

**Lubricating substance optimisation in high pressure die casting – a
comparison of inner and surface mould cooling for P661(BMW) and P672
(MB) steering case production**

Philip Alpha Conteh

**For a masters degree in Process Technology and Industrial
Environmental Protection**

Mining University of Leoben; February, 2002

Lubricating substance optimisation in high pressure die casting – a
comparison of inner and surface mould cooling for P661(BMW) and P672
(MB) steering case production

by

Philip Alpha Conteh

Supervised by

O. Univ. Prof. Dr. Werner Kepplinger

(Head of the Process Engineering and Industrial Environmental Protection Institute)

and

Ao. Univ. Prof. Dr. Josef Draxler

(Asst. Head of the Process Engineering and Industrial Environmental Protection Institute)

Process Engineering and Industrial Environmental Protection Institute

Mining University of Leoben; February, 2002

Acknowledgement

My thanks goes to O. Univ. Prof. Dr. Werner Kepplinger, Head of the Process Engineering Department, and Ao. Univ. Prof. Dr. Josef Draxler, Asst. Head of the Process Engineering Department, for supervising this thesis.

To Josef Bärnthaler, a former Leobener, who showed me the way to the Mining University of Leoben (MUL), during his time as a civil worker in "Haus der Stille" (House of Silence)

To the MUL authorities, especially O. Univ. Prof. Sturm, a former foreign students referee and O. Univ. Prof. Peter Paschen, a former rector at the MUL, who despite all the hustle and bustle of life during my stay in Austria made it possible that I continue studying in MUL.

Father Karl Maderner ofm, former director of House of Silence, who with the guidance and protection of God morally and financially assisted me through these years.

Mr. A. Hinterdorfer, Mr. J. Track, Mr. Bieder, Mr. W. Zederbauer and Mr. Hagl, Mr. Schmidt my contact partners at the Georg Fisher Ltd. who gave me the technical assistance I needed for this job.

Of course, to my countless number of friends, relatives and acquaintances, both far and near, old and new, who in one way or the other gave a helping hand or spirit, I say: "Thank You!"

Dedication

To Mum who is watching with delight the fulfilment of her dreams; to Dad who would have loved to share the pleasure of his thoughts-if it were not for his unfriendly working environment and to Catherine who has always been saying: "Daddy, I'm missing you!"

Certification

I declare in lieu of oath that I did this thesis by myself using only literature mentioned at the end of this volume.

Abstract

The aim of this thesis was to optimise the amount of lubricating substance used in the production of Mercedes Benz (P661) and Barisches Motoren Werk (P672) steering cases.

To ensure this, the two forms of mould cooling,

(i) inner mould cooling (using Farolin U as cooling agent) and

(ii) surface mould cooling (using Graco CP506 as lubricating substance) were investigated.

For the production of these steering cases, the Bühler SC 120 and the Idra 120 high pressure (i.e. 1200 bars) “die” casting machines were used.

After discussion with the contractors, the pre-study of the production process and the literature research, experiments were carried out on the machines under investigation.

As a result, room for quality improvement (technical changes, personal development) and lubricating substance optimisation possibilities were obvious.

To reach these conclusions, special capitals were considered and thoroughly evaluated.

- The need for optimising industrial processes, the scope and target of the work (Chapter 1)
- Related literature review (Chapter 2)
- Description of the plant and experiments conducted (Chapter 3)
- Analyses of the experimental results (Chapter 4) and
- Conclusions and suggestions (Capital 5) based on the above chapters.

Zusammenfassung

Schlussfolgerungen:

Die Untersuchung und Analyse der Ergebnisse für diese Arbeit ergibt folgende Schlussfolgerungen:

1. Der Schmiermittelmengenverbrauch pro Guss (l/Gusszeit) war 1.80, 1.51 and 1.60 für die SC I, SC II und die Idra Maschine. Dies korrespondiert zu einer Schmierzeit von 6.5, 6.9 and 6.6 Sekunden.
2. Die durchschnittliche Schmiermitteltemperatur war 15.4°C.
3. 3640.27 kJ war die durchschnittliche eingebrachte Wärmemenge von der Schmelze in die „die“ Maschine pro Guss
4. 3684.94, 3592.66 und 3701.17 kJ war jeweils die durchschnittliche Wärmeabfuhr durch die Oberflächenkühlung an der SC I, SC II und der Idra Maschine.
5. 120.90, 32.51, und 117.32 kJ. war jeweils die durchschnittliche Wärmezufuhr an der SC I, SC II und der Idra, von der „inneren Kühlung“ .
6. 28.53, 30.76 und 22.13 kJ war jeweils die durchschnittliche Wärmemenge, die durch Konvektion von der SC I, SC II und der Idra Maschine abgeführt wurde.
7. 47.70, 49.36 und 34.30 kJ war jeweils die durchschnittliche Wärmemenge, die durch Strahlung von der SC I, SC II und der Idra Maschine abgeführt wurde
8. Von der SC I, SC II und der Idra, waren 16.7 %, 7.7 % und 2.5 % Ausschuss.

Die folgenden Punkte waren für die Produktion von fehlerfreien Druckgussteilen von Bedeutung:

1. Die Verwendung von möglichst niedrigen Einschusstemperaturen, so dass aber noch eine komplette und sichere Befüllung des „die“ Hohlraumes gewährleistet ist.
2. Die Aufrechterhaltung einer passenden „die“ Durchschnittstemperatur frei von steilen Temperaturgradienten
3. Die Sicherstellung, dass die eingeführte Schmelze nicht an der Oberfläche anhaftet.
4. Verwendung eines Einschussdruckes, der gross genug für einen hohen Druckimpuls welche durch das Erstarrungsprodukt am Ende der Injektionsphase übertragen werden soll.
5. Die Gewährleistung der inneren Kühlung und der Oberflächenkühlung

Wenn diese Bedingungen eingehalten werden, verhindert man die Entstehung von Faltenbildung, Porosität und ungewollte Oberflächenerscheinungen.(Lückenbildungen)

Allgemein können Fehler auch zurückgeführt werden auf:

1. Ungeeignete und nicht zufriedenstellende Einsatzmaterialien für den Guss.
2. Unzufriedenstellende Durchführung beim Guss von dem Arbeiter bzw. falsche Aufträge von dem Vorarbeiter an den Arbeiter.
3. Die Verwendung von ungeeigneten Werkzeugen, Einrichtungen, Hilfsmitteln oder Muster.
4. Unprofessionelle Unternehmensführung bezogen auf Motivation, der Produktionsdurchführung, schlechte Organisation, schwache Arbeitsdisziplin bzw. mangelnde Weiterbildung.

Empfehlungen:

Auf Basis der Literatur, der Erfahrungen und den Ergebnissen während den Voruntersuchungen und der Untersuchungsphase in dem Betrieb, wurde die Notwendigkeit für eine Qualitätsverbesserung offensichtlich. Qualitätsverbesserung laut Definition bedeutet, "überall in der Organisation ergriffene Maßnahmen zur Erhöhung der Effektivität und Effizienz von Personal, Tätigkeiten und Prozesse um zusätzlichen Nutzung sowohl für die Organisation als auch für ihre Kunden zu erzielen"

Deswegen folgende Empfehlungen:

1. Informationsmanagement:

Optimierung ist nicht nur abhängig von den im Betrieb aufgenommenen Erfahrungen und Ergebnissen, sondern auch von der Verfügbarkeit und der richtigen und akkuraten Aufzeichnung und Aufbewahrung der selbigen (Informationen), und es kann in weiterer Folge zu einem besseren (und einwandfreieren) Managementsystem kommen, wie unten angeführt:

- Die richtige und genaue Ausfüllung von allen Informationsblättern
- Adäquate Aufbewahrung von Informationen für zukünftige Anwendungen und Referenzen
- Eine einfache Auffindbarkeit von gesammelten und aufbewahrten Informationen
- Die Einführung von Informationsblättern, wo es notwendig ist, z. B für das Heiz-Kühl Gerät.
- Neuentwurf von einigen Informationsblättern, z. B. Gießparameterüberwachungsformular soll Zeit, Formtemperaturen vor und nach der Kühlung, Toleranzen, Maßnahmen für Abweichungen etc., enthalten
- Die Schmiermittelanlage soll Informationen über die Mischungsverhältnisse, Temperatur vor und nach der Spülung, Typ, Menge etc. von Spülmittel enthalten. Auch Pumpen- und Pumpinformationen.

- Bessere und periodische Ausbildung und Weiterbildung für alle (insbesondere Arbeiter) in diesem Bereich.
- Informationsblätter (Mappe, hang-outs, Ordner, etc.) sollen regelmässig auf den neuesten Stand gebracht werden.

2. Regulieren und Einstellen von Ausrüstungen

In Industrieprozessen ist die Einstellung und Regulierung von Ausrüstungen oder Set-Points unvermeidlich. Trotzdem, können die Konsequenzen gravierend sein, wenn diese nicht richtig oder genau durchgeführt werden; oder Standardprozeduren nicht befolgt werden.

Deswegen folgende Empfehlungen:

- Standardisieren der Ausrüstungs-Set-Punkte (z. B. der Heiz-Kühlgeräte Set-Points)
- Änderungen an der Maschine sollen immer aufgeschrieben werden (Datum, Zeit, Änderungen, Unterschrift, etc)
- Personal soll informiert werden über jede neue Änderung an der Operation, dem Prozess, den Ausrüstungen, etc.
- Die Änderungen oder Regulierungen von vielen Parametern auf einmal sollen minimiert oder eliminiert werden.

3. Online Prozess Optimierung:

Diese soll Methoden für die Erreichung von Einstellungen, Einstellungswerten oder Referenzwerten enthalten, mit dem Ziel, eine konstante und kontinuierliche Verbesserung der Prozesse und Operationen zu gewährleisten.

4. Schmiermittelmenge / Schmierzeit:

Die Schmierzeit hat einen direkten Bezug zur Schmiermittelmenge pro Gusszeit bzw. an den Produktionskosten. Mit der Einhaltung des gegenwärtigen Schmiermittel- Mischungsverhältnisses (i.e. 1:180), und der Einhaltung der ermittelten Schmierzeit (6.6sec.) basierend auf den Untersuchungsergebnissen, die als optimale Schmierzeit angenommen werden kann, wird eine optimale Produktion, Auslegung, Produktqualität und eine vernünftige Kostenverminderung für die Produktion von BMW und MB Lenkgehäuse gewährleistet.

5. Kühlmittel:

Da die Heiz-Kühlgeräte in erster Linie eine Aufheizung anstatt einer Abkühlung der Formen durchführen, ist folgendes zu berücksichtigen:

- Das Einstellen der Heiz-Kühlgeräte-set-points um Kühlung anstatt Aufheizung zu gewährleisten
- Erhöhung der Ölströmung des Heiz-Kühlgerätes.
- Erhöhung der Kühlwasserströmung für eine bessere Kühlung des Öles in dem Heiz-Kühlgerät.
- Anstatt der Regelung der Schmierzeit ist eine Änderung der Set-points des Heiz-Kühlgerätes durchzuführen, um Produktionsanforderungen (z. B. Produkt Qualität und Menge) nachzukommen,

Wenn die oben angeführten Punkte beachtet werden, besteht die Möglichkeit einer signifikanten und entsprechenden Reduktion von Schmiermittel. Jede weitere Reduktion benötigt trotzdem weitere experimentelle Erhebungen.

Table of contents

Acknowledgement

Dedication

Certification

Abstract

Zusammenfassung

1. INTRODUCTION

1.1. Why industrial process optimisation	1
1.2. Scope and target of study	3

2. LITERATURE REVIEW

2.1. Casting processes	
2.1.1. General	5
2.1.2. High pressure die casing process	17
2.1.3. High pressure die casing alloys	19
2.2. Lubricating substance	
2.2.1. General	23
2.2.2. Lubricating process	25
2.3. Cooling substance	
2.3.1. General	27
2.3.2. Cooling process	31
2.4. Convection.....	36
2.5. Radiation	37
2.6. Required cooling efficiency	38

3. EXPERIMENTS

3.1. Plant description	40
3.2. Experiments theoretical background	
3.2.1. Lubricating substance (surface mould cooling)	42
3.2.2. Cooling substance (inner mould cooling).....	46
3.2.3. Quality control	47

4. EXPERIMENTAL RESULTS AND ANALYSES

4.1. Lubricating substance (surface mould cooling).....	51
4.2. Cooling substance (inner mould cooling).....	58
4.3. Convection.....	64
4.4. Radiation	65
4.5. Required cooling efficiency	65
4.6. Quality control.....	68

5. SUMMARY

5.1. Conclusions	71
5.2. Suggestions.....	72

6. LITERATURE CITED.....

List of symbols.....	79
List of tables	83
List of diagrams	87

1. INTRODUCTION

1.1. Why industrial process optimisation

The importance of optimising industrial processes arise from the need to reduce manufacturing costs, meet environmental regulations, and enhance performance, while at the same time meet product quality requirements.

The requirements for methods of optimisation then arise from the theoretical, mathematical and engineering complexity necessary to describe and upgrade systems, processes, equipment, and devices that occur in practice.

Like complex systems, quiet simple systems contain parameters, which change with time, can be altered, adjusted or vary in a random manner; they can sometimes be represented by theory, which contain certain approximations.

For many reasons, however, the theory is imperfect, yet it must be used to predict the optimum operating conditions of a system such that the performance criterion is certified. At best, such theory can only predict that the system is near to the desired optimum. Optimisation methods are then used to explore the local region of operation and predict the way the system parameters should be adjusted to bring the system to optimum or near to optimum.

In an industrial process, for example, the criterion for optimum operation is often in the form of minimum cost, where the product cost depends on a large number of interrelated controlled parameters in the manufacturing process. The optimisation of such an industrial process has the requirement that a single quantity (e.g. method of mould lubrication or mould cooling, type and amount of lubricating material used, metal temperature, etc) is to be minimised by variation of a number of controlled parameters (e.g. lubricating time and pressure). In addition, there may also be parameters which are not controlled but which can be measured, and possibly some that cannot even be measured.

The importance of optimisation lies not in trying to find out all about a system but in finding out,

with the least possible effort, cost, and means, the best way to adjust the system while at the same time meeting quality requirements.

If this is carried out well, systems can have a more economic and improved design, they can operate more accurately or at less cost and the unnecessary use of high amounts of raw materials (e.g. lubricating substance) which increases cost of production can be reduced.

In addition, the system designer or operator will have a better understanding of the effect of parameters interaction and variation on his design or operation. [1]

The basic engineering optimisation problem is to minimize a scalar quantity E which is the value of a function of n system parameters or variables x_1, x_2, \dots, x_n . These variables must be adjusted to obtain the minimum required, i.e. to;

$$\text{minimize } E = f(x_1, x_2, \dots, x_n).$$

In aluminium high pressure die casting, the use of lubricating material, which at the same time serves as a cooling agent is required for the following reasons:

1. As a separating substance, preventing the molten material or cast product from sticking onto the metal mould
2. Ensuring a smooth surface for the cast product and
3. Cooling the outside surface of the mould.

The amount of lubricating substance/cooling substance used for this purpose is enormous and contributes on its own right to the production cost of BMW – Bayrisches Motoren Werk (P661) and MB - Mercedes Benz (P672) steering boxes at the Georg Fischer Automotive Ltd. in Herzogenburg.

Optimising the use of the lubricating material in this process while at the same time meeting quality requirements can lead to a significant reduction in manufacturing cost, saving of our limited raw material and protecting our beloved living environment.

Thus, the essence of industrial process optimisation in the high pressure die casting of these products need not be over emphasised; but rather be embraced as an integral and important aspect which should stand the test-of-time or be a-state-of-the-art procedure in industrial, environmental, engineering, and economic development.

1.2. Scope and target of study

In an attempt to reduce cost in the high pressure die casting process for the production of P661 (BMW) and P672 (MB) steering cases, the optimisation of the lubricating substance, Graco CP 506, produced in Gleisdorf by Graz, which at the same time serves as a cooling agent for the mould surface was investigated.

In addition, the heat absorbing oil, Aral Farolin U produced by the Aral Lubricating Substance Industry in Vienna, used for inner mould cooling was also investigated.

For the optimal use of these two substances in the production process, a comparison of the two forms of mould cooling-inner mould cooling and surface (spray) mould cooling being applied were also investigated and compared for both products to determine their heat extraction efficiencies.

Both forms of mould cooling (inner and surface) were applied in the MB (P672) and BMW (P661) steering case production at a pressure of 1200 bars and a molten metal temperature of 660 °C using the Idra 1200 and the SC 1200 pressure die casting machine respectively.

For inner mould cooling, the heat absorbing oil is automatically circulated in the mould via in-built canals at different points of both the stationary and the moving half of the dies (see subsection 2.3.2; p. 31).

For surface mould cooling on the other hand, the Graco CP 506 – water medium (CPW) which serves primarily as a lubricating agent and secondarily as a cooling substance, is automatically sprayed on the mould cavity via suspended nozzles (see dig. 2.2.2.1; p. 26) after removing the cast product.

The recommended mixing ratio of this lubricating-cooling-agent by the manufacturer is 1:150 i.e. 1 part Graco CP 506 to 150 parts water. Because of production reasons, however, this investigation was carried out with a presently used mixing ratio of 1:180, and by altering the lubricating time the following parameters were subsequently monitored:

- Amount of lubricating substance (Graco CP) used per cast cycle
- Pressure difference in the lubricating pipes during operation and in still stand
- Temperature gradient of the mould during operation
- Temperature gradient of the heat absorbing oil (Farolin U) and
- The quality of the products .

The used plant ratio of 1:180 was maintained because it was used not only in the investigated machines (Bühler SC 10/120 - I, Bühler SC 10/120 - II and Idra 1200) but also in all other pressure casting machines in the aluminium foundry. Its alteration could have rendered the machines not under investigation vulnerable to production problems.

2. LITERATURE REVIEW

2.1. Casting processes

2.1.1. General

Casting is a fabrication process whereby a molten metal is poured into a mould cavity having the desired shape; upon solidification, the metal assumes the shape of the mould but experiences some shrinkage during this process.

Generally, casting techniques are employed when:

- The finished shape is too large, long, or complicated that any other method would be impractical
- A particular alloy is so low in ductility that forming by either hot or cold working would be difficult
- In comparison to other fabrication processes (rolling, stamping, drawing, forming, extruding or a combination of these metal forming processes), casting is the most economical. [2]

Different casting techniques are commonly employed in industrial processes for different production purposes; they include: sand casting, continuous casting, strip casting, die casting, etc.

Engineering products include, aluminium alloy castings, extrusions, forging and impacts.

Aluminium casting methods include, pressure-die, permanent-mould, green and dry-sand, investment and plaster casting; whereby the castings are produced by filling moulds with molten aluminium for products with intricate contours and hallow or cored areas. Whatever casting

technique is employed, a solid metallic polycrystalline product always results through the solidification of the molten metal.

The important parameters for the solidification process are:

- The temperature at the beginning of the crystallisation
- The nuclei formation rate and
- The nuclei growth rate in the undercooled melt.

Influencing parameters for the crystallisation are nuclei building and nuclei growth; and the centre from which the crystallisation of the molten material begins is referred to as the nucleus with two types of distinguishable nuclei, specific and foreign nucleus.

Based on their origin, one can distinguish between homogenous nucleus (specific nucleus) and heterogeneous nucleus (foreign nucleus).

The transition from liquid to solid generally results in heat release (heat of liquefaction); simply because the inner energy of the melt is greater than that of the solid . At the melting temperature, the temperature where no nucleus growth occurs, the free enthalpy (ΔG) of the liquid (G_L) and the solid phase (G_S) are equal, i.e. :

$$\Delta G = G_L - G_S = 0$$

Equation 2.1

The prerequisite for nucleus growth is undercooling; and the higher the rate of undercooling the higher the tendency of the liquid phase transition to the solid phase (see dig. 2.1.1.1.a and 2.1.1.1.b).

