Analysis of the factors contributing to the heat balance of an high pressure die-casting mould.

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ABSTRACT

The solidification and cooling dynamic of a metal alloy, in macroscopic terms, can be theoretically treated evaluating the different contributions to the heat transfer from the liquid to the mould and the external environment [1].
Resistances to heat flux, coming from the inside of the die-casting, are generally to be traced back to metal solidification, to the die-casting-mould interface and to the mould itself. In the die-casting case the heat absorbed from the external environment and the one removed through lubrication and blow operations cannot be ignored [2-3].

The theoretic and scientific treatment of the heat balance allows us to analyse which are the prevalent factors for heat balance in case of the die-casting process.
Real temperature monitoring and process simulation in working conditions are today the most used methods in order to understand the influence of every single factor. A sensitivity analysis, whether virtual or real, represents the best approach to define which is the contribution of every single factor within a well-defined production cycle or to a specific die-casting component.

KEY WORDS

Die-casting, Mould, Heat balance, Simulation

THE HEAT BALANCE OF A HIGH PRESSURE DIE-CASTING MOULD

In case of **die-casting**, one of the peculiar features, is the achievement of castings characterized by very limited size tolerances (Fig. 1). Such condition is possible thanks to the use of a metallic mould and to the fact that, during solidification (Fig. 2), the metal cannot shrink freely as forced, by the applied pressure, to adhere to the die surfaces.

The die plays an important role within the productive process and it is evident that the knowledge of the factors contributing to the die heat balance is necessary and useful for a proper equipment design.

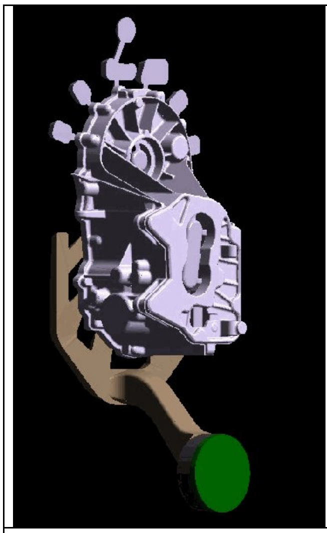	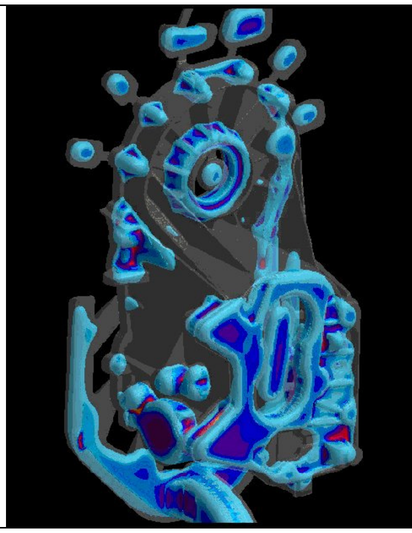
Fig 1. Geometry of a die-casting	*Fig. 2 Solidification of a die-casting*

The numerical approach to the energy balance, in case of permanent mould casting more than in high pressure die-casting, and the analysis of positive and negative thermal contributions are so important to deserve a detailed treatment with the support of the results achieved through process simulations. (Fig. 1 and Fig. 2).

The heat input due to the die-casting is absorbed by the mould mass, but its thermal regime does not only depend on its volume, but also on other factors, such as the presence of thermal regulation channels, coatings application on the surface (lubricants, paints, etc.) and the emission towards the external environment. (Fig. 3)

The balance expresses the mould temperature rise (with mass M and specific heat Cp), from the starting temperature Ti and the final temperature Tf, as a function of the difference between the latent heat and the heat losses, due to cooling channels, to the lubrication of the mould surface and to the external environment.

$$M \times Cp(Tf - Ti) = CaloreLatente - asport.\mathrm{lub}rifica - asport.circuiti - asport.esterna$$

The continuative production with a permanent mould aims at minimizing the cycle time that, from the thermal point of view, fixes the frequency of the thermal oscillations.
The production start-up is affected by thermal pulses to each cycle with temperature values that tend, in the same points, to rise up to the reaching of a stable and repetitive situation; the

thermal regime can be then defined as that state in which the temperature, in a generic point at the end of the cycle, coincides with the one at the beginning of the cycle (Fig. 4).

The statement is clearly valid with reference to any instant of the single working cycle, therefore the maximum or minimum temperature value will be reached in the intended point always at the same time.

In case of die-casting, the maximum value of the mould surface heat is obtained when the injected alloy has reached a 70-80% solidification, while the minimum one after the lubrication phase (Fig. 4).

From a general estimation, it may be considered that the 80% of the heat is absorbed by the die and the thermal regulation circuits, the 15% by the lubricant application and the remaining 5% by the external environment. Such percentages vary as a function of the cycle time, that, due to the intended high productivity is quite limited; for instance the lubricant contribution, under the same conditions, can raise from a 15% up to a 50% if the total cycle time has a 30% reduction.

