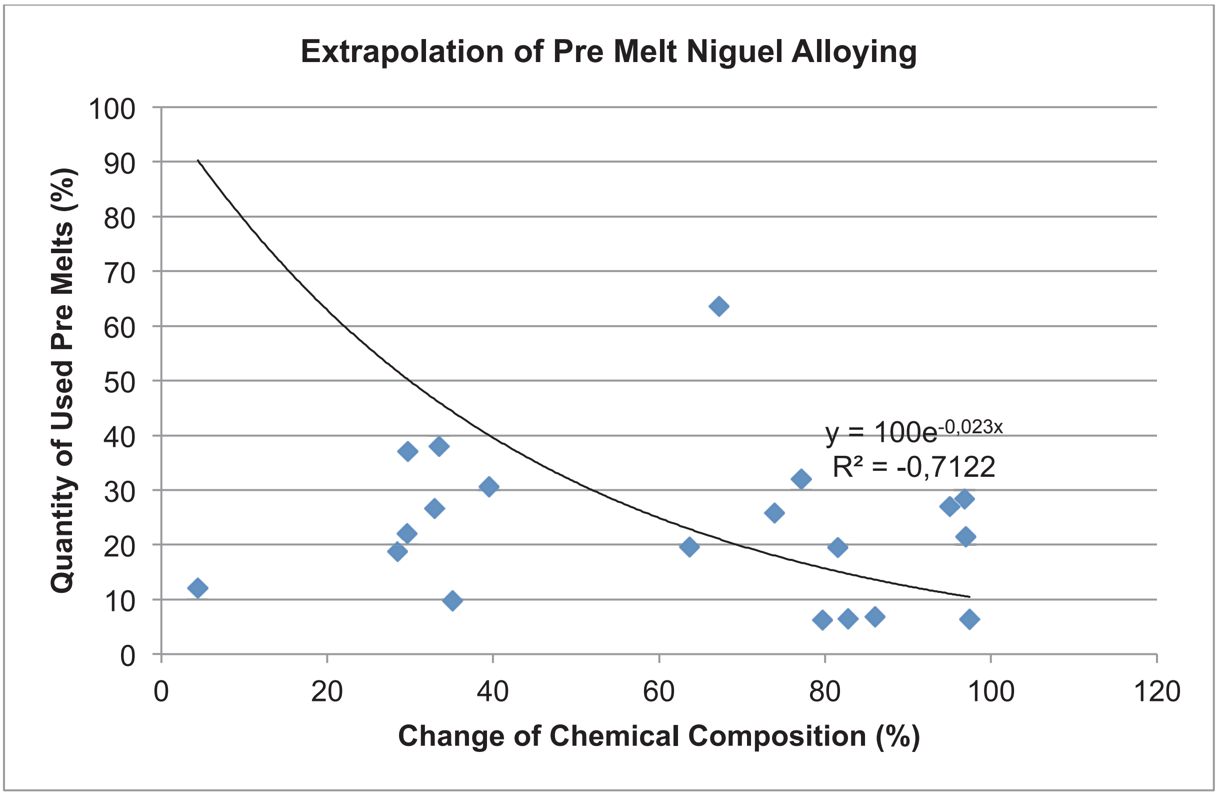

Figure 11-35: Extrapolation of Pre Melt Niguel Alloying

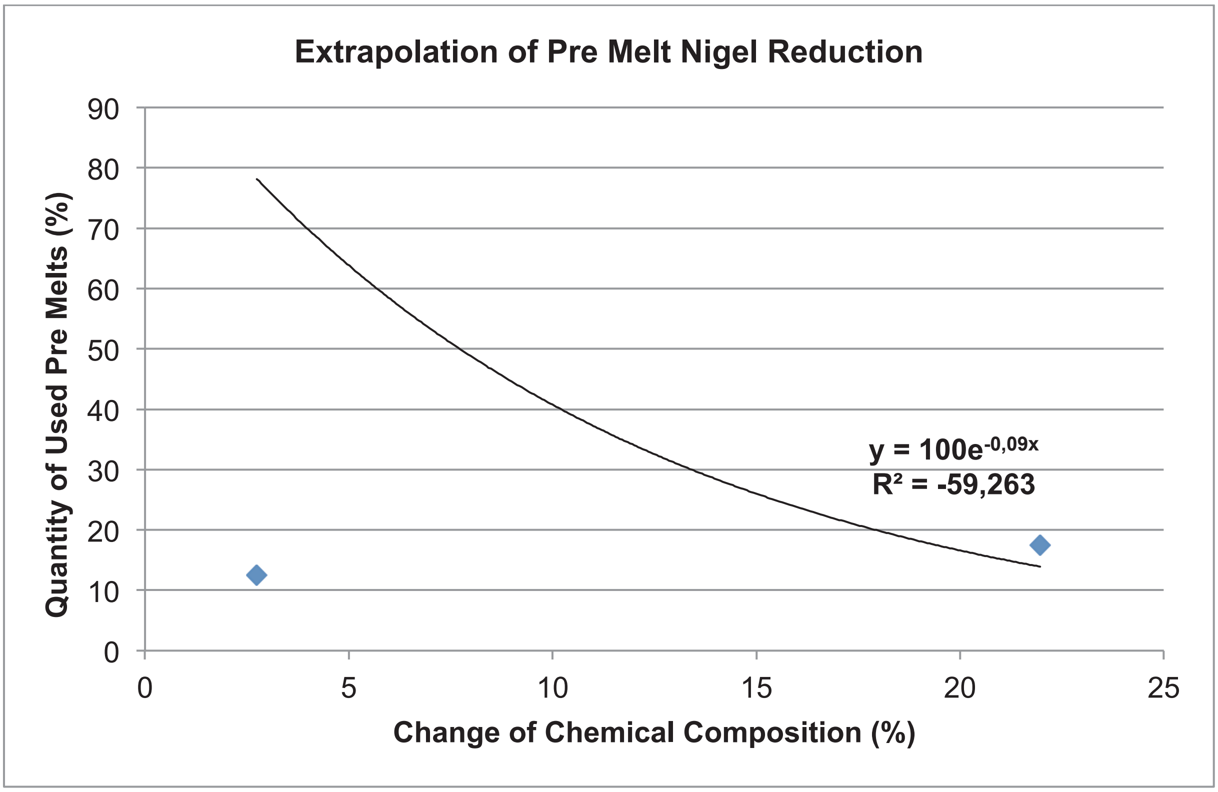