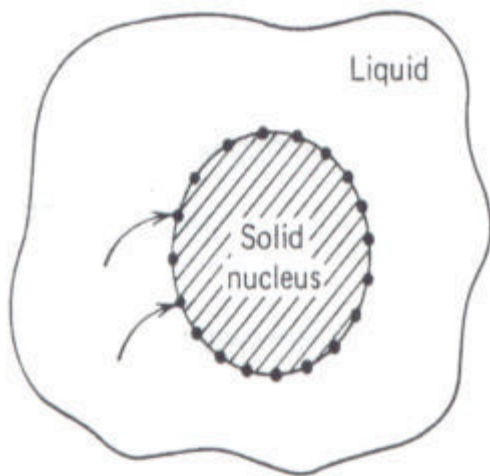


Fig. 2.1.1.1.a: Schematic view of atoms joining a solid nucleus from the liquid [3]

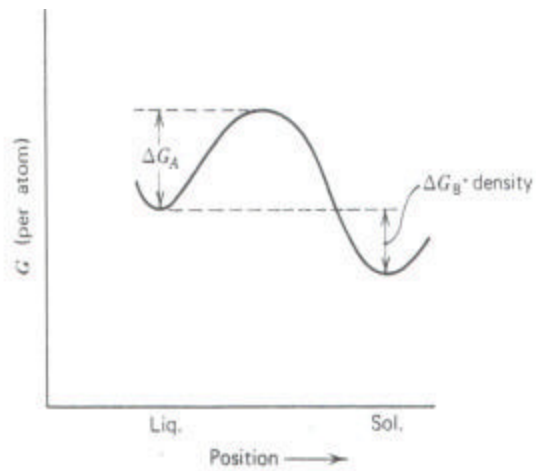


Fig. 2.1.1.1.b: Variation of free energy per atom as it moves from liquid onto solid nucleus [3]

For a homogeneous nucleation concept (see dig. 2.1.1.2.a, 2.1.1.2.b and 2.1.1.2.c) the amount of energy by the nucleation in relation to the volume, ΔG_v , (volume term) is smaller, and this reduction, for a sphere-like nucleus from the melt is:

$$\Delta G_v = -L_m \cdot \frac{\Delta T}{T_s} \cdot \frac{4\pi r^3}{3}$$

Equation 2.2

Where:

ΔG_v Volume term transformation energy [kJ/kg. K]

$-L_m$ Latent heat / Melting heat [kJ/kg. K]

ΔT Temperature difference [K]

T_s Solidification temperature [K]

r Radius [mm]

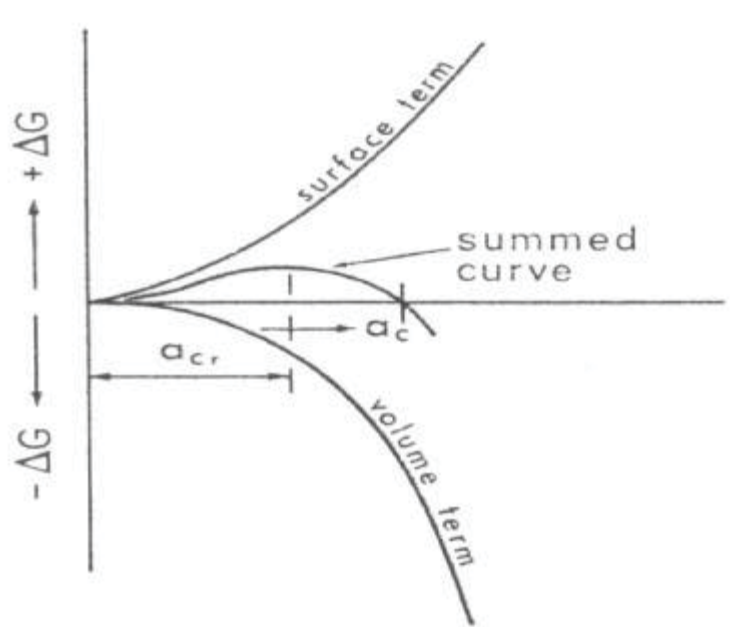


Diagram 2.1.1.2.a: Critical size, a_{cr} of the nucleus for thermodynamic stability [4].

A formed nucleus builds a surface boundary between the liquid and the solid phase, which leads to a change in the surface area energy, ΔG_s . (surface term):

$$\Delta G_s = 4\pi \cdot r^2 \cdot \sigma$$

Equation 2.3

The total temperature gradient ΔG (which can be positive or negative) at the solidification front with the specific boundary area energy, σ [J/m^2] is:

$$\Delta G = \Delta G_v + \Delta G_s = -L_m \cdot \frac{\Delta T}{T_s} \cdot \frac{4\pi \cdot r^3}{3} + (4\pi \cdot r^2 \cdot \sigma)$$

Equation 2.4

The critical radius a_{cr,r^*} for the nuclei by non-spontaneous nucleus building can be obtained through derivation of equation 2.4:

$$a_{Cr} = \frac{2\sigma T_s}{L_m \Delta T} \quad \text{Equation 2.5}$$

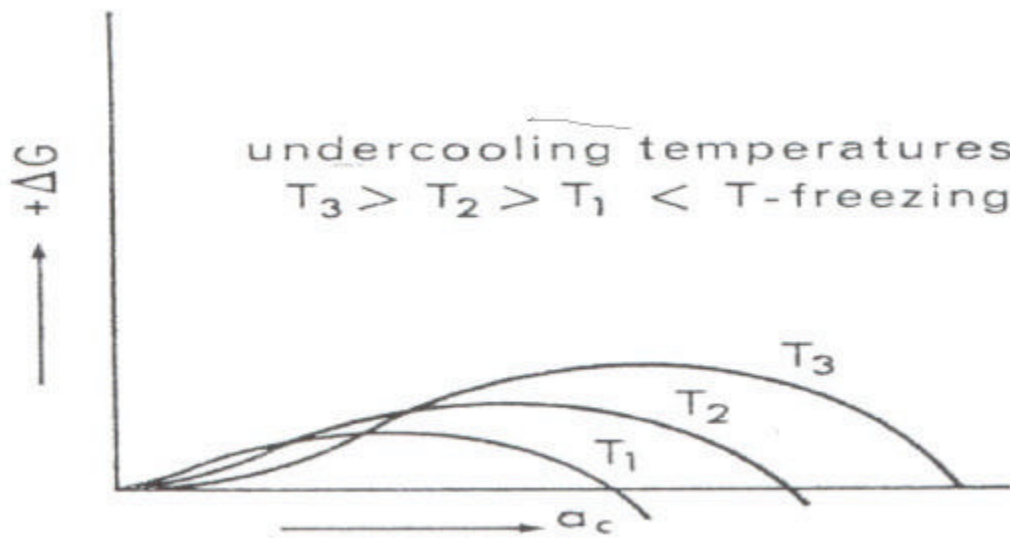


Diagram 2.1.1.2.b: The effect of undercooling temperature on the critical size, a_c [4]

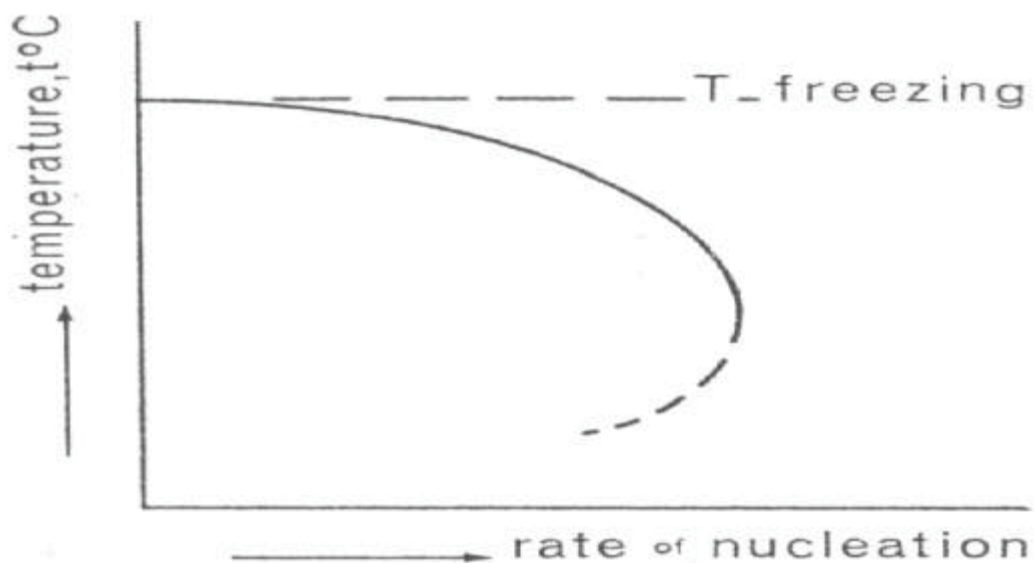


Diagram 2.1.1.2.c: The effect of undercooling temperature on the nucleation rate.[4]

From this equation, it is clear that the nucleus size reduces with increase in undercooling (see dig.2.1.1.2.b). Furthermore, from equation 2.4 and 2.5, the needed activation energy for the nucleus formation (see dig. 2.1.1.3) can be calculated as:

$$\Delta G^*_{hom} = \frac{16\pi\sigma^3 T_s^2}{3L_m^2 (\Delta T)^2}$$

Equation 2.6

The activation energy for the nucleus formation reduces with increase in undercooling and with smaller resulting specific boundary area energy. This kind of nucleus building is referred to as non-spontaneous nucleus building. A reduction in activation energy from the dihedral angle γ , is dependent on the melt and the underlying substance (dig.2.1.1.4).

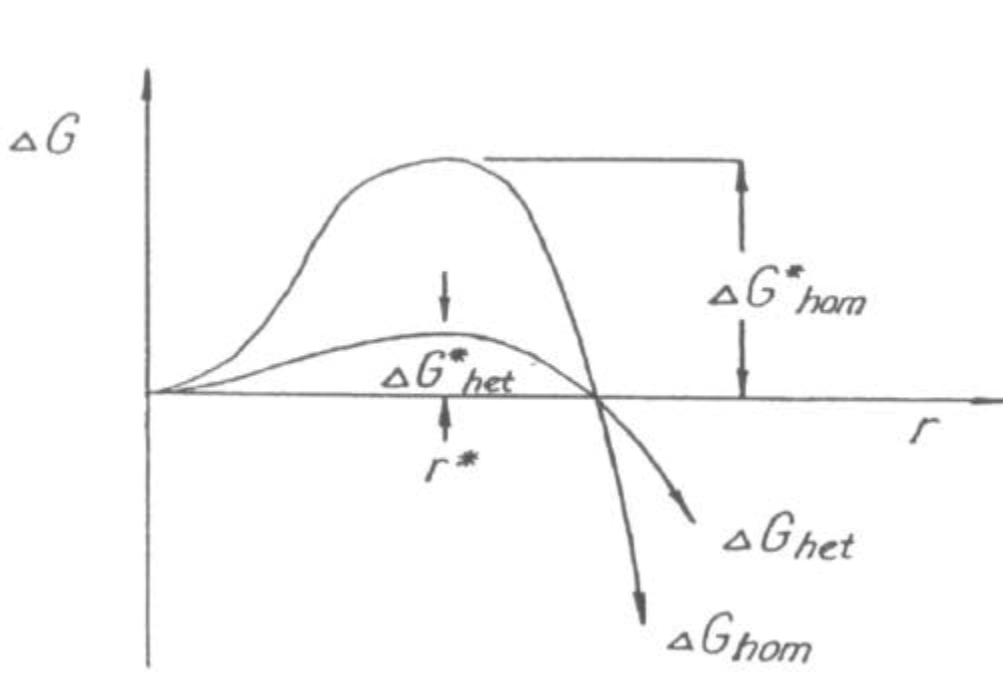


Diagram 2.1.1.3: Activation energy for: spontaneous and non-spontaneous nucleus building [5].

The activation energy for the heterogeneous nucleus building is:

$$\Delta G_{het}^* = \frac{16 \cdot \pi \cdot \sigma_{sl} \cdot T_s^2}{3 \cdot L^2 \cdot (\Delta T)^2} * f(\gamma) = \Delta G_{hom}^* * f(\gamma) \quad \text{Equation 2.7}$$

Whereby,

$$f(\gamma) = \frac{(2 + \cos\gamma)(1 - \cos\gamma)^2}{4} \quad \text{Equation 2.8}$$

With:

$f(\gamma)$ Function being dependent of the dihedral angle

γ Dihedral angle between the underground layer and the solid melt.

The smaller the dihedral angle γ , the bigger the chemical relationship between the melt and the substrate.

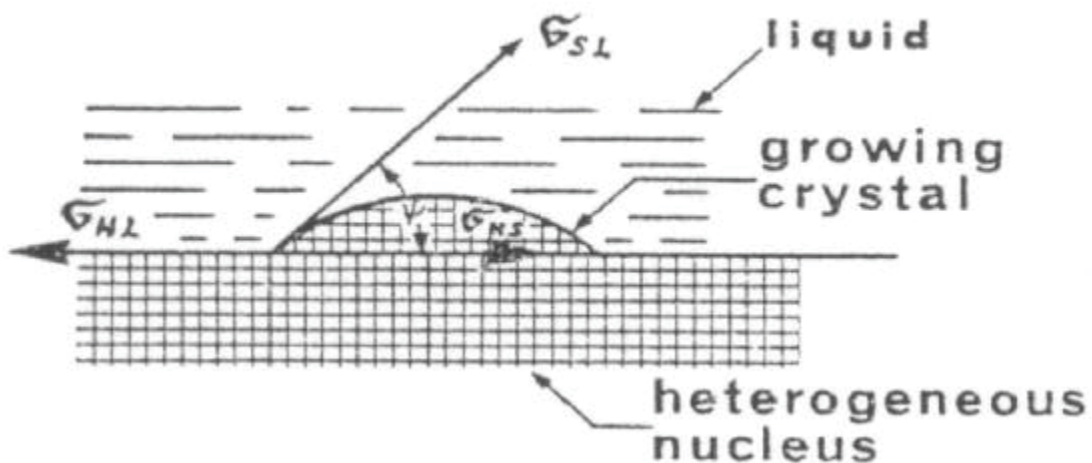


Diagram 2.1.1.4: Surface energy relations affecting the wetting of heterogeneous nuclei by the liquid metal [4].

The heterogeneous nucleus building begins at a lower undercooling compared to the homogenous nucleus building, which can only take place when the melt is free of inclusions, oxides, nitrides, etc.

The nucleus building can be as a result of the following factors:

- Mechanical or electromagnetic mixing
- Shock-like collision
- Pressure increase
- Vibration
- Blow-up of inert gases

The crystallisation velocity (CV) and the number of nuclei (NN) increase with increase in undercooling. In the case of a greater number of nuclei and a lower crystallisation velocity, a fine grain microstructure results (see diagram 2.1.1.5.a). A reverse case results in large grain structure (see diagram 2.1.1.5.b).

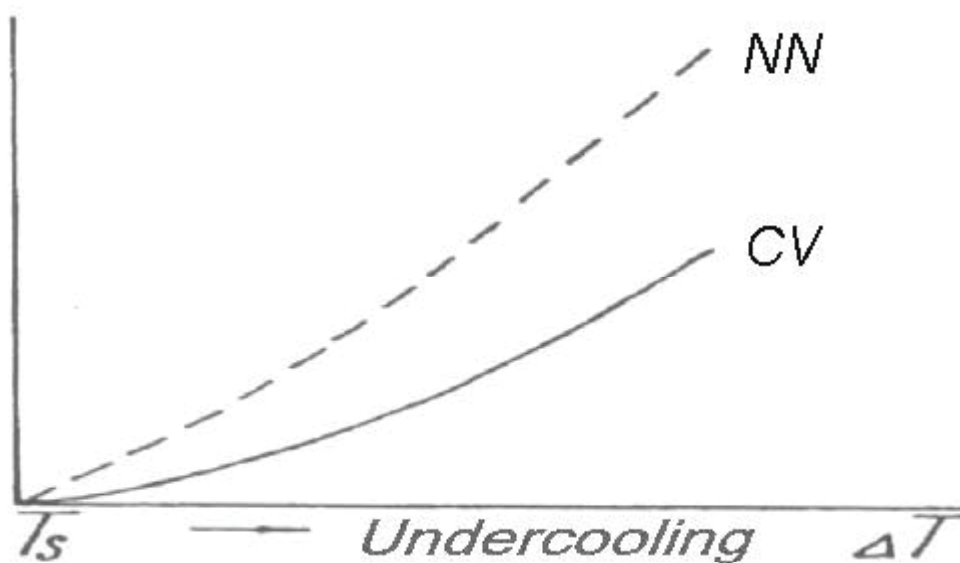


Fig. 2.1.1.5.a: Amount of nucleus and crystallisation influence on the nucleus for a. fine grain size [6]

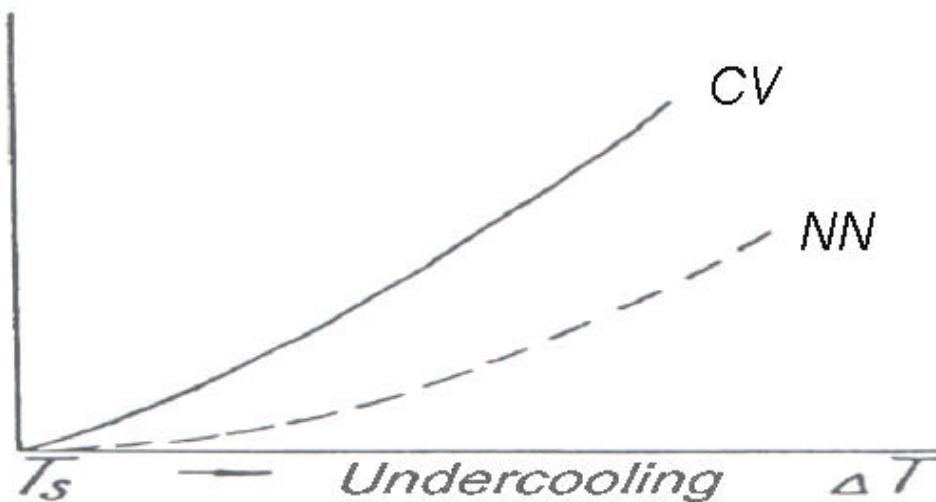


Fig. 2.1.1.5.b: Amount of nucleus and crystallisation influence on the nucleus for a large grain size [6]

The nucleus building velocity depends on the following parameters:

- The amount of undercooling
- Surface tension of the melt
- Movement of the atoms during transition from the liquid to the solid state.

The nucleus building velocity can be increased by the introduction of active surface substances (e.g. titandiboride). These active surface substances reduce the required nucleus building energy, since crystallisation centres already exist by lower undercooling.

The growth of crystals is controlled by the following mechanisms:

- Surface kinetics
- The capillary and
- Heat and mass diffusion.

By the solidification of metals, the boundary area of the nucleus can either be rough or smooth.

The influence of the surface kinetics by metals will be increased because of the low entropy of the melt and the growth is in the direction normal to the plane with higher boundary energy. The already built nucleus grows until it collides with another nucleus.

Alloys have a solidification interval; whereas pure metals solidify at a particular temperature. The ratio of the alloy elements concentrations in the solid state, C_S (at. %) and the concentrations in the corresponding molten rest C_L , (at. %) at the particular temperature is described by the distribution coefficients k_o .

$$k_o = \frac{C_S}{C_L}$$

Equation 2.9

When $k_o < 1$, the alloying elements reduce the melting temperature and when $k_o > 1$, the opposite occurs.

These concentration changes are dependent on the velocity of the mass diffusion on the solidification front, the alloying element concentration and the temperature profile. Mixing processes at the solidification front in non-equilibrium leads to increase in the solid phase.

For the type of heat extraction at the boundary area that determines the temperature gradient ($G = dT/dx$), one can differentiate between positive and negative temperature gradients.

By positive temperature gradients or an established solidification, the heat of liquefaction will be extracted through the crystal. The growth direction is opposite to the direction of heat extraction. By pure metals a smooth solidification front results, where as by alloys the morphology depends on the quotient of the temperature gradients and the growth velocity of the solidification front

By negative temperature gradients, the heat will be extracted through the melt. The crystal growth direction dictates the direction of heat removal. By pure metals, the morphology is dendrite.

Constitutional undercooling is achieved when the actual temperature gradient is lower than that in the equilibrium state ($G_t < G_g$). The width of this area depends on the quotients of the diffusion coefficients and the growth velocity at the solidification front. The type and nature of the phase boundary depends on the size of the constitutional undercooling. A concentration slope builds in front of the phase boundary that pushes all diffusion layers in the inside of the melt.