Figure 11-36: Extrapolation of Pre Melt Niguel Reduction

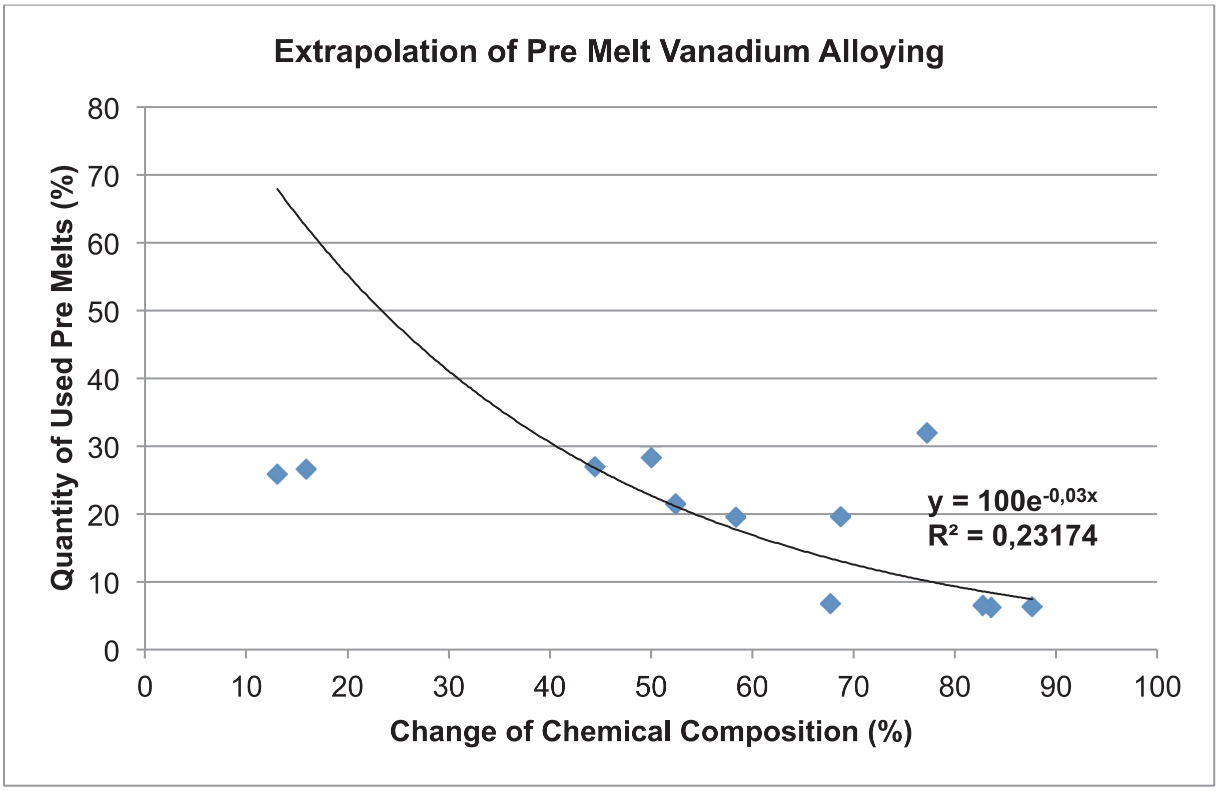

Figure 11-37: Extrapolation