The situations that increase constitutional undercooling according to W. Kurz [7] are as follows:

- Lower temperature gradient in the melt
- Higher alloy content and
- Smaller diffusion coefficient

According to V. Kondic [4], the following variables effect crystal growth of alloys, based on Chalmers experiments:

- C_o , the original concentration of the solute in the melt,
- G , the temperature gradient at the interface, in °C per unit distance (l) from the interface,
- R , the rate of growth of the solid.

These situations result in dendrite building and growth. The dependence of the velocity of the solidification front of the alloy composition and the temperature gradient leads to different morphologies (see dig. 2.1.1.6.) A smooth solidification front or plate results below the critical growth velocity ($v < v_c$). Through an increase in the solidification velocity ($v > v_c$), the smooth solid front goes over to a cellular and dendrite solid front; and by increasing the solidification velocity further, the dendrite micro structure goes over to the cellular again. [7]

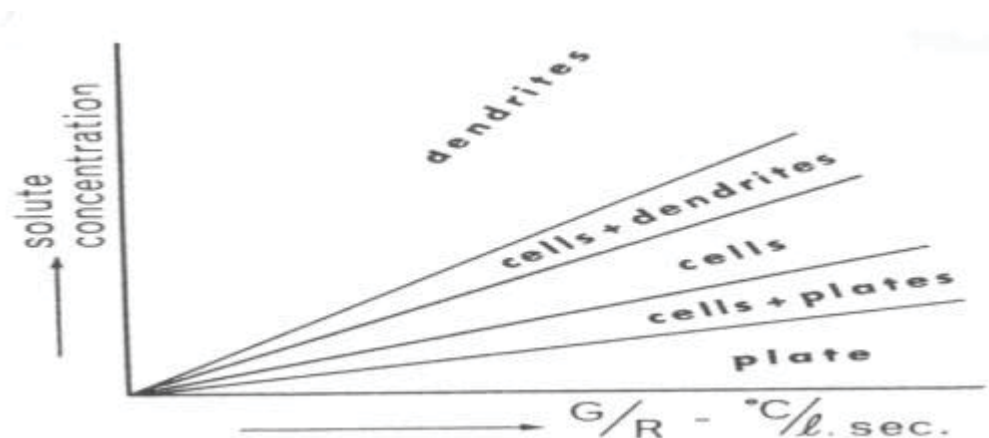


Diagram 2.1.1.6: Micromorphology of crystal growth related to solute concentration and cooling conditions (e. g. v_{ef}).[4]

The reduction of the positive temperature value under the critical value leads to the transition from the dendrite morphology to the cellular morphology. The smooth solidification front goes over to the rough solidification front, according to S. Spaic [5], when the following condition is not fulfilled:

$$\frac{G}{v_{ef}} = \frac{M \cdot c_o}{D} \cdot \frac{1 - k_o}{k_o} \quad \text{Equation 2.10}$$

With:

- G Temperature gradient
- M Liquidus line gradient [K/at. %]
- C_o Alloy elements concentration [at. %]
- k_o Distribution coefficient
- v_{ef} Solidification front growth rate [mm/s]
- D Diffusion coefficient [m^2/s]

Cell stability is dependent on the temperature gradient and the growth of the solidification front. It increases with increase in the quotients of the temperature gradient of the solidification front and the growth velocity.

The dendrite microstructure will be finer and the diffusion length before the solidification front shorter, with increased growth rate of the solidification front (v_{ef}). By high solidification rate, the dendrite will be large for the diffusion process and the morphology of the solidification front returns to the cell morphology.

Absolute stability (v_a) is the velocity at which the smooth solidification front is formed again.

This velocity is:

$$v_a = \frac{\Delta T_o \cdot D}{k_o \cdot v_{ef} \cdot \Gamma}$$

Equation 2.11

Whereby:

ΔT_o Solidification interval for equilibrium temperature

Γ Gibbs -Thomson coefficient.

In a case where an alloy shows a smaller solidification interval or the value of k_o moves towards 1, a relative lower velocity for attaining the absolute stability of the solidification front is needed.

2 .1. 2. High pressure die casting process

In pressure die casting, the liquid metal is forced into a metal mould called a „die“ under pressure and at a relatively high velocity, and allowed to solidify with the pressure maintained. A two-piece permanent steel mould or die is employed for this purpose and the shape of the resulting product /cast is exactly that of the inside mould structure.

The product is thereby, by speedy repetition of the process cycle, complex, relatively of thin wall with high measurement precision and smooth surface.

On a die-casting machine, the die half called the „cover die“ is stationary; the other die half which opens and closes, is known as the „ejector die“. Diagram 2.1.2.1 below show a die casting machine used in the production of MB-P672 steering cases, at the Georg Fischer +GF+.

Dies are usually so arranged that when both halves are placed together the cavity of the complete casting is obtained. The dies are equipped for feeding the molten metal, and they have vents for gases to escape and a mechanism for clamping and injection.

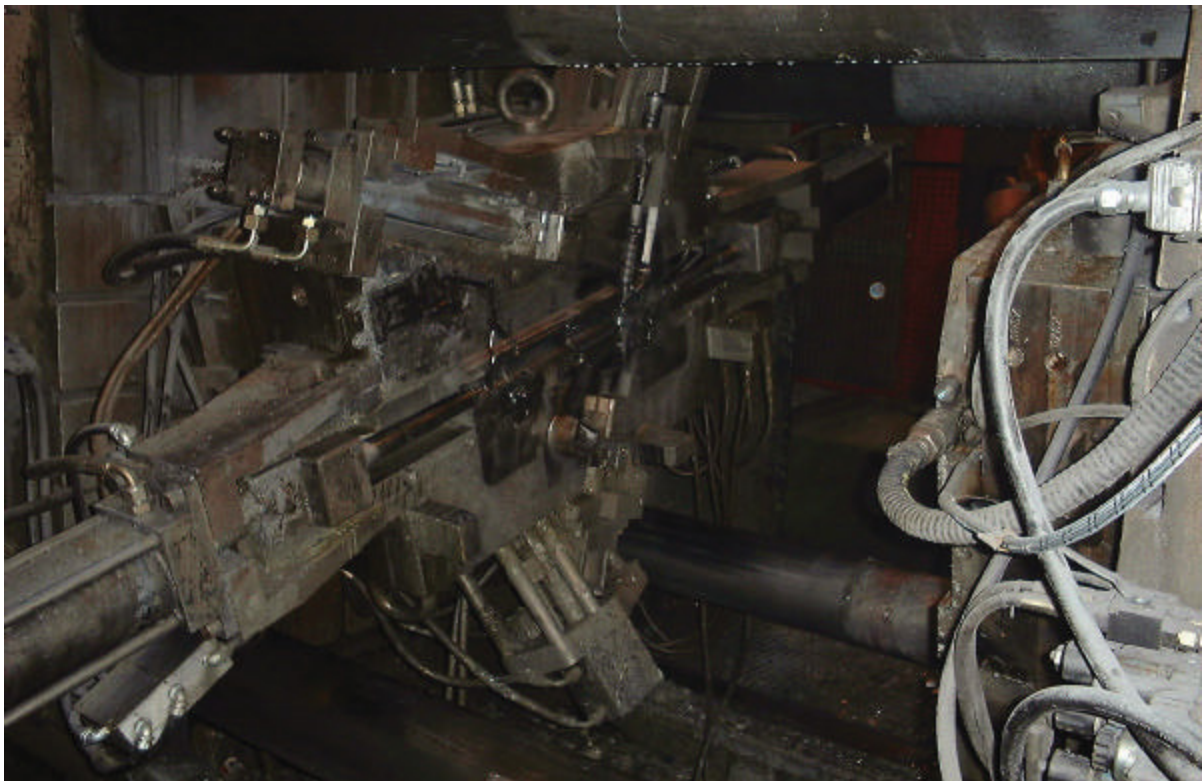


Diagram 2.1.2.1: A die casting machine showing the “cover die” (l) and the “ejector die” (r).

The amount of molten metal required for the casting will be dosed either through a bailing spoon or through an automated dosing procedure in the cold pressure chamber where it is pushed into the die with a piston at a high pre-set pressure.

Because of the nature of the die casting process, complex and sophisticated metal techniques are not usually required. Only occasionally, it is necessary to obtain complete freedom from dissolved gases in the metal or a high level of grain refinement. The rapid rate of solidification usually ensures that any gas porosity is fine and adequately dispersed and grain structures are small and equiaxed.

For pressure die casting, the die construction material is usually a special hot-work tool, an alloy steel containing chromium for greater strength and hardness, dimensionally stable, withstand heat checking, not get soldered to the cast alloy, be tough, resist corrosion and oxidation and have good response to nitriding. It is usually heat treated to achieve its optimum strength and toughness, and finally nitrided to give an extremely hard wearing surface Table 2.1.2.1 below shows the specifications of the dies used for the production of P661 and P672.

Table 2.1.2.1: W300 die specifications [8]

Specific heat [J/g K]			Density [g/cm ³]			Chemical composition							
20°C	500°C	600°C	20°C	500°C	600°C	C	Si	Mn	Cr	Mo	Ni	V	W
0.46	0.55	0.59	7.8	7.64	7.6	0.36	1.1	0.4	0.5	1.3		0.4	

The specifications of the die clearly show the alloy composition and the densities and specific heats at various temperatures.

The major functions of die casting machines (hot chamber machine, cold chamber machine and air-blown or goose neck machine) are as follows:

- Closing the two halves of the die by moving the movable half (ejector die) towards the fixed half (cover die);
- Securing the two die halves firmly together, so that they do not separate due to the pressure of the molten metal;
- Forcing the molten metal into the die; and
- Opening the die by moving the ejector die away from the fixed die.[9]

2.1.3. High pressure die casting alloys

Predominately alloying is carried-out to:

- Increase strength

- Change most physical properties (density, melting-temperature range, heat content, coefficient of thermal expansion, and electrical and thermal conductivity) by addition of one or more alloying elements
- Effect electrochemical properties and corrosion resistance.

Alloys of aluminium are used in die casting more extensively than for any other base metal. The properties of aluminium metal and its alloys make it the most economical and attractive for a wide variety of uses, namely:

- Appearance, light weight and fabricability
- Physical properties (a highly reflective surface, high electrical and thermal conductivity, non-ferromagnetic)
- Mechanical properties (aluminium has a density of 2.7 g/cm^3 , i.e. approx. 1/3 as much as steel (7.83 g/cm^3) and
- Corrosion resistance (Al resists the kind of progressive oxidation that causes steel to rust away).

Primarily aluminium is used for metallurgical purposes such as, aluminium-based alloy casting and wrought products, alloying additions to metals, coating on metals to prevent corrosion and oxidation and as reducing agent to produce metals from their oxides and fluorides.

Of the large number of alloys that have been developed for casting, Al-Cu, Al-Cu-Si, Al-Si, Al-Mg, Al-Zn-Mg, and Al-Sn are the six basic types.

The binary alloy system in diagram 2.1.3.1 below for Al-Si alloys reveals the properties and cast structure of this industrial alloy based on strengthening aluminium crystals with solute silicon atoms and by micro-dispersion of the second phase, essentially made of hard but brittle silicon crystals.

Additional alloying elements may be used to raise the level or alter properties; the ductile and brittle phases can be varied by composition, casting and heat treatment.[4]

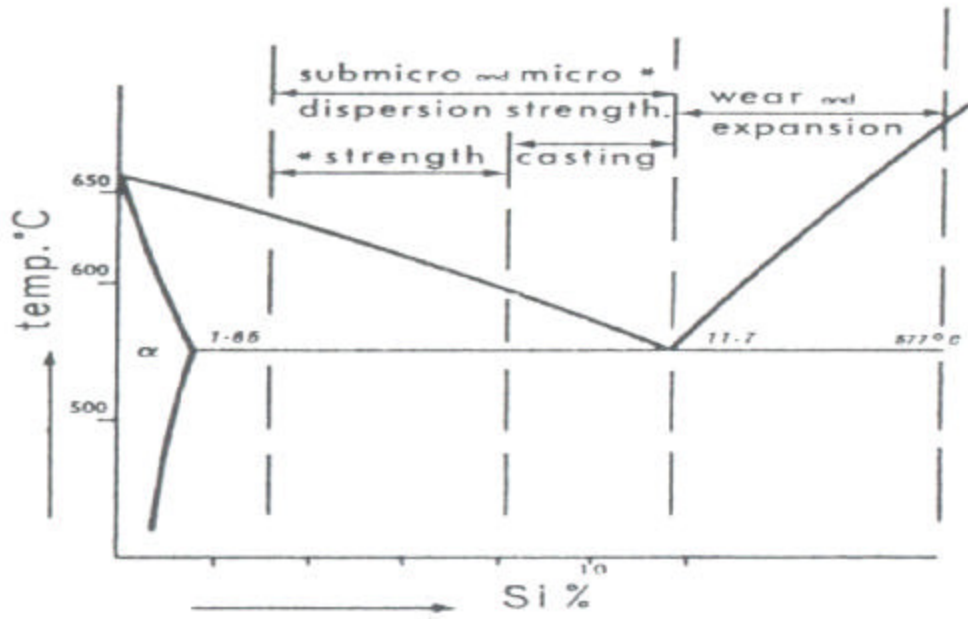


Diagram 2.1.3.1: Al-Si alloys - properties and cast structure [4]

For high pressure casting, one can distinguish two groups of alloys, the aluminium-silicon and the aluminium-magnesium alloys of which silicon is the most important alloying element in the first group.

Table 2.1.2.2 below shows a comparison of the different properties of this aluminium-silicon group of alloys.

Table 2.1.2.2: A comparison of the various material properties for aluminium pressure casting alloys (based on DIN 1725 Part 2, Feb. 1986) [10]

Material identification	Castability	Surface treatment		Corrosion resistance against		Extrusion	Welding
		mechanical polishing	decorative anodic oxidation	wetting	see water		
GD-AISi9Cu3	excellent	good	not applied	definite	not applied	very good	definite
GD-AISi12Cu	excellent	good	not applied	enough	not applied	good	definite
GD-AISi12	very good	good	not applied	good	enough	good	definite
GD-AISi10Mg	excellent	good	not applied	good	enough	very good	definite
GD-AIMg9	enough	excellent	enough	excellent	very good	excellent	not applied

Generally, in the high-pressure die casting of P661 and P672, the alloy 226 (AlSi9Cu3) is used. This alloy contains other elements in low and varying amounts (as required or as usual impurities) as shown in table 2.1.2.3.

Table 2.1.2.3: Alloy for general use in die pressure casting of P661 and P672 products (DIN EN 1706) [10]

Material identification	Alloy number	Alloy chemical composition									
		Si	Fe	Cu	Mn	Mg	Zn	Ti	Ni	Pb	Sn
AlSi9Cu3	226	8.1-11.0	max.1.2	2.0-3.5	0.1-0.5	0.1-0.5	1.2	0.15	0.3	0.2	0.1

Al-Cu-Si alloys are the most widely used aluminium casting alloys. The amounts of both additions vary widely so that the Cu predominates in some alloys and the Si in others.

In these alloys silicon (the highest impurity level after iron in electrolytic commercial aluminium), improves castability, hot tear resistance and feeding characteristics, reduces hot shortness and rendering it heat-treatable.

For die casting, 5-12% Si is recommended. The basis for this recommendation is the introduction of hard silicon particles into the tough aluminium matrix and the relationship between cooling rate and fluidity and the effect of percentage of eutectic on feeding. Si reduces specific gravity and coefficient of thermal expansion as well.

Iron content of 0.7% or greater is preferred in most die casting operations to maximise elevated-temperature strength, to facilitate ejection, and to minimise soldering to the die face. Iron content is usually 1+/-0.3%. Improved ductility through reduced iron content has been an incentive resulting in widespread efforts to develop a tolerance for Fe as low as approx. 0.25%. This efforts focus on refinements and improved die lubrication.

Copper generally reduces resistance to general corrosion, reduces hot tear resistance, decreases castability, respond to solution heat treatment and subsequent ageing with increase in strength and hardness and a decrease in elongation. The strengthening is maximum between 4-6% Cu.

Magnesium enhances response to heat-treatment for Al-Si-Cu alloys with more than 3-4% Cu and increases strength. In other to reduce the corrosion rate, the alloys must be free of minor

amounts of Pb, Cd, or Sn. The major elements increasing strength are copper, magnesium, manganese, silicon, and zinc. [11]

To ensure that in the liquid form the alloys can be injected under pressure into the steel dies, these alloys should have a low enough melting temperature.

Such castings are used for automotive parts, lawnmower housing, radiators, braking systems, reinforcing beams, suspension components, steel pressed parts, gear cases, cylinder heads for air-cooled engines, office and household appliances with moderately complex shapes.

The need for expensive machining and forming operations are eliminated by this processing procedure.

Some technical information for the foundry alloy 226 (AlSi9Cu3) used in the high pressure die casting for the production of P661 and P672 are listed in table 2.1.2.4 below.

Table 2.1.2.4: Properties of the high pressure foundry alloy 226 (AlSi9Cu3) [10]

Quantity [580°C]	Symbol [unit]	Value
Density	ρ [kg/m ³]	2420
Specific Heat capacity	Cp [J/kg. K]	1090
Heat conductivity	? [w/mK]	190
Introduction temperature range	T [°C]	660
Form	S	solid

2.2. Lubricating substance

2.2.1. General

Lubricants are required in nearly all-contour roll forming of aluminium alloys. For high-pressure, high-speed or severe forming operations, the rolls and work-piece may be flooded with a liquid that function both as a lubricant and a coolant (e.g. Graco CP 506). Soluble oil in water is preferred for this type of operation. When a more effective lubricant is required, a 10 % soap solution or an extreme-pressure compound may be used. These are better suited for minimising tool wear and providing a high quality finish, but they are more difficult to remove.

The die lubrication is the third critical element (after metal temperature and die temperature) in the aluminium forging process and lubricant types and application systems are the subject of major engineering and developmental emphasis.

Lubricants used in aluminium alloy forging are subject to severe service demands. They must:

- Be capable of modifying the surface of the die to achieve the desired reduction in friction
- Withstand the high die and metal temperatures and pressures employed and
- Yet leave the forging surface and forging geometry unaffected.

Lubricant formulations are typically highly proprietary and are developed either by the lubricant manufacturers or by the forgers themselves. The composition of lubricants varies with the demands of the forging process used and the forging type.

The major active element in aluminium alloy forging lubricants is graphite; however, other organic and inorganic compounds are added to colloidal suspensions in order to achieve the desired results. Carriers for aluminium alloy forging lubricants vary from mineral spirits to mineral oils to water.

When molten metal is cast into a relatively cool die, the rates of heat transfer through the lubricating substance, cooling agent, conduction, convection, radiation, etc. and hence the speed of solidification, can be very fast indeed. Unless special precautions are taken it would be almost impossible to cast any but the simplest shapes. Control of heat transfer from metal to die is achieved, firstly, by dressing the die with an insulating-lubricating coating and, secondly, by control of metal and die temperature.

For water soluble separating substance when this substance reaches the contours of the mould die it evaporates. Thereby reducing the heat of the mould surfaces. By the introduction of the lubricating substance, the extracted heat is mainly determined by the amount of water in the GCPW medium. With a mixing ratio of 1:180 (Graco CP : Water), the lubricating substance heat extraction calculations were basically based on the properties of water.

In this case, the amount of heat extracted by the lubricating substance Q_{lub} , can be estimated as [12]:

$$Q_{Lub} = m_{Ev} \cdot Ct + (m_{Lub} - m_{Ev}) \cdot Cp_w \cdot \Delta T \quad \text{Equation 2.12}$$

With

$$m_{Ev} = (Q_m + Q_C - Q_{con} - Q_{rad} - m_{lub} \cdot C_p \cdot \Delta T) / \Delta h_v \quad \text{Equation 2.13}$$

and

$$Ct = \Delta h_v + Cp_w \cdot \Delta T \quad \text{Equation 2.14}$$

Where,

Q_{lub}	Extracted amount of heat [kJ] from the mould surface during lubrication,
$m_{lub}; m_{Ev}$	Mass of lubricating substance [kg]; mass of the evaporated water [kg],
Q_m	Heat introduced from the molten metal [kJ/kg],
Q_C	Heat introduced/extracted by the cooling agent (heat exchanger) [kJ/kg],
Q_{con}	Heat extracted through convection [kJ/kg],
Q_{rad}	Heat extracted through radiation [kJ/kg],
Δh_v	Heat of evaporation for water [kJ/kg],
Cp_w	Specific heat of water [kJ/kg. K],
ΔT	Initial and boiling water temperature difference [K]

2.2.2. Lubricating process

Lubricant application is typically achieved by spraying the lubricant onto the dies; however, in some cases, lubricants are applied to forging stock prior to reheating or just prior to forging.

Several pressurised-air or airless spraying systems are employed, and with high-volume highly automated aluminium forging processes, lubricant application is automated by single or multiple-axis robots.

Lubricants can be applied with or without heating. However, where lubricants are also used as coolants, heating is not recommended. State-of-the-art systems have the capability of applying very precise patterns or amounts of lubricant under fully automated conditions such that the forging processes are optimised and repeatable.

Diagram 2.2.2.1 below shows a lubricating process during normal production of P661 in Georg Fischer +GF+.

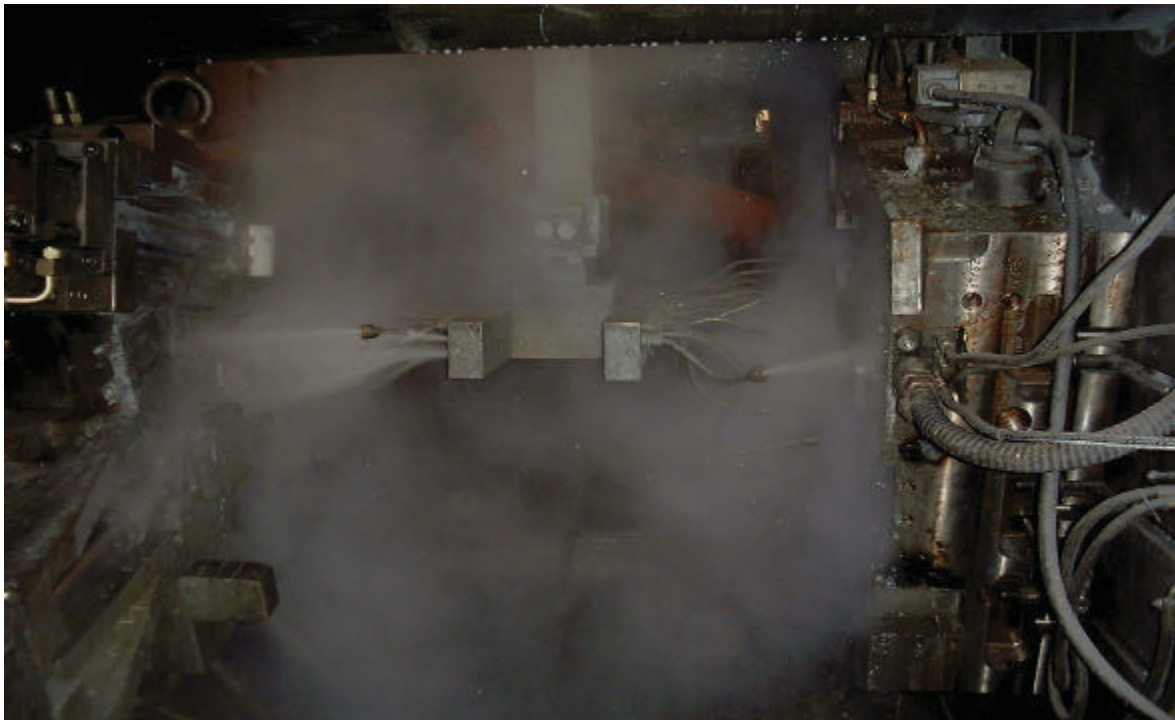


Fig. 2.2.2.1: Lubricating process during normal production of Mercedes Benz steering cases (P661)

Between each shot the die is sprayed with a coolant and lubricant and/or parting agent and this used to be an oil-based product, but for environmental reasons has generally been changed to one based on water. The parting agent gives minimal build-up problems on the die and contributes significantly to the ability of pressure die casting to maintain the accuracy of its

products (unlike, for instance, gravity die casting, where a rather thick die coat is used).

In aluminium high pressure die casting, the use of lubricating material, which at the same time serves as a cooling agent is required for the following reasons:

- As a separating substance, preventing the molten material or cast product from sticking onto the metal mould
- Ensuring a smooth surface for the cast product and
- Cooling the outside surface of the mould.

2.3. Cooling substance

2.3.1. General

Generally, a heat absorbing oil is used for the inner mould cooling. In Georg Fisher Ltd. the heat absorbing oil, Aral Farolin U is used for this purpose.

Some properties of the heat absorbing oil based on the manufacturer are listed in table 2.3.1.1 below

Table 2.3.1.1: Aral Farolin U properties [13]

Quantity [200°C]	Symbol [unit]	Value
Density	ρ [g/ml]	0.748
Kinematic viscosity	γ [mm ² /s]	1.40
Introduction temperature range	T [°C]	10/+320
Specific heat capacity	Cp [kJ/kgK]	2,621
Heat conductivity	λ [W/mK]	0.120
Prandtl number	Pr	22.80
Form	L	liquid
Flow rate	\dot{V} [l/min]	12

The amount of heat per casting that is released from the molten metal is generally transported to:

- The cast piston
- The cast chamber
- The stationary/moving die insert, that makes up the mould and
- The form insert, that builds the form inside room.

From the piston, chamber and the inserts the heat is transported to:

- The cooling agent
- The lubricating substance
- The environment through radiation and convection
- The pillars and holdings through the mould [12]

The amount of heat Q_M , that is released (pro casting) from the melt up to the time of removing the cast product from the mould can be calculated from the following relationship [12]:

$$Q_M = Q_1 + Q_S + Q_2 + Q_P$$

Equation 2. 15

With,

Q_1 Amount of heat released up to the solidification of the cast product [kJ]

Q_S Heat of solidification [kJ]

Q_2 Heat released up to reaching the cast product temperature , T_A , after the solidification [kJ]

Q_P Heat released during the form filling process through friction and molten material kinetic energy conversion [kJ].

The amount of heat Q_P , released is very small and can be neglected. For the others, the following relationships hold:

$$Q_1 = Cp_l \cdot m_p \cdot (T_c - T_s)$$

Equation 2.16

$$Q_s = L_m$$

Equation 2.17

$$Q_2 = Cp_s \cdot m_p \cdot (T_s - T_A)$$

Equation 2.18

With

T_c the initial temperature of the melt (casting temperature),

T_s the solidification temperature,

T_p the average temperature of the cast product during removal from the mould (cast temperature),

m_p the mass of the cast product,

Cp_l the alloy specific heat in liquid state,

Cp_s the alloy specific heat in solid state

L_m the alloy specific heat of solidification

Heat will be transported through the contact area between the cast product and the mould to the die blocks. The amount of heat extracted through inner mould cooling by the heat absorbing substance per cycle can be determined by measuring the inflow and outflow temperatures at the set flow rate of the coolant.

The extracted heat per unit time over the inner cooling cycle, for the heat absorbing medium is [12]:

$$P_c = \dot{V} \cdot \rho \cdot Cp \cdot (T_2 - T_1) \quad (2.19)$$

Whereby, Cp is the specific heat of the heat absorbing substance which is normally dependent on the temperature; ρ its density (also temperature dependent); $T_2 - T_1$ is the inlet and outlet temperature difference of the cooling agent and V is the flow rate (flow volume per unit time).

The extracted amount of heat, Q_c per cast cycle, t_c for the inner cooling cycle is:

$$Q_c = P_c \cdot t_c \quad \text{Equation 2.20}$$

For heat extracted by the cooling medium, the following influencing factors are responsible.

1. Mould material,

2. Type of cooling medium,
3. Heat extracting medium velocity of flow,
4. Diameter of the cooling pipe,
5. Length of the pipe based on the given contour area and
6. The cooling pipes distance from the given contour area [12].

2.3.2. Cooling process

The heat extracting substance Aral Farolin U is used for the inner mould cooling process in the production of P661 and P672. This oil produced by the Aral Lubricants Ltd. by Vienna is used for inner mould cooling using the ROBAMAT or THERMOCAST heat exchangers which are equipped with a cooling and heating programme. Diagram 2.3.2.1 below show the ROBAMAT heat exchanger during operation.



Diagram 2.3.2.1: The ROBAMAT heat exchangers during operation (l = back view, r =front view).

For the P661 production the cooling process description, distribution box and scheme for both the stationary and moving dies are shown below, in the form of tables and diagrams.

Table 2.3.2.1: P661 moving die half cooling process description [19]

Cycle	Connection	Heat exchanger set point	Description
1	P3 + P4	150	Pusher no. 3 + 4
2	Inserts + Edges	160	Moving insert + Holdings
3	P1	130	Pusher 1: high pressure
4	P2	90	Pusher 2: casting nucleus

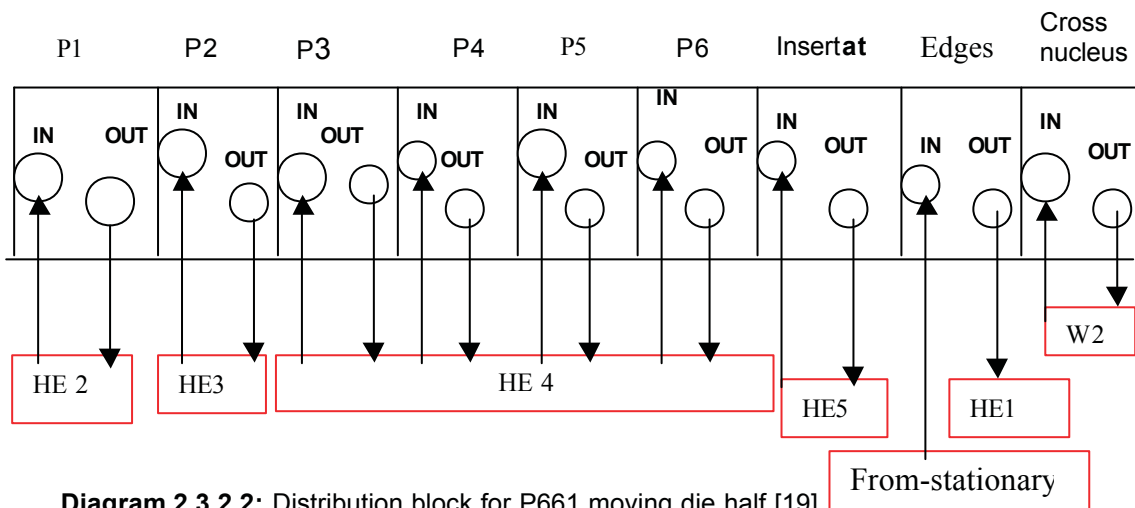


Diagram 2.3.2.2: Distribution block for P661 moving die half [19]

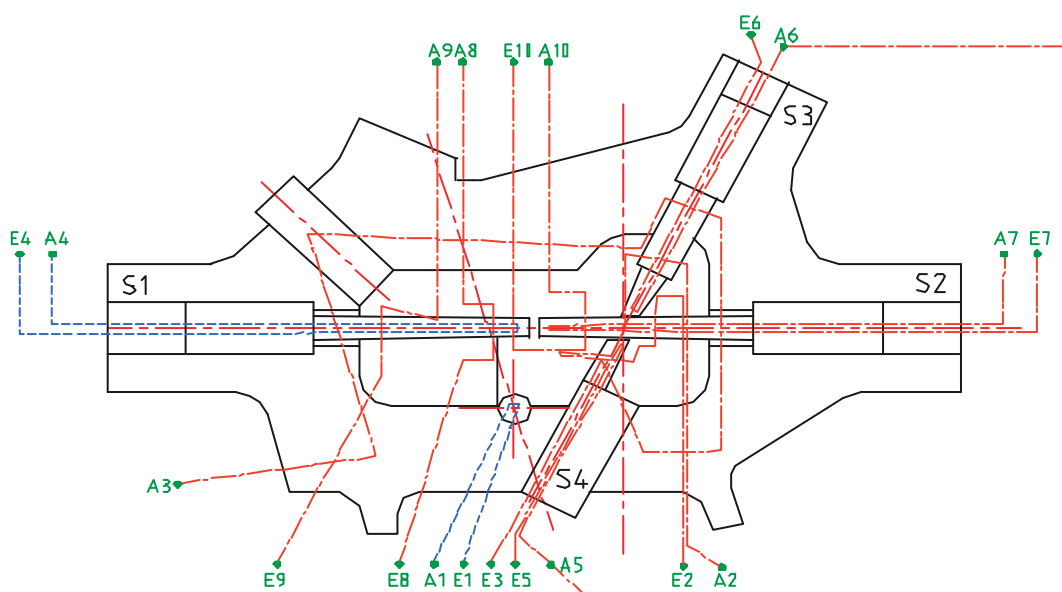


Diagram 2.3.2.3: Moving die half cooling scheme for P661 production. (with A = out, E = in and S = P for pusher) [19]

For the P661 production, the stationary die half cooling description, distribution block and scheme are shown below.

Table 2.3.2.2: P661 stationary die half cooling process description [19].

Cycle	Connection	Heat exchanger set point	Description
	E1 - A1	160	Solid insert + Holdings
W1	E3 - A3	Water	Spot cooling

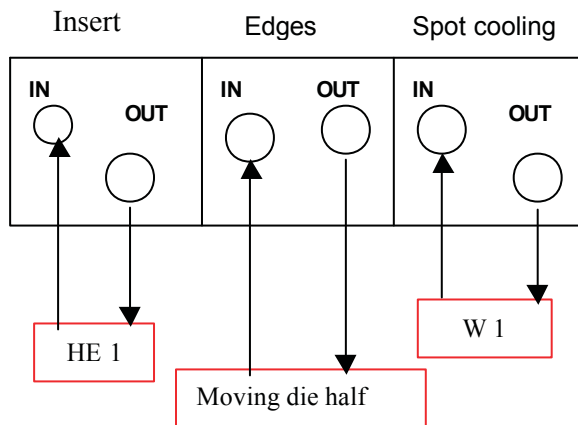


Diagram 2.3.2.4: Distribution block for P661 production stationary die half [19]

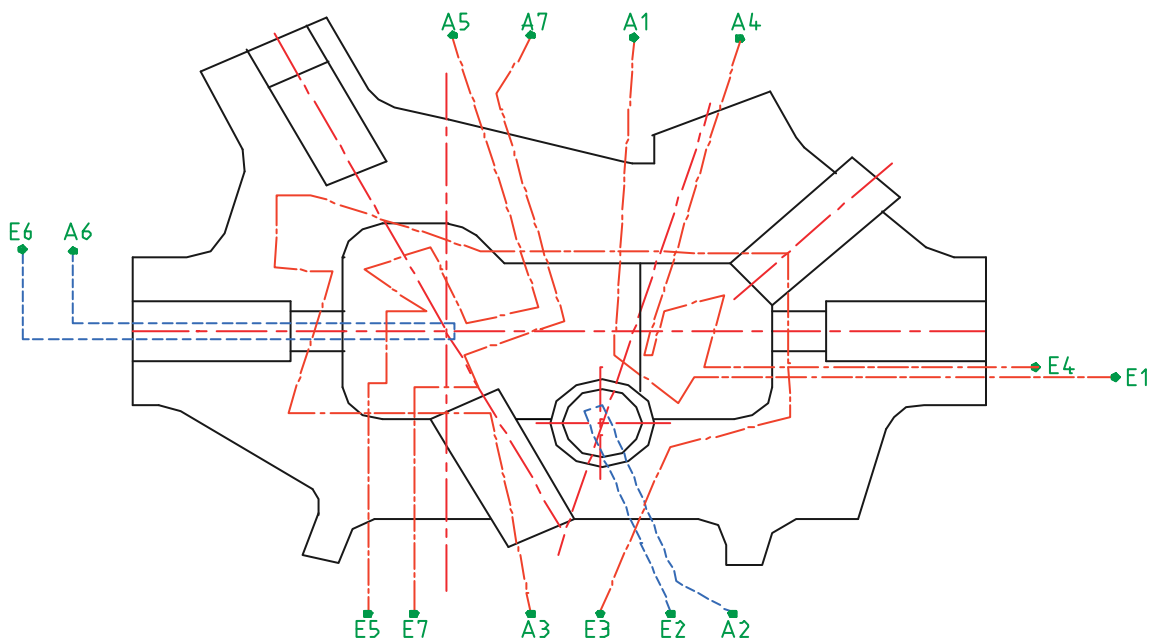


Diagram 2.3.2.5: Stationary die half cooling scheme for P661 production. (with A = out, E = in and S = P for pusher) [19]

For the cooling process during the P672 production, the cooling process description, distribution block and cooling scheme for both the stationary and moving dies are shown in the diagrams and tables below.

Table 2.3.2.3: P672 moving die half cooling process description [19].

Cycle	Connection	Heat exchanger set point	Description
W1		Water	Cross nucleus...10 l/min
E1	P1	90 °C	Main pusher nucleus
E2	P2	90 °C	Main pusher nucleus
E3	P5,P7,P6,P3	140 °C	Cross head pusher-big
E4	P4	120 °C	Cross head pusher-small
E5	Insert1, Insert2, BFS	150 °C	Insert 1 + 2, Edges cooling

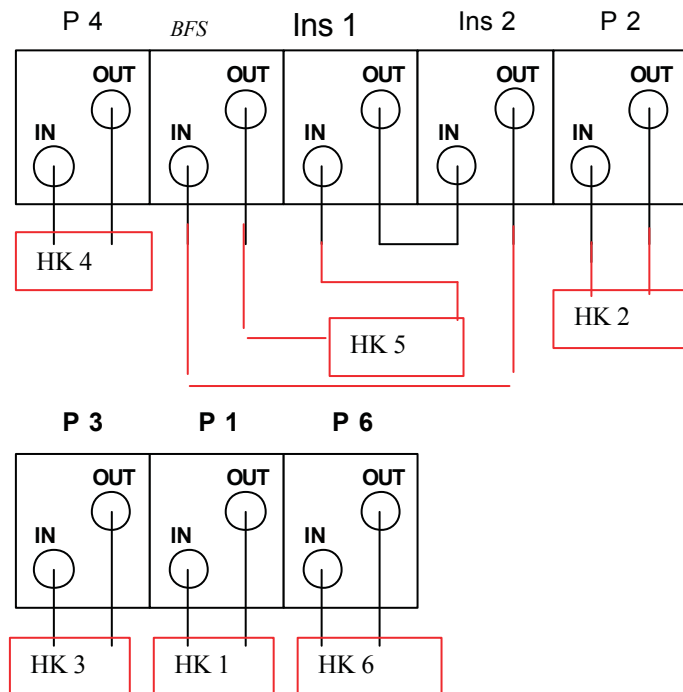


Diagram 2.3.2.6: Moving die half cooling scheme distribution block for P672 production [19].

Table 2.3.2.4: P672 stationary die half cooling process description [19]

Cycle	Connection	Heat exchanger set point	Description
HE 6	E1 - A1 E4 - A4	160 °C	Insert with spot cooling
W 2	E2 - A2 E3 - A3		Spot cooling by cross nucleus (not in use)

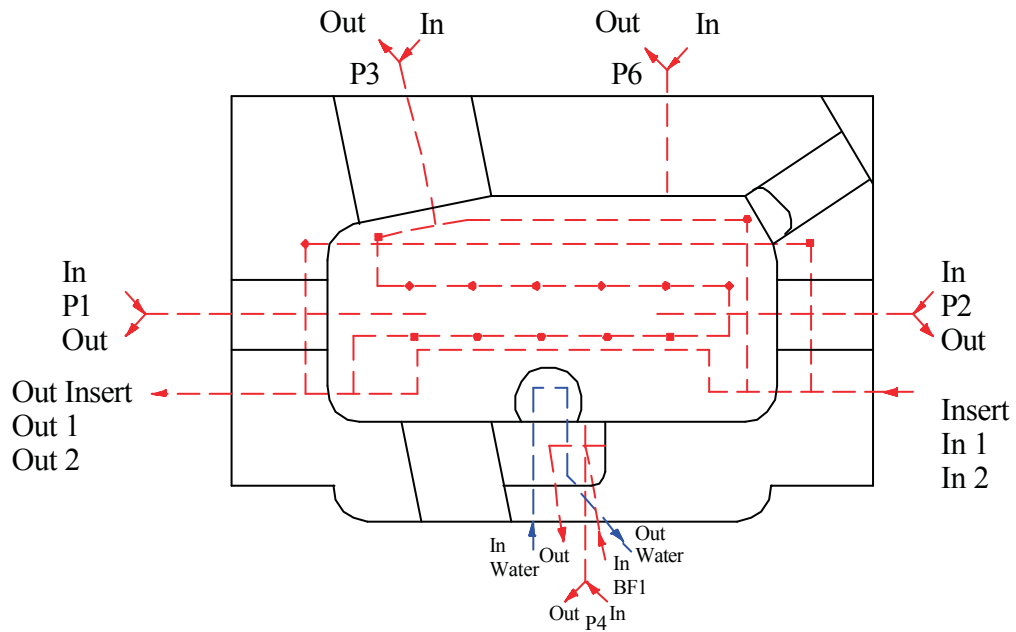


Diagram 2.3.2.7: Moving die half cooling scheme for P672 production[19].