of Pre Melt Vanadium Alloying

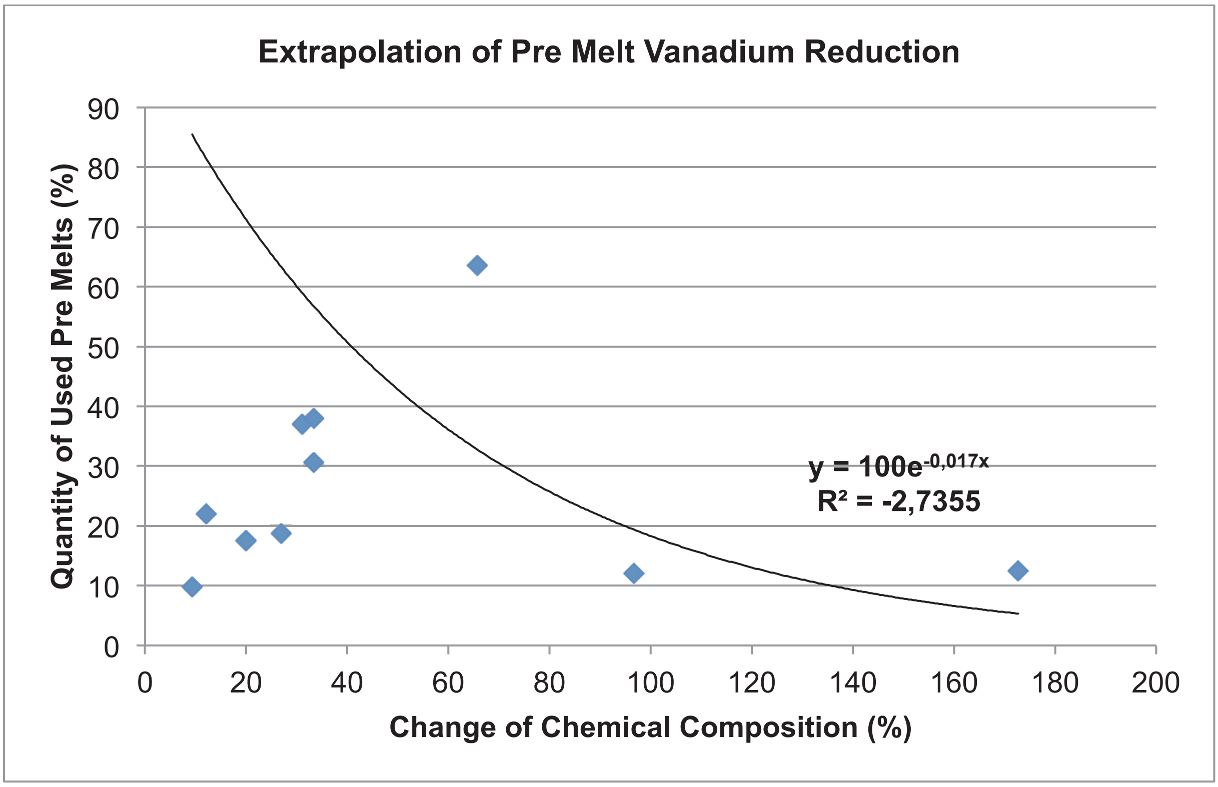

Figure 11-38: Extrapolation of Pre Melt Vanadium Reduction