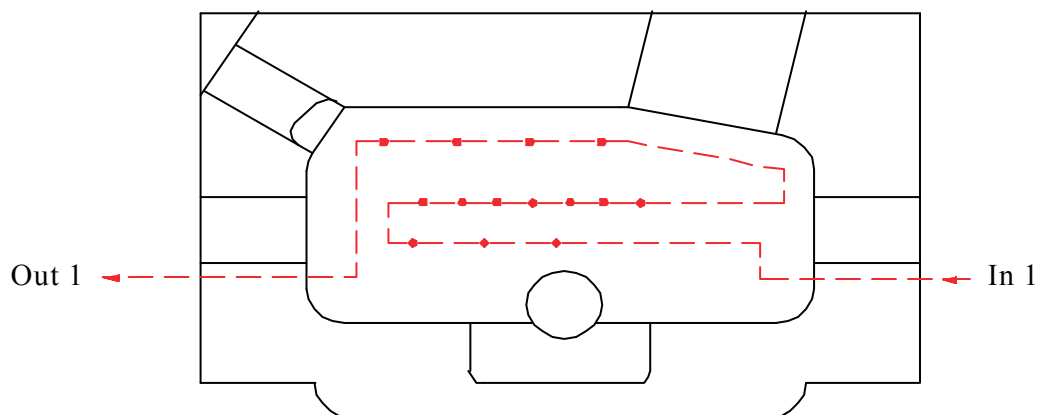


Diagram 2.3.2.8: Stationary die half cooling scheme for P672 production [19].

2.4. Convection

During casting, the amount of heat removed from the casting machine through convection Q_{conv} , to the surrounding can be calculated as follows [12]:

$$Q_{conv} = \alpha_{conv} \cdot A \cdot \Delta T \cdot t_c$$

Equation 2.21

With

α_{conv} Heat transfer coefficient for convection [W/m^2K],

A Form area [m^2],

t_c Cast cycle [s],

ΔT Average temperature difference between the form and the surrounding air [K].

For the free movement of air on the form in vertical direction (at least 30cm high), the following approximation holds:

$$\alpha_{conv} = 1.77 \cdot (\Delta T)^{\frac{1}{4}}$$

Equation 2.22

With a surrounding air temperature of about 30°C, the amount of heat that is removed through convection is relatively low and lies in the range of 5 – 10 %.

2.5. Radiation

The amount of heat that is removed through radiation Q_{rad} , from the forms during casting can be calculated through the following relationship [12]:

$$Q_{rad} = \sigma \cdot \varepsilon \cdot A \cdot (T_a^4 - T_u^4) \cdot t_c \quad \text{Equation 2.23}$$

With

σ $5.67 \cdot 10^{-8}$ [W/m²K⁴], Stefan-Boltzmann constant,

ε 0.70 – 0.99, radiated surface emission coefficient,

A Radiated surface [m²],

T_a Average radiated surface temperature [K],

T_u Temperature of the surrounding [K],

t_c Cast cycle [s],

This relationship can also be written in the following form:

$$Q_{rad} = \alpha_{rad} \cdot \varepsilon \cdot A \cdot \Delta T \cdot t_c \quad \text{Equation 2.24}$$

With

α_{rad} Heat transfer coefficient for radiation [$\text{W}/\text{m}^2\text{K}$]

The value of the coefficient α_{rad} , is dependent on the temperature of the radiated surface

With a surrounding air temperature of about 30°C , the amount of heat that is extracted through radiation is also relatively low and lies in the range of 5 – 10 %.

2.6. Required cooling efficiency

The total amount of heat that is extracted from the form during a cast cycle is [12]:

$$Q_{ex} = Q_{lub} + Q_C + Q_{conv} + Q_{rad} + Q_L \quad \text{Equation 2.25}$$

With Q_L being the lost heat (heating of pillars, holdings etc.), this is neglected as the heat removal through convection and radiation have been taken into account.

In a steady state condition, i.e. when the temperature gradient in the cast-melt system is the same in every cast cycle, the introduced amount of heat from the melt must be equal to the amount of heat that is extracted from the form:

$$Q_m = Q_{ex} \quad \text{Equation 2.26}$$

From this, the total required cooling efficiency for the inner cooling cycle is:

$$P = (Q_m - Q_{\text{lub}} - Q_{\text{conv}} - Q_{\text{rad}} - Q_L) / t_c$$

Equation 2.27

3. EXPERIMENTS

3.1. Plant description

The Georg Fischer +GF+ Automotive Limited in Herzogenburg is a daughter company of the international Georg Fischer concern with its headquarters in Schaffhausen, Sweden.

In 1862, the plant site in Herzogenburg was a factory for the production of locks and keys founded by the Grundmann brothers who laid the foundation stone for the present industry.

In 1929 and 1954, the iron foundry and light metals foundry were respectively incorporated into the original plant

The exclusive production and finishing of iron and aluminium automotive parts began in 1990 and the industry was certified with the QS-9000 (Qualitätssicherung/Quality assurance) in 1997.

The introduction and certification of an environment management system based on EMAS-Verordnung occurred in 1998.

Part of the plant site is rented to the KABA-GEGE company that produces locks and keys.

With approximately 900 workers, a turnover of about 2 billion Shilling was achieved in the year 2000.

With over 75%, is the export quota as supplier for the automotive industries, naturally high. Products include steering boxes, gearboxes, wheel supports, oil cases etc. from the light metal foundry; and elbow outlets, crank shafts, break drums and plates, break carriers, exhaust manifolds, off-gas elbows, exhaust pipes, etc from the iron foundry

Customers for these products include: Bayrische Motor Werk (BMW), Mercedes Benz (MB), General Motors (GM), Volks Wagen (VW), Opel and Audi

In the aluminum foundry, amongst other products, the BMW and MB steering cases are produced using the Bühler SC 120/10-I, Bühler SC 120/10-II and the Idra 1200 machine. The alloy AISi9Cu3 is used for this purpose.

Using 5t, 10t and 15t electro ovens, the solid alloy is melted at approx. 660 °C and then transported to pre casting storage bins where it is then dosed into the die machine cold chamber for casting at a pressure of 1200bars.

After the high pressure casting, the product is removed, cooled in a water bath; the dies are cooled by Faroli U (inner mould cooling) and Graco CP 506 (surface mould cooling) in preparation for the next shot.

Diagram 3.1.1 below shows a representation of the stages involved in the production of the steering cases in Georg Fisher Ltd.

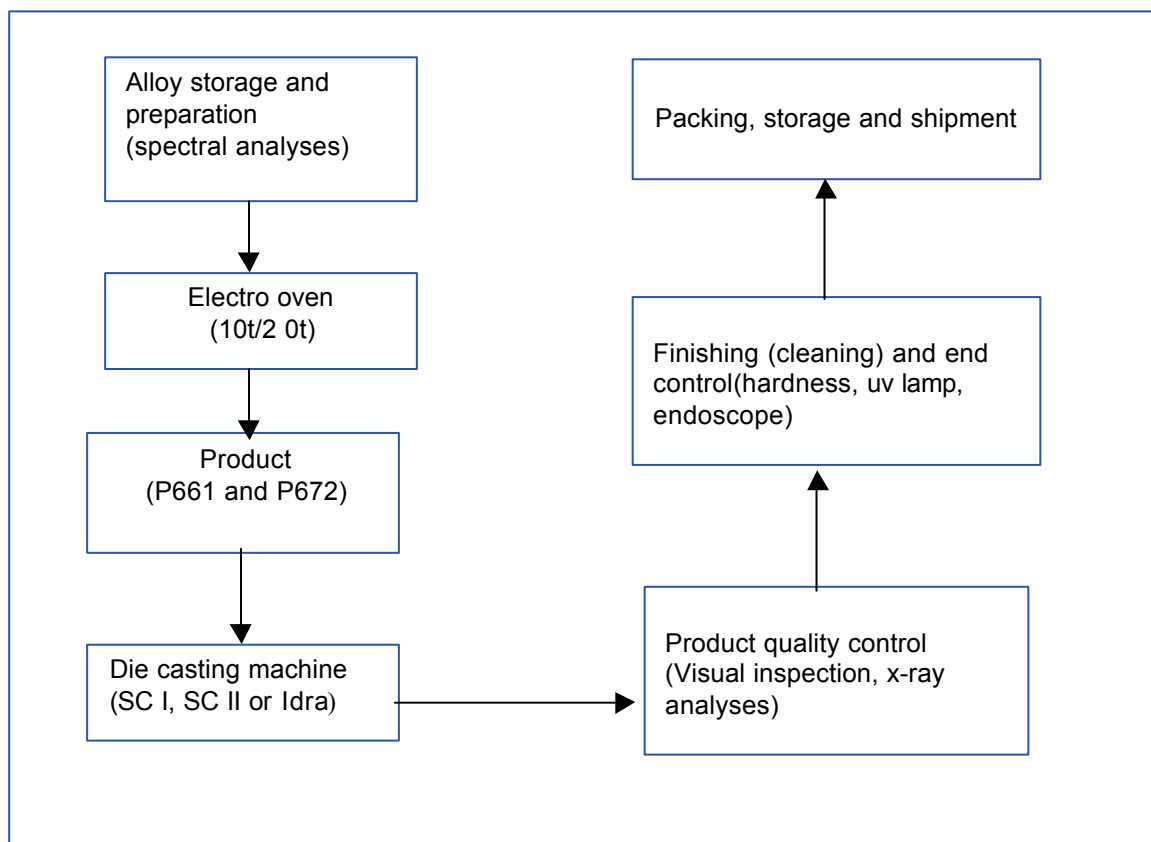


Diagram 3.2.1: Schematic flow showing the stages in the P661 and P672 production

3.2. Experiments theoretical background

3.2.1. Lubricating substance (surface mould cooling)

With the aim of optimising the amount of lubricating substance used for surface mould cooling the following parameters were taken into consideration:

1. Amount of lubricating substance:

To determine the amount of lubricating substance used per lubricating cycle, a plastic bag, a stop watch, a measuring cylinder and a bucket were used.

The plastic bag was carefully wrapped around the lubricating head and held in such a way that no lubricating substance was lost during the lubricating cycle. After that, the automatic lubricating phase was activated. The lubricating time was also independently measured using a stop watch.

At the end of the lubricating period the plastic bag was carefully removed and its contents emptied in a plastic bucket. This was then measured using a measuring cylinder.

The measured amount corresponded to the amount of lubricating substance used per cast cycle or lubricating cycle.

Also the amount of lubricating substance was monitored by recording the flow meter readings on the lubricating pipes, both in still stand and during lubrication.

2. Lubricating time:

The lubricating time was measured using a stop watch at two points:

Point #1: By the flow meter:-the elapse time between the start and the end of lubrication

Point #2: By the lubricating head:-the time from lubrication start to lubrication end.

These two methods were employed in other to compare the automatically set lubricating time to the measured lubricating time.

3. Lubricating pressure:

The lubricating pipe pressure was also monitored at all new lubricating time settings. This was done by simply recording the indicated pipe pressure on the flow meter during operation and in still stand.

4. Mould temperature:

Mould temperature measurements were carried out (after removing the cast product, lubricating and cooling) using a handy thermometer at different pre-set points of both mould halves in other to determine the following :

- Temperature gradient across the moulds after mould lubrication.
- The amount of heat extracted by the lubricating substance
- Weak points and or improvement possibilities in the lubricating process.

Temperature measurement points for the P661 production after the lubrication and cooling process are shown below in diagram 3.2.11 and 3.2.1.2.

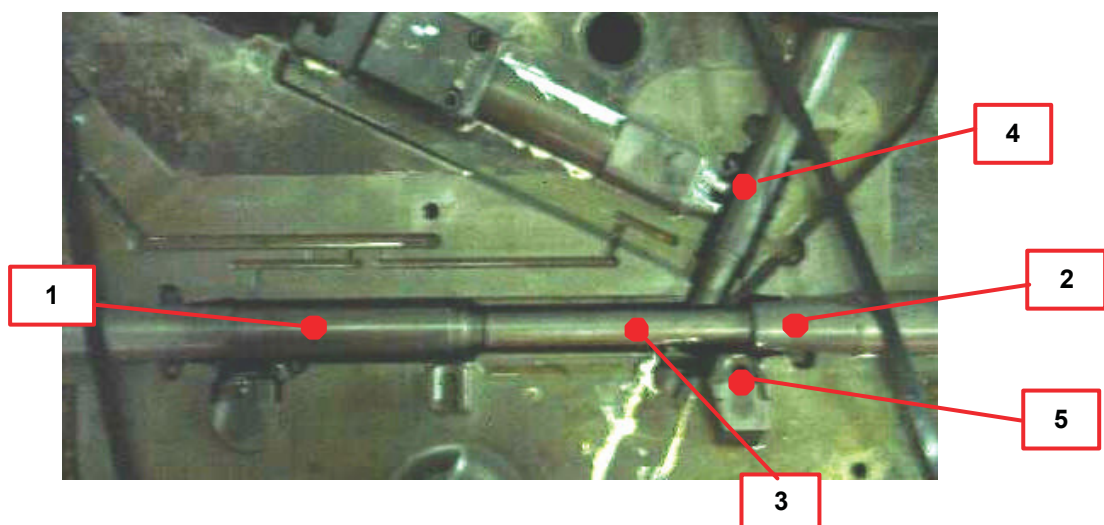


Diagram 3.2.1.1: Temperature measurement points on the moving mould for P661 production [19]



Fig. 3.2.1.2: Temperature measurement points on the stationary mould for P661production [19]

Table 3.2.1.1: Description of the mould temperature measurement points for the P661 Production [19]

Position	Form area	Measurement area	Temperature
1	Pusher nucleus	Suspension area	160 °C
2	Casting nucleus	Suspension area	100 °C
3	Moving insert	Middle cut	180 °C
4	Pusher nucleus: Cross head (up)	Vent connection area	160 °C
5	Pusher nucleus: Cross head (under)	Pipe end area	160 °C
6	Stationary insert	Middle cut	180 °C
X	Temperature tolerance	See formula-Fo-DG-02	(+/-40C)

Mould temperature measurement points for the P672 production were also carried out and the measurement points are shown below in diagram 3.2.1.3, followed by a description of these mould measurements points.

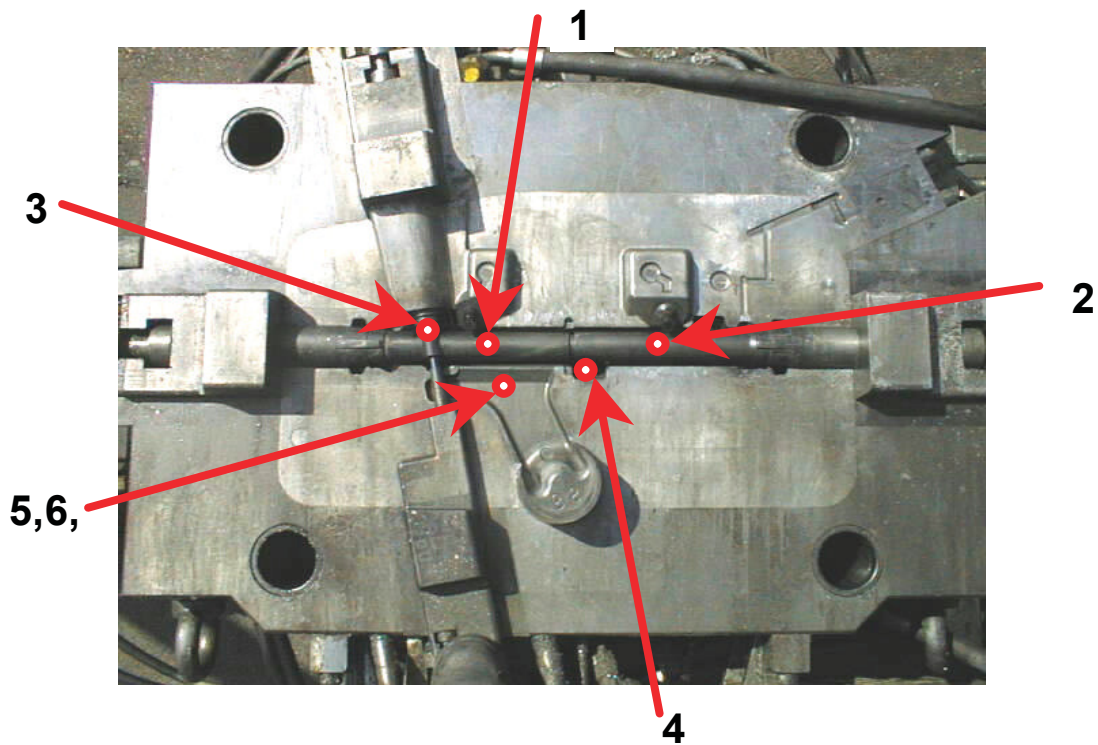


Fig.3.2.1.3: Temperature measurement points on the moving mould side for P672 production [19]

Table 3.2.1.2: Description of the moving mould temperature measurement points for the P672 production [19]

Position	Form area	Measurement area	Temperature
1	Moving insert	Main pusher	170 °C
2	Moving insert	Main pusher	170 °C
3	Moving insert	Cross head pusher (big)	140 °C
4	Moving insert	Middle eye	140 °C
5	Moving insert	Form insert: cut areas	200 °C

Table 3.2.1.3: Description of the stationary mould temperature measurement point for the P672 production [19]

6	Stationary insert	Form insert: cut area	200 °C
---	-------------------	-----------------------	--------

5. Lubricating substance temperature:

To determine the temperature of the lubricating substance before lubrication, a thermometer and a measuring cylinder was used.

Some amount of the lubricating substance was drained into the measuring cylinder, from the drain valves on the lubricating substance delivery lines.

The thermometer was inserted at a reasonable depth into the lubricating substance in the cylinder and the indicated temperature was recorded as the lubricating substance inlet temperature.

3.2.2. Cooling substance (inner mould cooling)

With the aim of optimising the cooling substance used for inner mould cooling in the production of steering cases for BMW and MB, the following parameters were investigated:

Mould temperature measurements were carried out as mentioned in section 3.2.1 above (after cast product removal, lubrication and cooling).

In addition to the mould temperature measurements, the heat exchanger inlet and outlet temperatures were also measured using a handy thermometer or recorded from the indicator.

These measurements were done in order to determine the following:

- Temperature gradient across the moulds after mould cooling
- The efficiency of the heat exchanger
- The amount of heat extracted by the cooling agent
- Weak points and or improvement possibilities in the overall cooling process.

3.2.3. Quality control

As often as necessary or required, the quality of the products were controlled at every new lubricating substance setting, It should be remembered at this point that the cooling agent settings were not altered during the experimentation.

The two basic objectives of inspection were:

- To reject castings that fail to meet the customer's requirements, and
- To serve as a means of maintaining the quality of workmanship and materials used in the foundry.

Defects were of three basic types:

1. major defects, which cannot be rectified, resulting in rejection of the casting and total loss;
2. defects that can be remedied but whose cost of repair may not justify the salvage attempt;
3. minor defects, which clearly allow the casting to be economically salvaged and thereby leave a reasonable margin of profit.

„Inspection of casting“ broadly covers a large number of methods and techniques used to check the quality of castings. These methods may be classified into five categories:

1. visual inspection;
2. dimensional inspection;
3. mechanical and chemical testing
4. flaw detection by non-destructive methods; and

5. metallurgical inspection.

Quality control procedures for this investigation were based on :

1. Visual inspection

All castings were subjected to a visual inspection, to ensure that the surfaces fulfil the requirements of both the customer and the producer.

Visible defects that can be detected provide a means for discovering errors in the pattern equipment or in the moulding and casting process.

They include: shifts, warped castings, swells, fins, blowholes, pinholes, gas holes, shrinkage cavities, porosity, drops, dirt, metal penetrations and rough surfaces, slag holes, scabs, hot tear (pulls), cold cracks, cold shut and mis-run. Diagram 3.2.3.1 below shows a MB steering case during visual inspection.



Diagram 3.2.3.1: A Mercedes Benz (MB;P672) steering case during visual inspection.

Visual examination proved inadequate in the detection of sub-surface or internal defects in which case a more sophisticated method was necessary.

2. Flaw detection by non-destructive methods (Radiographic or X-ray Examination)

Non-destructive tests were conducted to examine the castings for any sub-surface or internal defects, which cannot be detected by visual examination, and for overall soundness or pressure tightness, which may be required in service. This test was valuable not only in detecting but even in locating the casting defects present in the interior of the casting, which could impair the performance of the machine member when placed in service.

Important non-destructive tests for castings include:

- Sound or percussion test (stethoscope test);
- Impact test;
- Pressure test;
- Radiographic examination;
- Magnetic particle inspection;
- Electrical conductivity test;
- Fluorescent dye penetrant inspection;
- Ultrasonic test; and
- Eddy current test

During this work, radiographic or X-ray examination was carried out to determine the quality of the steering cases under the investigated conditions through the detection of unallowable sub-surface or internal defects based on “boundary pattern or conditions”.

This proofing was done in the Georg Fisher +GF+, aluminium foundry radiographic room with the assistance of experienced operators.

The radiographic analyses was not based on radioactive material but on electromagnetic waves. Electromagnetic waves having low wavelengths (varying between 10^{-6} and 10^{-10} cm) was used as a means of inspection. These waves generally called x-rays, have properties similar to those of light waves, but they have much shorter wavelengths, which lie outside the range of human sensitivity. These x-rays can, however, be detected by a sensitive photographic film. Owing to their shorter wavelengths, these waves can penetrate materials that are normally opaque to light. The denser the material, the shorter the wavelength required to penetrate it.

The x-rays are produced by an x-ray tube which carries two sealed copper elements, the cathode and the anode. The cathode bears an electrically heated filament which generates electrons; when these electrons strike the tungsten target fixed to the anode they are driven towards the positively charged anode.

The striking of the electrons causes their kinetic energy to be partly converted into heat, which is conducted away through the cooling fins provided on the anode and the remainder of the energy is converted into electromagnetic waves, termed x-rays. The x-rays pass out of the tube through a window in the form of a beam. The intensity of these x-rays is controlled by regulating the current passing through the filament. Similarly, the wavelength of the ray is inversely proportional to the voltage applied between the two poles. The shorter the wavelength, the greater the depth of penetration.

If there is a cavity or a hole in the casting under inspection, and, when such a casting is kept against the x-rays, the rays finding less obstruction penetrate more freely than at the place where the metal is more dense or solid. The rays that penetrate and emerge from the casting are observed by a photographic plate. Thus the part of the photographic plate opposite the defect will receive more rays and be more exposed than the rest of the plate. This will produce a contrasting image on the negative.

To protect the viewer from continuous exposure to rays, the image is observed in a closed room through a transparent glass. The voltage required for the x-ray machine depends on the density of the metal and its section thickness. [4]

4. EXPERIMENTAL RESULTS AND ANALYSES

4.1. Lubricating substance (surface mould cooling)

The lubricating process measurement results for the SC I, SC II and the Idra machine are shown in table 4.1.1, 4.1.2 and 4.1.3 respectively below.

Table 4.1.1: SCI Lubrication measurement results

Test	Date	Time	Lubricating substance (Acheson Graco/Water)						Lubricating pipe pressure [bar]			
			Amount			Lubricating cycle [sec.]			Still stand		Operation	
			M1 [l/min.]	M2 [l/min.]	Measured [l/lub.cycle]	Program.	Measured	Temp. [°C]	M1	M2	M1	M2
1	10601	16:45	8.0	8.5	2.2	7.0	8.0	13.0	4.5	4.0	4.5	3.2
2	230601	10:00	8.0	9.0	1.85	6.5	7.1	12.0	4.2	4.0	4.0	3.6
3	230601	16:00	8.0	9.0	1.7	6.0	7.0	13.0	4.5	3.8	4.0	3.6
4	250601	10:00	8.0	9.0	1.6	6.5	7.0	13.0	5.0	4.0	5.0	3.2
5	250601	15:15	9.0	9.0	1.65	6.5	6.5	12.0	4.8	4.5	3.2	4.0

Table 4.1.2: SCII Lubrication measurement results

Test	Date	Time	Lubricating substance (Acheson Graco/Water)						Lubricating pipe pressure [bar]			
			Amount			Lubricating cycle [sec.]			Still stand		Operation	
			M1 [l/min.]	M2 [l/min.]	Measured [l/lub.cycle]	Program.	Measured	Temp [°C]	M1	M2	M1	M2
1	300501	12:00	5.0	10.0	1.45	7.0	6.5	19.2	4.0	3.6	3.6	3.4
2	310501	09:00	8.0	9.0	1.8	6.5	6.5	18.7	4.0	3.6	3.5	3.4
3	270601	10:30	6.0	10.0	1.4	7.0	7.5	14	4.0	3.6	3.6	3.4
4	290601	12:00	6.0	9.0	1.4	7.0	7.1	13.5	4.0	3.8	3.5	3.0
5	20701	10:45	7.0	10.0	1.5	7.0	7.0	15.0	4.0	3.8	3.6	3.4

Table 4.1.3: IDRA Lubrication measurement results

Test	Date	Time	Lubricating substance (Acheson Graco/Water)						Lubricating pipe pressure [bar]				
			Amount			Lubricating cycle [sec.]			Temp. [°C]	Still stand		Operation	
			M1 [l/min.]	M2 [l/min.]	Measured [l/lub.cycle]	Program.	Measured	M1		M2	M1	M2	
1	310201	18:20	7.0	12.0	1.8	7.3	7.0	20.0	3.8	3.9	3.0	3.2	
2	10601	08:30	7.0	12.0	1.4	6.1	6.0	17	3.8	3.8	3.2	3.2	
3	10601	14:00	7.0	12.0	1.7	7.0	6.0	19.0	4.6	4.7	3.3	3.4	
4	10601	17:15	6.0	12.0	1.5	6.1	6.0	14.0	4.4	4.2	4.0	3.6	

From the above experimental information, the following were calculated:

1. Amount of lubricating substance:

To determine the amount of lubricating substance used in the die casting process, the manually measured amount of substance (using a plastic bag), was compared to the indicated amount on the flow meters (M1 and M2) of the delivery pipes.

This comparison is shown below in tables 4.1.4, 4.1.5 and 4.1.6 in litres pro lubricating cycle (litre/lub. cycle) and in litres pro seconds (l/sec) for the conducted tests.

Table 4.1.4: A comparison of the amount of lubricating substance used on the SC I machine

Test	Date	Time	Amount of Lubricating substance				
			Meter [l/min]	Meter [l/lub.cycle]	Meter [l/sec.]	Measured [l/lub.cycle]	Measured [l/sec.]
1	10601	16:45	16.5	1.93	0.28	2.2	0.28
2	230601	10:00	17	1.84	0.28	1.85	0.26
3	230601	16:00	17	1.70	0.28	1.7	0.24
4	250601	10:00	17	1.84	0.28	1.6	0.23
5	250601	15:15	18	1.95	0.30	1.65	0.25
Average amount of lubricating substance			1.85	0.29	1.80	0.25	

Table 4.1.5: A comparison of the amount of lubricating substance used on the SC II machine

Test	Date	Time	Amount of Lubricating substance				
			Meter [l/min]	Meter [l/lub.cycle]	Meter [l/sec.]	Measured [l/lub.cycle]	Measured [l/sec.]
1	300501	12:00	15	1.75	0.25	1.45	0.22
2	310501	09:00	17	1.84	0.28	1.8	0.28
3	270601	10:30	16	1.87	0.27	1.4	0.19
4	290601	12:00	15	1.75	0.25	1.4	0.20
5	20701	10:45	17	1.98	0.28	1.5	0.21
Average amount of lubricating substance				1.84	0.27	1.51	0.22

Table 4.1.6: A comparison of the amount of lubricating substance used on the IDRA machine

Test	Date	Time	Amount of Lubricating substance				
			Meter [l/min]	Meter [l/lub.cycle]	Meter [l/sec.]	Measured [l/lub.cycle]	Measured [l/sec.]
1	310201	18:20	19	2.31	0.32	1.8	0.26
2	10601	08:30	19	1.93	0.32	1.4	0.23
3	10601	14:00	19	2.22	0.32	1.7	0.28
4	10601	17:15	18	1.83	0.30	1.5	0.25
Average amount of lubricating substance				2.07	0.31	1.60	0.26

The variation in the two methods used to determine the amount of lubricating substance used is further depicted in diagram.4.1.1, 4.1.2 and 4.1.3 below.

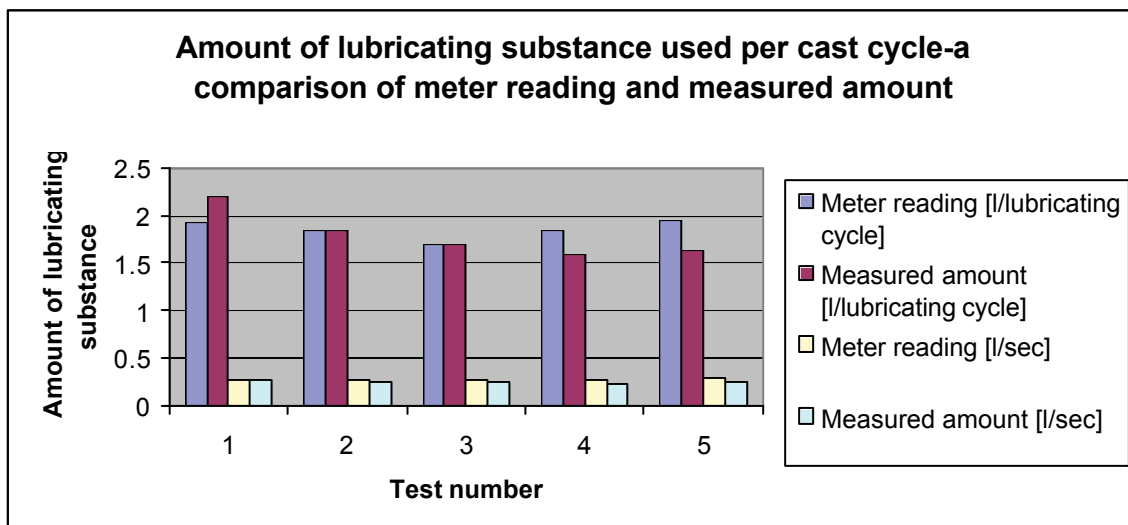


Diagram 4.1.1: A comparison of the amount of lubricating substance used on the SC I machine

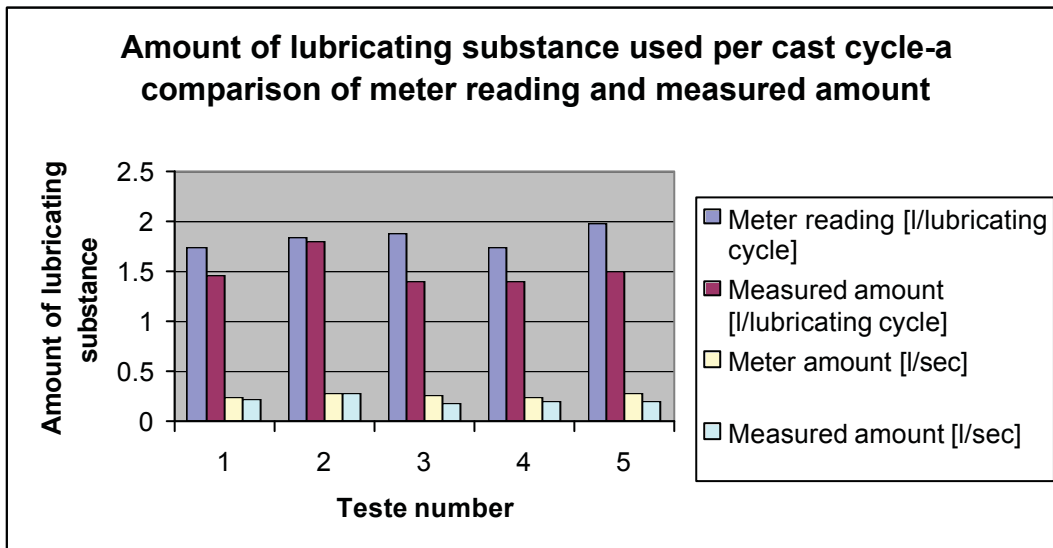


Diagram 4.1.2: A comparison of the amount of lubricating substance used on the SC II machine

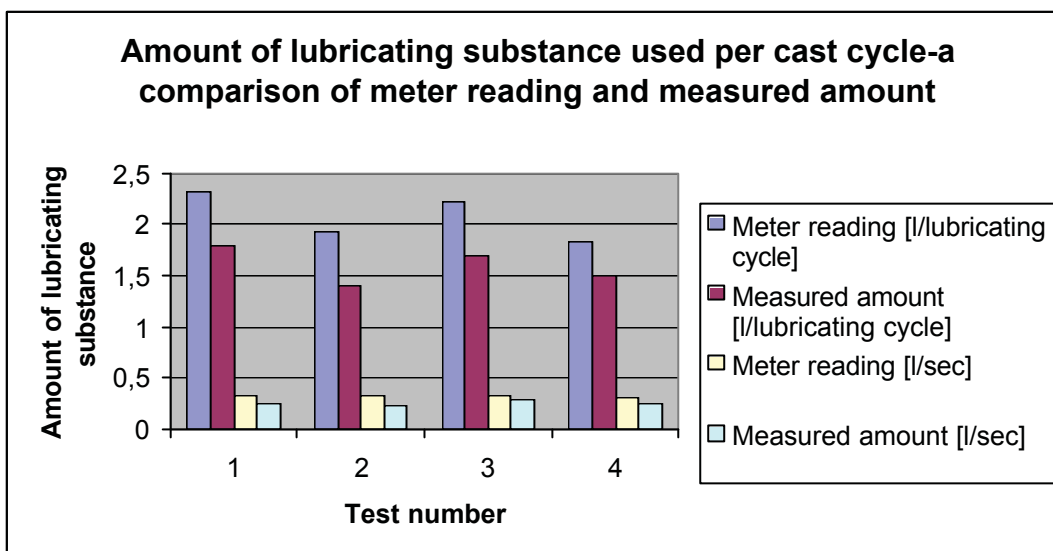


Diagram 4.1.3: A comparison of the amount of lubricating substance used on the IDRA machine.

Generally, the amount of lubricating substance used per lubricating cycle or per second was higher as indicated by the meter readings compared to the experimentally measured amount.

2. Lubricating time:

The lubricating times which had a direct proportion to the amount of lubricating substance used per cast cycle were also controlled using a stop watch, to determine variations from the programmed lubricating time. Table 4.1.7, 4.1.8 and 4.1.9 below show the variations of the measured to the programmed lubricating time.

Table 4.1.7: SC I Lubricating cycle variation-programmed versus measured

Test	Lubricating cycle		
	Programmed	Measured	Variation [sec]
1	7.0	8.0	-1
2	6.5	7.1	-0.6
3	6.0	7.0	-1
4	6.5	7.0	-0.5
5	6.5	6.5	0

Table 4.1.8: SC II Lubricating cycle variation-programmed versus measured

Test	Lubricating cycle		
	Programmed	Measured	Variation [sec]
1	7.0	6.5	0.5
2	6.5	6.5	0
3	7.0	7.5	-0.5
4	7.0	7.1	-0.1
5	7.0	7.0	0

Table 4.1.9: Idra Lubricating cycle variation-programmed versus measured

Test	Lubricating cycle		
	Programmed	Measured	Variation [sec]
1	7.3	7.0	0.3
2	6.1	6.0	0.1
3	7	6.0	1
4	6.1	6.0	0.1

Positive and negative variations were recorded when the set lubrication times were controlled using a stop watch. These variations were however not significantly high and as such the programmed lubricating times were confirmed as reliable and used for all relevant calculations and deductions.

An average of 6.5, 6.9 and 6.6 seconds of lubricating time was deducted for the SC I, SC II and the Idra machine respectively.

3. Lubricating pressure:

The pressures at which the dies were lubricated were monitored by recording the lubricating pipe pressures both during operations and in still stands. In table 4.1.10, 4.1.11 and 4.1.12 below the obtained pressures are presented.

Table 4.1.10: SC I Lubricating pipe pressure variation

Test	Lubricating pipe pressure [bar]					
	M 1			M 2		
	Still stand	Operation	Difference	Still stand	Operation	Difference
1	4.5	4.5	0	4.0	3.2	0.8
2	4.2	4.0	0.2	4.0	3.6	0.4
3	4.5	4.0	0.5	3.8	3.6	0.2
4	5.0	5.0	0	4.0	3.2	0.8
5	4.8	3.2	1.6	4.5	4.0	0.5

Table 4.1.11: SC II Lubricating pipe pressure variation

Test	Lubricating pipe pressure [bar]					
	M 1			M 2		
	Still stand	Operation	Difference	Still stand	Operation	Difference
1	4.0	3.6	0.4	3.6	3.4	0.2
2	4.0	3.5	0.5	3.6	3.4	0.2
3	4.0	3.6	0.4	3.6	3.4	0.2
4	4.0	3.5	0.5	3.8	3.0	0.8
5	4.0	3.6	0.4	3.8	3.4	0.4

Table 4.1.12: Idra Lubricating pipe pressure variation

Test	Lubricating pipe pressure [bar]					
	M 1			M 2		
	Still stand	Operation	Difference	Still stand	Operation	Difference
1	3.8	3.0	0.8	3.9	3.2	0.7
2	3.8	3.2	0.6	3.8	3.2	0.6
3	4.6	3.3	1.3	4.7	3.4	1.3
4	4.4	4.0	0.4	4.2	3.6	0.6

Generally the pressures in still stand and during operations were not constant. The pressure differences (still stand pressure – operation pressure) also showed variations, indicating rises and drops along the delivery pipes.

4. Lubricating substance temperature:

The average lubricating substance temperatures for the various tests, on the various machines are shown below, in table 4.1.13.

Table 4.1.13: Lubricating substance inlet temperature.[°C]

Test	Machine			Average lubricating substance inlet temperature
	SC I	SC II	Idra	
1	13.0	19.2	20.0	
2	12.0	18.7	17.0	
3	13.0	14.0	19.0	
4	13.0	13.5	14.0	
5	12.0	15.0		
Average temperature	12.6	16.08	17.5	15.39

The average lubricating substance inlet temperature was 15.4 °C.

It should be noted however, that the experimentation period was the peak summer season (i.e. late May to the beginning of July) and that considerable variations can be expected during the colder (e.g. winter) periods.

5. Amount of heat extracted by the lubricating substance:

Using equation 2.12 in page 25, the amount of heat extracted by the lubricating substance is calculated in table 4.1.14 below.

Table 4.1.14: Amount of heat extracted by the lubricating substance

Test	SC I				SC II				Idra			
	\dot{V} [l/lu.cy]	m_{lub} [kg]	m_{Ev} [kg]	Q_{lub} [kJ]	\dot{V} [l/lu.cy]	m_{lub} [kg]	m_{Ev} [kg]	Q_{lub} [kJ]	\dot{V} [l/lu.cy]	m_{lub} [kg]	m_{Ev} [kg]	Q_{lub} [kJ]
1	2.20	2.20	1.35	3684.94	1.45	1.45	1.35	3592.66	1.80	1.80	1.39	3701.17
2	1.85	1.85	1.35	3684.94	1.80	1.80	1.35	3592.66	1.40	1.40	1.39	3701.17
3	1.70	1.70	1.35	3684.94	1.40	1.40	1.35	3592.66	1.70	1.70	1.39	3701.17
4	1.60	1.60	1.35	3684.94	1.40	1.40	1.35	3592.66	1.50	1.50	1.39	3701.17
5	1.65	1.65	1.35	3684.94	1.50	1.50	1.35	3592.66				
Av.	1.80	1.80	1.35	3684.94	1.51	1.51	1.35	3592.66	1.60	1.60	1.39	3701.17

The average amount of heat extracted [kJ] from the SC I, SC II and the Idra machine during surface mould cooling was 3684.94, 3592.66 and 3701.17, respectively.

4.2. Cooling substance (inner mould cooling)

In table 4.2.1, 4.2.2 and 4.2.3 the experimental results for the cooling substance are shown below for the SC I 1200, SC II 1200 and the Idra 1200 machine, respectively.

Table 4.2.1: Cooling substance experimental results for the SC I machine

Test No.	Temperature [°C]																	
	Form (after cooling)						Heat exchanger (out)						Heat exchanger (in)					
	Measurement point						Indicator						Indicator					
	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
1	166	179	156	144	197	225	170	100	159	161			173	70	142	152		
2	159	122	153	163	181	224	170	94	153	159	150	180	182	67	167	126	131	97
3	165	140	207	160	173	204	153	88	138	138	167	145	100	56	145	127	128	82
4	238	175	230	174	231	220	103	144	147	165	145		187	92	151	168	152	
5	218	174	220	169	200	224	144	99	149	149	156	147	199	90	147	140	168	146

Table 4.2.2: Cooling substance experimental results for the SC II machine

Test No.	Temperature [°C]																	
	Form (after cooling)						Heat exchanger (out)						Heat exchanger (in)					
	Measurement point						Indicator						Indicator					
	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
1	178	182	152	136	220	250	113	146	128	130	135	143	142	136	112	121	126	137
2	161	169	206	132	137	149	171	99	164	160			176	91	153	152		
3	197	123	190	161	146	230	167	100	150	170	150	150	168	100	142	168	142	150
4	176	110	180	160	136	220	96	131	107	64	61	107	103	165	135	62	131	153
5							100	168	143	66	157	151	101	135	118	67	74	107

Table 4.2.3: Cooling substance experimental results for the Idra machine

Test No.	Temperature [°C]																	
	Form (after cooling)						Heat exchanger (out)						Heat exchanger (in)					
	Measurement point						Indicator						Indicator					
	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
1	142	200	143	126	134	150	113	185	122	86	146	173	98	172	110	73	123	151
2	155	199	175	140	188	242	110	174	132	92	190	173	98	163	122	87	167	166
3	160	140	109	103	140	172	113	168	130	88	184	172	110	165	128	82	186	181
4	159	156	150	111	167	219	110	173	129	88	192	180	113	158	99	90	173	171

From these experimental results, the following were calculated:

1. Mould temperature:-measured versus expected:

The measured average temperatures for the form measurement points, after cooling are shown in table 4.2.4 below:

Table 4.2.4: Measured average form temperature after cooling [°C]

Form measurement point	Machine		
	SC I	SC II	Idra
1	189.20	178.00	154.00
2	158.00	146.00	173.80
3	193.00	182.00	144.00
4	162.00	147.20	120.00
5	196.00	159.70	157.00
6	219.00	212.20	196.00
Measured average form temperature	186.20	170.85	157.47

The measured average temperatures for the measurement points are further depicted in diagram 4.2.1 below

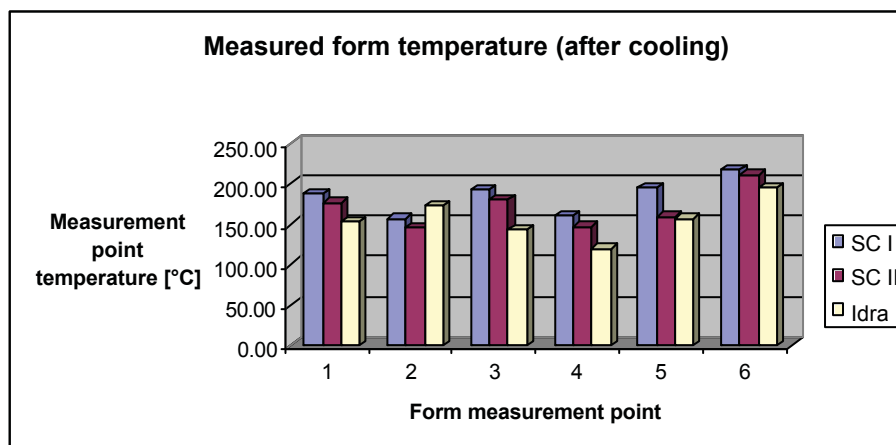


Diagram 4.2.1: Measured average temperature for the form measurement points (after cooling) [°C]

From all the tests conducted the SC I machine had a higher average die temperature followed by the SC II and then the Idra. Therefore, it can be concluded that, the SC I die was either poorly cooled or more heat was introduced into it (e.g. from the heat exchanger) compared to the other

two machine dies. Also, the highest average temperatures were recorded for the measurement point # 6 (stationary insert).

Table 4.2.2 below shows the expected mould temperatures at the different measurement points for the two products, with a tolerance of +/- 40 °C.

Table 4.2.5: Expected mould temperature for the form measurement points (after cooling) [°C]

Measurement point	1	2	3	4	5	6	Tolerance
P 672 product	170	170	140	140	200	200	(+/-) 40
P 661 product	160	100	180	160	160	180	(+/-) 40

A comparison of the average measured temperatures for the mould measurement points and the expected average temperatures for the same, after cooling are shown below (table 4.2.3, 4.2.4 and 4.2.5) for the production of P661 and P672:

Table 4.2.6: Measured average mould temperatures for the SC I machine - expected versus measured [°C].

Measurement point	1	2	3	4	5	6	Tolerance
P 661 product (expected temperature)	160	100	180	160	160	180	(+/-) 40
P 661 product (measured temperature)	189	158	193	162	196	219	(+/-) 40
Temperature difference.	29	58	13	2	36	39	(+/-) 40

Other than the measurement point # 2, with a variance of 58°C, all other measurement points were within the acceptable temperature ranges with a tolerance of +/- 40°C for the production of P 661 using the SC I pressure die casting machine (see table 4.2.3.). Nonetheless, it is worth noting that all measured temperatures were higher than the expected temperatures.

Table 4.2.7: Measured average mould temperatures for the SC II machine - expected versus measured [°C].

Measurement point	1	2	3	4	5	6	Tolerance
P 672 product (expected temperature)	170	170	140	140	200	200	(+/-) 40
P 672 product (measured temperature)	178	146	182	147	160	212	(+/-) 40
Temperature difference	8	-24	42	7	-40	12	(+/-) 40

Using the SC II die casting machine, for the production of P 672, the average mould temperatures after cooling were within the acceptable ranges (see table 4.2.4.) with some measured values being even lower than the expected.

Table 4.2.8: Measured average mould temperatures for the Idra machine - expected versus measured [°C].

Measurement point	1	2	3	4	5	6	Tolerance
P 661 product (expected temperature)	160	100	180	160	160	180	(+/-) 40
P 661 product (measured temperature)	154	174	144	120	157	196	(+/-) 40
Temperature difference	-6	74	-36	-40	-3	16	(+/-) 40

From table 4.2.5, the measurement point #2 was above the accepted tolerance range of +/- 40°C with most of the other points indicating a lower measured temperature compared to the expected mould temperature. Here, a much better cooling was performed or less heat was introduced into the dies.

2. Amount of heat introduced into the die machines from the molten alloy:

In table 4.2.6 below, the average amount of heat introduced into the die machines was calculated using equation 2.14 of page 28. Here, it was theoretically calculated and assumed that the same amount of heat was introduced into all three machines from the molten alloy.

Table 4.2.9: Amount of heat introduced into the die machine per cast cycle from the molten alloy

C_{p_s}	C_{p_l}	m_P	T_C	T_S	T_P	Q_1	Q_2	Q_S	Q_m
[kJ/kg K]	[kJ/kg K]	[kg]	[K]	[K]	[K]	[kJ]	[kJ]	[kJ]	[kJ]
1.09	1.07	4.085	933.45	783	538	657.61	1090.90	1891.76	3640.27

From these calculations, approximately 3640.27 [kJ] of heat was introduced into the die machines during every cast cycle from the molten alloy.

3. Amount of heat extracted from/introduced into the die casting machine by the cooling substance:

Table 4.2.7, 4.2.8 and 4.2.9 below show the calculated average temperatures of the heat exchangers indicators, the temperature differences (inlet temperature – outlet temperature), the

density (temperature dependent), flow rate, specific heat (temperature dependent), and the heat extracted (per unit time and per cast cycle) for the cooling processes using equation 2.19 (p. 30).

Table 4.2.10: Amount of heat per cast cycle extracted by the Farolin U for the P661 production using the SC I machine.

Test	Heat exchanger temperature [K]			Farolin U			Cast cycle	Heat extracted	
	outlet	inlet	difference	flow rate	density	specific heat		per unit time	per cast cycle
	T_1	T_2	$T_2 - T_1$	\dot{V} [l/sec]	ρ [g/ml]	C_p [kJ/kg K]		P_C [kJ/s]	Q_C [kJ]
1	147.50	134.25	-13.25	0.200	0.797	2.331	32.0	-4.919	-157.409
2	151.00	128.33	-22.67	0.200	0.797	2.331	32.0	-8.415	-269.279
3	138.17	106.33	-31.83	0.200	0.797	2.331	32.0	-11.818	-378.179
4	140.80	150.00	9.20	0.200	0.797	2.331	32.0	3.415	109.296
5	140.67	148.33	7.67	0.200	0.797	2.331	32.0	2.846	91.080

Table 4.2.11: Amount of heat per cast cycle extracted by the Farolin U for the P672 production using the SC II machine.

Test	Heat exchanger temperature [°K]			Farolin U			Cast cycle	Heat extracted	
	outlet	inlet	difference	flow rate	density	specific heat		per unit time	per cast cycle
	T_1	T_2	$T_2 - T_1$	\dot{V} [l/sec]	ρ [g/ml]	C_p [kJ/kgK]		P_C [kJ/s]	Q_C [kJ]
1	132.50	129.00	-3.50	0.200	0.797	2.331	37.0	-1.299	-48.077
2	148.50	143.00	-5.50	0.200	0.797	2.331	37.0	-2.042	-75.549
3	147.83	145.00	-2.83	0.200	0.797	2.331	37.0	-1.052	-38.919
4	94.33	124.83	30.50	0.200	0.797	2.331	37.0	11.323	418.954
5	130.83	100.33	-30.50	0.200	0.797	2.331	37.0	-11.323	-418.954

Table 4.2.12: Amount of heat per cast cycle extracted by the Farolin U for the P661 production using the Idra machine.

Test	Heat exchanger temperature [°K]			Farolin U			Cast cycle	Heat extracted	
	outlet	inlet	difference	flow rate	density	specific heat		per unit time	per cast cycle
	T_1	T_2	$T_2 - T_1$	\dot{V} [l/sec]	ρ [g/ml]	C_p [kJ/kgK]		P_C [kJ/s]	Q_C [kJ]
1	137.50	121.17	-16.33	0.200	0.797	2.331	32.0	-6.064	-194.039
2	145.17	133.83	-11.33	0.200	0.797	2.331	32.0	-4.207	-134.640
3	142.50	142.00	-0.50	0.200	0.797	2.331	32.0	-0.186	-5.940
4	145.33	134.00	-11.33	0.200	0.797	2.331	32.0	-4.207	-134.640

From the above, the following were worth noting:

1. A positive value for QC [kJ] implies inner mould cooling and a negative value implies inner mould heating.
2. For the SC I, the heat exchangers did more of mould heating than mould cooling.
3. For the SC II, apart of test # 4, the heat exchangers were always heating the moulds instead of cooling them.
4. For the Idra dies, the heat exchangers did a mould heating job.
5. Through the lubricating process, a great amount of heat was extracted from the forms and hence have to be reheated by the cooling agent in other to acquire the required mould temperature in preparation for the next shot.

4.3. Convection

Using equation 2.21 in page 36, the amount of heat extracted through convection is shown below in table 4.3.1.

Table 4.3.1: Amount of heat extracted through convection

Variable	Symbol	Unit	SC I	SC II	Idra
Area	A	[m ²]	0.912	0.968	0.912
Form temperature	T _a	[K]	459.2	443.85	430.47
Air temperature	T _u	[K]	303.0	303.0	303.0
Temperature difference	ΔT	[K]	156.2	140.85	127.47
Heat transfer coefficient	α _{conv}	[W/m ² .K]	6.257	6.098	5.947
Cast cycle	t _c	[sec]	32	37	32
Convection heat	Q _{conv}	[Wh]	7.923	8.545	6.146
Convection heat	Q _{conv}	[kJ]	28.525	30.761	22.125

From the SC I, SC II and Idra, 28.52, 30.76 and 22.13 [kJ] of heat was respectively extracted through convection.

4.4. Radiation

Using equation 2.23 in page 37, with a radiated surface emission coefficient (ϵ) of 0.8 and the temperature dependent heat transfer coefficient for radiation (α_{rad}), the amount of heat extracted through radiation is shown below in table 4.4.1.

Table 4.4.1: Amount of heat extracted through radiation

Variable	Symbol	Unit	SC I	SC II	Idra
Area	A	[m ²]	0.912	0.968	0.912
Form temperature	T _a	[K]	4.45E+10	3.88E+10	3.43E+10
Air temperature	T _u	[K]	8.43E+09	8.43E+09	8.43E+09
Temp. Difference	ΔT	[K]	3.60E+10	3.04E+10	2.59E+10
S-B constant	σ	[W/m ² .K]	5.670E-08	5.670E-08	5.670E-08
Average cast cycle	t _c	[sec]	32	37	32
Radiation heat	Q _{rad}	[Wh]	13.251	13.710	9.527
Radiation heat	Q _{rad}	[kJ]	47.703	49.358	34.298

From the SC I, SC II and Idra, 47.70, 49.36 and 34.30 [kJ] of heat was respectively extracted through radiation.

4.5. Required cooling efficiency

Using equation 2.25 in page 38, the total amount of heat extracted from the form during a cast cycle for the different machines is presented below in table 4.5.1.

Table 4.5.1: Total amount of heat extracted [kJ] per cast cycle

Machine	Q _{lub} [kJ]	Q _c [kJ]	Q _{conv} [kJ]	Q _{rad} [kJ]	Q _{ext} [kJ]
SC I	3684.940	-120.898	28.525	47.703	3761.168
SC II	3592.660	-32.509	30.761	49.358	3672.779
Idra	3701.170	-117.315	22.125	34.298	3757.593

Here the heats for the inner mould cooling Q_c , were considered as introduced heats because of their negative values (i.e. inner mould heating instead of inner mould cooling)

Using Sankey diagrams (dig. 4.5.1, 4.5.2 and 4.5.3) below, the average heat flow on the SC I, SC II and the Idra machine are presented.

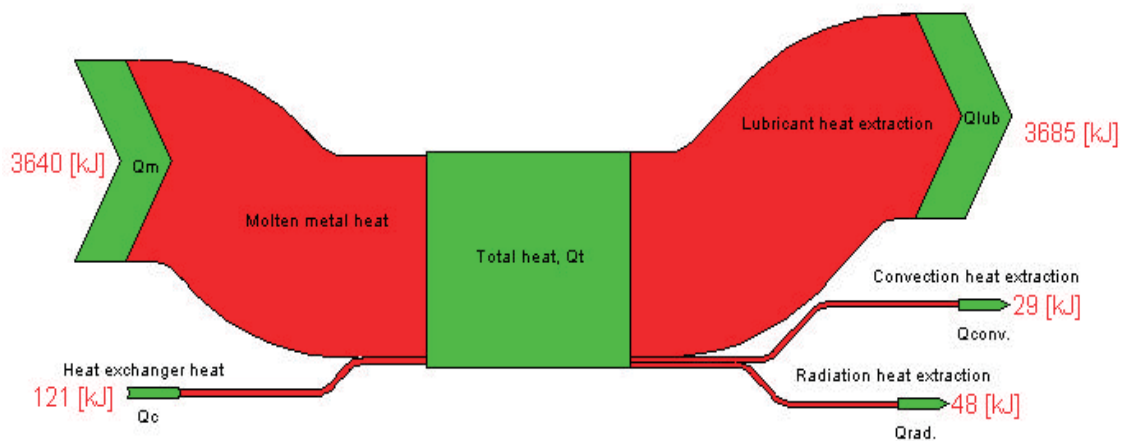


Diagram 4.5.1: Average heat flow on the SC I machine.

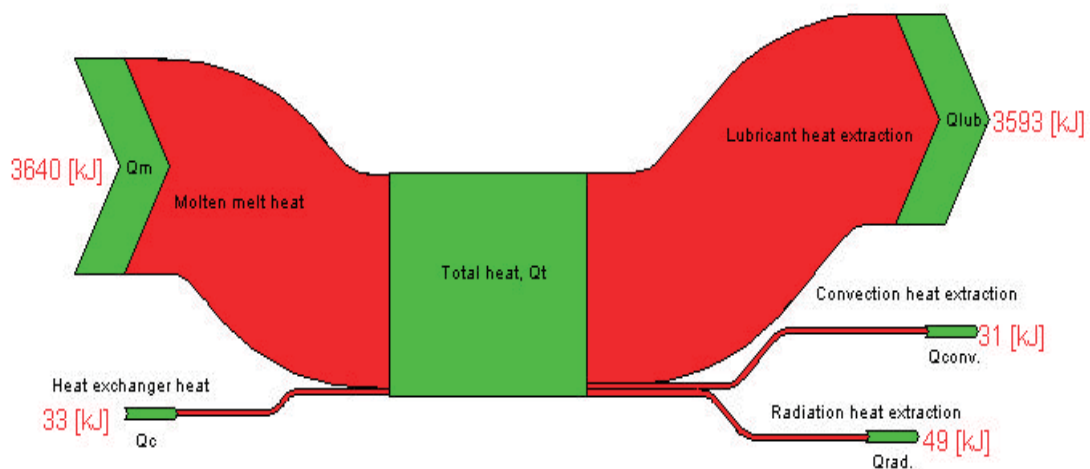


Diagram 4.5.2: Average heat flow on the SC II machine.

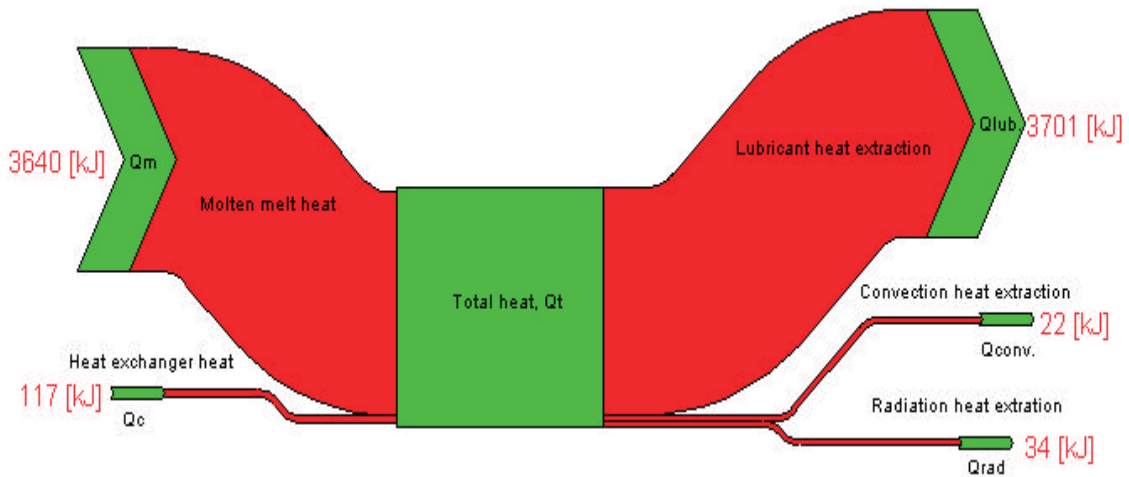


Diagram 4.5.3: Average heat flow on the Idra machine.

Using equation 2.27 in page 39, the total required cooling efficiency for the inner cooling cycle per cast cycle is presented below in table 4.5.2.

Table 4.5.2: Required cooling efficiency for the inner cooling cycle.

Machine	Q_m [kJ]	t_c [sec]	Q_{lub} [kJ]	Q_{conv} [kJ]	Q_{rad} [kJ]	P [kJ]
SC I	3640,270	32	3684,94	28,525	47,703	-3,778
SC II	3640,270	37	3592,66	30,761	49,358	-0,879
Idra	3640,270	32	3701,17	22,125	34,298	-3,666

Low and negative cooling efficiencies were calculated for the inner cooling cycles. This was probably because, a high amount of heat was extracted through the mould surface cooling.

4.6. Quality control

The quality control results for the MB and BMW steering case products are shown below.

Table 4.3.1: Tested cast products quality results

Machine/Product	SC I machine (P661 product)					SC II machine (P672 product)					Idra machine (P661 product)			
	1	2	3	4	5	1	2	3	4	5	1	2	3	4
Test number.	1	2	3	4	5	1	2	3	4	5	1	2	3	4
Amount tested	10	10	10	20	10	10	10	20	15	10	10	10	10	10
Amount OK	8	9	9	16	8	10	9	19	13	9	10	9	10	10
Amount faulty	2	1	1	4	2	0	1	1	2	1	0	1	0	0

Based on the above quality control results, for the cast products tested, the following were calculated and or deducted:

1. Percentage of good/faulty products based on amount tested.

Table 4.3.2 below shows the percentage of good and bad cast products for each test conducted.

Table 4.3.2: Percentage of good and bad products per conducted test

Machine/Product	SC I machine / P661 product					SC II machine / P672 product					Idra machine / P661 product			
	1	2	3	4	5	1	2	3	4	5	1	2	3	4
Test number.	1	2	3	4	5	1	2	3	4	5	1	2	3	4
% ok	80	90	90	80	80	100	90	95	87	90	100	90	100	100
% faulty	20	10	10	20	20	0	10	5	13	10	0	10	0	0

At least 10% faulty products were confirmed during each test conducted on the SC I machine products, compared to the SC II and the Idra

The percentages confirmed using x-ray analyses are shown below in table 4.3.3.

Table 4.3.3: Tested cast products quality control results in percentages

Machine/product	SC I machine / P661 product	SC II machine / P672 product	Idra machine / P661 product
Total amount tested	60	65	40
Total ok	50	60	39
Total faulty	10	5	1
% ok	83.3	92.3	97.5
% faulty	16.7	7.7	2.5

Based on these analyses, the SC I machine produced more faulty products (16.7 %) than the SC II (7.7 %) and the Idra machine (2.5 %) combined.

2. Amount of lubricating substance/lubricating time versus quality of casting:

Generally, the quality of the products had no direct relationship with the lubricating time. They varied from one cast machine to the other. With an average lubricating time of 6.5 sec., for the SC I, 16.7 % faulty products were confirmed. With an average lubricating time of 6.9 sec., for the SC II, 7.7 % faulty products were confirmed and with an average lubricating time of 6.6 sec., for the Idra only 2.2 % faulty products were confirmed.

3. Pressure versus quality of castings:

The SC I with a higher percentage of faulty products also showed a greater range of variation in the operating lubricating pressure (i.e. 0 – 1.6 bars); suggesting the presence of problems along the lubricating process e.g. plugged-up nozzles, fluctuations on the pump performance, etc.)

4. Mould temperature versus quality

With an expected average die temperature of 156°C for the SC I, it recorded the highest average die temperature of 186.20°C and the highest number of faulty products. The Idra on the other hand recorded the lowest, 157.47°C and showed the lowest number of faulty products.

The only individual variation of average die temperature (measured vs. expected) from the tolerable range was recorded on the SC I dies

5. Amount of heat introduced versus products quality

With the assumption that the same amount of heat was introduced into the cast machines from the molten alloy, further calculations revealed that a significantly high amount of heat was further introduced into the SC I from the heat exchangers (121 kJ). This was confirmed by the high average temperature of the dies (186.2°C) and was most likely responsible for the higher percentage of faulty products (16.7 %) observed from the quality control analyses.

5. SUMMARY

5.1. Conclusions

The investigation and analyses of results of this work led to the following conclusions:

1. The optimal amount of lubricating substance used per casting (l/cast cycle) was 1.80, 1.51 and 1.60 for the SC I, SC II and Idra machine, respectively. These corresponded to lubricating times of 6.5, 6.9 and 6.6 seconds.
2. The average temperature of the lubricating substance was 15.4°C.
3. 3640.27 kJ was the average amount of heat introduced into the die machines pro casting, from the molten metal.
4. 3684.94, 3592.66 and 3701.17 kJ was the average amount of heat extracted through surface cooling from the SC I, SC II and the Idra machine, respectively.
5. 120.90, 32.51, and 117.32 kJ. was the average amount of heat introduced into the SC I, SC II and the Idra respectively, by the cooling substance.
6. 28.53, 30.76 and 22.13 kJ of heat was extracted through convection from the SC I, SC II and the Idra, respectively.
7. 47.70, 49.36 and 34.30 kJ of heat was removed through radiation from the SC I, SC II and the Idra, respectively.
8. From the SC I, SC II and the Idra, 16.7 %, 7.7 % and 2.5 % of faulty products were confirmed, respectively.

The following points were of importance for the production of a sound pressure die-casting products.

1. The use of as low an injection temperature as will ensure complete filling of the die cavity.
2. Maintaining a suitable average die temperature free from sharp local temperature gradients
3. Ensuring that the injected metal does not impinge directly upon die surfaces.
4. Employing an injection pressure high enough for a strong pressure pulse to be transmitted through the solidifying casting at the end of the injection stroke.
5. Both inner and surface mould cooling should be ensured.

When these conditions are observed the incidence of porosity, shrinkage voids and surface imperfections are reduced to negligible proportions.

Broadly, defects may have been attributed to:

1. Unsuitable or unsatisfactory raw materials used in casting;
2. The application of unsatisfactory casting practices by the individual worker or incorrect advice by the supervisor;
3. The use of improper tools, equipment, appliances, or patterns; and
4. Unprofessional management policies relating to the fixing of incentive plans and setting up of production procedures, faulty organisation and poor work discipline, or lack of training.

5.2. Suggestions

On the basis of the literature, the experience and results obtained during the pre-experimentation and experimentation phase in the plant, the need for quality improvement was obvious. Quality improvement by definition means, actions taken throughout the organization to increase the

effectiveness and efficiency of personnel, activities and processes in order to provide added benefits to both the organization and its customers.

As such, the following are suggested:

1. Information management:

Optimisation is based not only on collected plant results and experience but also on the availability of correctly and accurately recorded and stored information, and a better and proper information management system through:

- The accurate recording of all information sheets
- Proper storage of information for future reference or use
- The easy retrievability of collected and stored information
- The introduction of information sheets where necessary, e. g. for the heat exchanger.
- Redesigning of some information sheets e.g. cast parameter monitoring form (Giessparameterüberwachungsformula) should include, time, form temperature before and after cooling, tolerances, measures for deviations, etc.
- Information from the lubricating substance plant should include: type, amount, mixing ratio, temperature before and after lubrication for the lubricating substance, pump information for lubricating substance, etc.
- Better and periodic education and training of all (especially operators) in this regards

2. Equipment adjustment and alteration of settings

In industrial processes, the adjustment or alteration of equipments and settings is unavoidable; however the consequences can be devastating if this is not done properly or standard procedures

are not followed. In this regard the following are suggested:

- Standardise equipment settings (e.g. heat exchanger set points)
- Changes on machines should be recorded (date, time, changes made, signature, etc)
- Personnel should be informed accordingly of any new changes in the operations, process, on equipment, etc.
- Minimise if not eliminate, the alteration or adjustment of many parameters at the same time
- Regularly update information sheets (files, hang-outs, original files, etc.)

3. On-line process optimisation:

This should include methods for achieving set values, set-points or reference values with the aim of constantly and continuously improving the process operations.

4. Amount of lubricating substance / Lubricating time:

The lubricating time has a direct relationship on the amount of lubricating substance used per cast cycle and hence the cost of production. With the present lubricating substance mixing ratio of 1:180 maintained, a 6.6 sec. lubricating times can be considered as optimal for the cast machines based on the analyses of the obtained experimental results for an optimised production, performance, product quality and a reasonable cost reduction for the production of the steering cases under investigation.

5. Cooling agent:

Since the heat exchangers were primarily doing a mould heating job instead of a mould cooling job, the following should be considered:

- Altering the heat exchanger set points to ensure cooling rather than heating
- Increasing the heat exchanger oil flow rate
- Increase the heat exchanger cooling water flow rate for better oil cooling
- In a bid to meet production demands (e.g. product quality and amount), instead of altering the lubricating time, it is advisable to alter the heat exchanger settings.

When the above are effected, the amount of lubricating substance per cast cycle can be correspondingly and significantly reduced. Further reductions however, need to be done experimentally.

6. LITERATURE CITED

- [1]. Adby, P.R. , Dempster, M.A.H.: Introduction to optimisation methods, 1. publ.,
Chapman and Hall, London, (1974). p.1 – 4.
- [2]. Alloys: preparation, properties, applications / ed. by Fathi Habashi. -1. ed. - Weinheim;
Wiley-VCH,(1998).
- [3] Verhoeven, J.D. Fundamentals of physical metallurgy, John Wiley & Sons, Inc. (1975). P 223
- [4] Kondic, V. , Metallurgical Principles of Foundding, first publication, London, p. 145-157.
- [5].Spaic, S. ; Proces nastajanja I karakteristike mikrostrukture u livemon stanju, Livarstvo, br. 4,
(1987), p. 99-112
- [6] Schumann, H. ; Metallographie, VEB, Deutscher Verlag für Grundstoffe, Leipzig, (1974)
- [7]. Kurz, W., Lux, B. ; Gerichtet Erstarrung, Z. Metallkunde 63 (1972), P. 509 - 515
- [8]. Böhler handbook
- [9]. Jain, P.L Principles of Foundry Technology, second edition, New Delhi, 1986. p. 109-113,
p. 194-211.

- [10]. Brunhuber, Ernst: Praxis der Druckgussfertigung, 4., Aufl. , Berlin : Schiele und Schön,
1991, S.408-411
- [11]. Aluminium and Aluminium Alloys, edited by J. R. Davies, prepared under the direction of
the ASM International, III. Series, OH, USA, May 1994.p 190-194
- [12]. Klein, F. , Pokora, E. and Leis, W. Schulungskurs, Prozessentwicklung / Herstellung von
Aluminium-Druckgußteilen, Arbeitsgemeinschaft Metallguß, FH Aalen, Deutschland, 2001.
- [13]. Produkt-Datenblatt Nr. 3007.002, Aral Lubricants GmbH, Bochum,1999.
- [14]. VDI – Wärmeatlas, Berechnungsblätter für den Wärmeübergang, Verein Deutscher
ingenieure VDI – Gesellschaft verfahrenstechnik und Chemieingenieurwesen (GVC),
7. Auflage, Berlin: Springer, 1997
- [15]. Anzel, I. ; Magistersko delo, FNT – montanistika, Univerza v Ljubljani, 1992
- [16]. Ref.: Metal Casting Technologies; vol. 45-No 5&6,Focus Australia-Exhibiting GIFA Hall, 14
Booth E23
- [17]. Foseco (F.S.) Limited, The Foseco foundryman`s handbook-facts, figures and formulae, 9th
edition, Tamworth, Staffordshire, Great Britain,1996.
- [18]. Campbell, John: Castings, Butterworth-Heinemann, Great Britain,1991

[19]. Georg Fisher +AG+ achieves

[20]. McAdams, W. H, Heat Transmission, third edition, international student edition, McGraw-Hill Kogakusha Ltd., Tokyo, 1933.

[21]. Poirier, D. R., Poirier, E. J., Heat Transfer Fundamentals for Metal Casting, Second edition, Connecticut, USA, 1993.

List of symbols

ΔG_v	Volume term transformation energy [J/mole]
$-L$	Latent heat [J/mole]
ΔT	Temperature difference [K]
T_s	Solidification temperature [K]
π	Pi
r	Radius [mm]
σ	Specific boundary area energy [J/m ²] is:
$f(\gamma)$	function is dependent of the dihedral angle
γ	Dihedral angle between the underground layer and the solid melt
C_o	Alloy elements concentration [at. %]
C_s	The alloy elements concentrations in the solid state [at. %]
C_L	The alloy element concentrations in the corresponding molten rest [at. %]
k_o	The distribution coefficient at a particular temperature

G	Temperature gradient [K]
M	Liquidus line gradient [K/at. %]
v	Solidification velocity [mm]
v_{ef}	Solidification front growth rate [mm/s]
v_c	Critical growth velocity [mm/s]
v_a	Absolute stability [mm/s]
a_{cr}	Critical radius [mm]
a_c	Critical size [mm]
Γ	Gibbs -Thomson coefficient
T_C	Initial temperature of the melt (casting temperature) [K]
T_S	Alloy solidification temperature [K]
T_P	The average temperature of the cast product during removal from [K] the mould (cast temperature) [K]
m_P	Mass of the cast product [kg]

m_{Ev}	Mass of evaporated water [kg]
m_{lub}	Mass of lubricating substance [kg]
Cp_l	Alloy specific heat in liquid state [kJ/kg K]
Cp_s	Alloy specific heat in solid state [kJ/kg K]
L_M	Alloy specific heat of solidification [kJ/kg K]
C_p	Specific heat [kJ/kg K]
Cp_w	Specific heat of water [kJ/kg K]
Δh_v	Heat of evaporation for water [kJ/kg]
Q_m	Heat of molten melt [kJ]
Q_s	Heat of solidification [kJ]
Q_{lub}	Heat extracted by the lubricating substance through surface mould cooling [kJ]
Q_C	Heat extracted by the cooling agent through inner mould cooling [kJ]
Q_{con}	Heat extracted through convection [kJ]
Q_{rad}	Heat extracted through radiation [kJ]

Q_L	Heat loss [kJ]
\dot{V}	Flow rate [l/s]
α_{conv}	Heat transfer coefficient for convection [$W/m^2 K$]
A	Area [m^2]
ρ	Density [kg/m^3]
ε	Radiated surface emission coefficient
α_{rad}	Heat transfer coefficient for radiation [$W/m^2 K$]

List of tables

Table 2.1.2.1: W300 die specifications [8]	19
Table 2.1.2.2: A comparison of the various material properties for aluminium pressure Casting alloys (based on DIN 1725 Part 2, Feb. 1986) [10]	21
Table 2.1.2.3: Alloy for general use in die pressure casting of P662 and P672 products (DIN EN 1706) [10]	22
Table 2.1.2.4: Properties of the high pressure foundry alloy 226 (AlSi9Cu3) [10]	23
Table 2.3.1.1: Aral Farolin U properties [13]	27
Table 2.3.2.1: P661 moving die half cooling process description [19]	32
Table 2.3.2.2: P661 stationary die half cooling process description [19]	33
Table 2.3.2.3: P672 moving die half cooling process description [19]	34
Table 2.3.2.4: P672 stationary die half cooling process description [19]	34
Table 3.2.1.1: Description of the mould temperature measurement points for the P661 Production [19]	44
Table 3.2.1.2: Description of the moving mould temperature measurement points for the	

P672 production [19] 45

Table 3.2.1.3: Description of the stationary mould temperature measurement point for

the P672 production [19] 45

Table 4.1.1: SCI Lubrication measurement results 51

Table 4.1.2: SCII Lubrication measurement results 51

Table 4.1.3: Idra Lubrication measurement results 52

Table 4.1.4: A comparison of the amount of lubricating substance used on the

SC I machine 52

Table 4.1.5: A comparison of the amount of lubricating substance used on the

SC II machine 53

Table 4.1.6: A comparison of the amount of lubricating substance used on the

Idra machine 53

Table 4.1.7: SC I Lubricating cycle variation-programmed versus measured 55

Table 4.1.8: SC II Lubricating cycle variation-programmed versus measured 55

Table 4.1.9: Idra Lubricating cycle variation-programmed versus measured 55

Table 4.1.10: SC I Lubricating pipe pressure variation 56

Table 4.1.11: SC II Lubricating pipe pressure variation	56
Table 4.1.12: Idra Lubricating pipe pressure variation	57
Table 4.1.13: Lubricating substance inlet temperature	57
Table 4.1.14: Amount of heat extracted by the lubricating substance	58
Table 4.2.1: Cooling substance experimental results for the SC I machine	59
Table 4.2.2: Cooling substance experimental results for the SC II machine	59
Table 4.2.3: Cooling substance experimental results for the Idra machine	59
Table 4.2.4: Measured average form temperature after cooling	60
Table 4.2.5: Expected mould temperature for the form measurement points (after cooling) [19]	61
Table 4.2.6: Measured average mould temperatures for the SC I machine - expected versus measured	61
Table 4.2.7: Measured average mould temperatures for the SC II machine - expected versus measured	61
Table 4.2.8: Measured average mould temperatures for the Idra machine - expected versus measured	62

Table 4.2.9: Amount of heat introduced into the die machine per cast cycle from the molten alloy	62
Table 4.2.10: Amount of heat per cast cycle extracted by the Farolin U for the P661 production using the SC I machine	63
Table 4.2.11: Amount of heat per cast cycle extracted by the Farolin U for the P661 production using the SC II machine	63
Table 4.2.12: Amount of heat per cast cycle extracted by the Farolin U for the P661 production using the Idra machine	63
Table 4.3.1: Amount of heat extracted through convection	64
Table 4.4.1: Amount of heat extracted through radiation	65
Table 4.5.1: Total amount of heat extracted [kJ] per cast cycle	65
Table 4.5.2: Required cooling efficiency for the inner cooling cycle	67
Table 4.3.1: Tested cast products quality results	68
Table 4.3.2: Percentage of good and bad products per conducted test	68
Table 4.3.3: Tested cast products quality control results in percentages	69

List of diagrams

Diagram. 2.1.1.1.a: Schematic view of atoms joining a solid nucleus from the liquid [3]	7
Diagram 2.1.1.1.b: Variation of free energy per atom as it moves from liquid onto solid nucleus [3]	7
Diagram 2.1.1.2.a: Critical size, a_{cr} of the nucleus for thermodynamic stability [4]	8
Diagram 2.1.1.2.b: The effect of undercooling temperature on the critical size, a_c [4]	9
Diagram 2.1.1.2.c: The effect of undercooling temperature on the nucleation rate [4]	9
Dig. 2.1.1.3: Activation energy for: spontaneous and non-spontaneous nucleus building [5]	10
Diagram 2.1.1.4: Surface energy relations affecting the wetting of heterogeneous nuclei by the liquid metal [4]	11
Diagram 2.1.1.5.a: Amount of nucleus and crystallisation influence on the nucleus for a fine grain size [6]	12
Diagram 2.1.1.5.b: Amount of nucleus and crystallisation influence on the nucleus for a large grain size [6]	13

Diagram 2.1.1.6: Micromorphology of crystal growth related to solute concentration and cooling conditions (e. g. v_{ef}).[4]	15
Diagram 2.1.2.1: A die casting machine showing the “cover die” (l) and the “ejector die” (r)	18
Diagram 2.1.3.1: Al-Si alloys - properties and cast structure [4]	21
Diagram 2.2.2.1: Lubricating process during normal production of Mercedes Benz steering cases (P661) [19]	26
Diagram 2.3.2.1: The ROBAMAT heat exchangers during operation (l = back view, r =front view)	31
Diagram 2.3.2.2: Distribution block for P661 moving die half [19]	32
Diagram 2.3.2.3: Moving die half cooling scheme for P661 production.(with A = out, E = in and S = P for pusher) [19]	32
Diagram 2.3.2.4: Distribution block for P661 production stationary die half [19]	33
Diagram 2.3.2.5: Stationary die half cooling scheme for P661 production. (with A = out, E = in and S = P for pusher) [19]	33
Fig. 2.3.2.6: Moving die half cooling scheme distribution block for P672 production [19]	34

Diagram 2.3.2.7: Moving die half cooling scheme for P672 production[19]	35
Diagram 2.3.2.8: Stationary die half cooling scheme for P672 production [19]	35
Diagram 3.2.1: Schematic flow showing the stages in the P661 and P672 production	41
Diagram 3.2.1.1: Temperature measurement points on the moving mould for P661 production [19]	43
Diagram 3.2.1.2: Temperature measurement points on the stationary mould for P661 production [19]	44
Diagram 3.2.1.3: Temperature measurement points on the moving mould side for P672 production [19]	45
Diagram 3.2.3.1: A Mercedes Benz (MB) steering case during visual inspection.	48
Diagram 4.1.1: A comparison of the amount of lubricating substance used on the SC I machine	53
Diagram 4.1.2: A comparison of the amount of lubricating substance used on the SC II machine	54
Diagram 4.1.3: A comparison of the amount of lubricating substance used on the Idra	54

Diagram 4.2.1: Measured average temperature for the form measurement points	
(after cooling)	60
Diagram 4.5.1: Average heat flow on the SC I machine	66
Diagram 4.5.2: Average heat flow on the SC II machine	66
Diagram 4.5.3: Average heat flow on the Idra	67