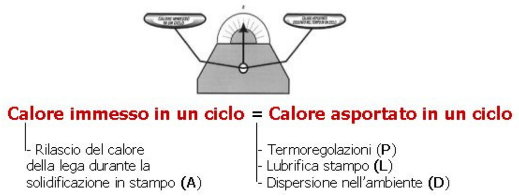

Fig. 3 Factors for the die heat balance

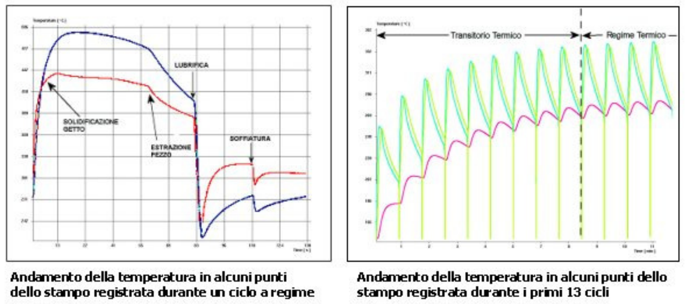

Fig. 4 The condition of the die thermal regime

The heat that the alloy releases is handed over in three different phases: liquid cooling (from the casting temperature to the liquid temperature), the transformation phase from liquid into solid (latent heat) and the final cooling from the solid temperature to ambient or ejection temperature. A numerical analysis, taking into account 1 Kg of aluminium alloy, makes clear that the main contribution is provided by the latent heat ranging at 430 kJ/kg, being about the 50% of the total heat (Fig. 5).

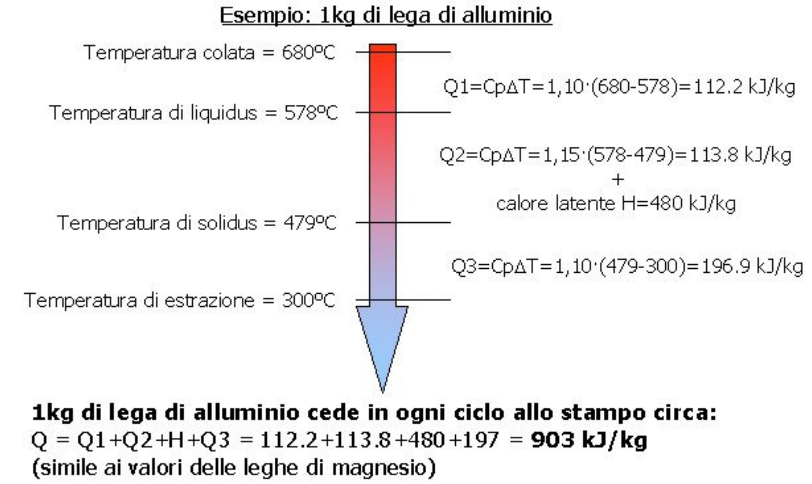

Fig 5. Released heat from one Kg aluminium alloy

The average working temperature of the die refers to the end of the cycle, with values ranging from 200 to 300 °C, and normally guarantees a good cavity filling and a quick and uniform cooling of the casting.
During the die pre-heating phase or when starting up a new production (Fig. 7), besides the production rejects, considerable thermal shocks may take place, leading also to surface cracks, which then grow due to the thermal fatigue in the following production phases.

The die heat balance is not so easy to be predicted and therefore the theoretical design is initially based on the search for the best compromise, taking into account the effects of a too high or too low mould temperature. In the first case the presence of high pressure deformations and soldering can cause a difficult ejection, the surface layer of the lubricant-separator tends to a quick lowering, when the mould tear and wear increases; the cycle time draws out and the size instability of the component may show considerable shrinkage porosities.

In the second case, the die lowering is due to high thermal gradients with the subsequent difficult ejection of the casting, that shrinks around core pins and lug bolts. The risk for cold shuts is much more present and cavity lacking fillings may take place. By the end of the filling routine, the casting temperatures aren't generally uniform in relation to the subsequent casting deformation after the ejection.

The natural loss towards the external environment is due to the following three phenomena:

- Loss for convection outwards which principally depends on the die area and on the temperature gradient between die and environment.
- Loss for radiation outwards which principally depends on the material emissivity and on the die temperature, as well as on how broad the die surface is.
- Loss for conduction towards the coldest layers of the machine the die is in contact with.

The following figure (Fig. 6) shows the temperature-time curves of some virtual thermocouples located at different depths with relation to the mould surface: the thermocouple n.1 reaches "under the skin" high values in a short time, follows the casting cooling and is influenced by the drastic heat loss of the lubrication phase; the disturbances have a lower effect at a depth of 5, 10 and 15 mm (thermocouples 2, 3 and 4 respectively) because of the die thermal inertia.

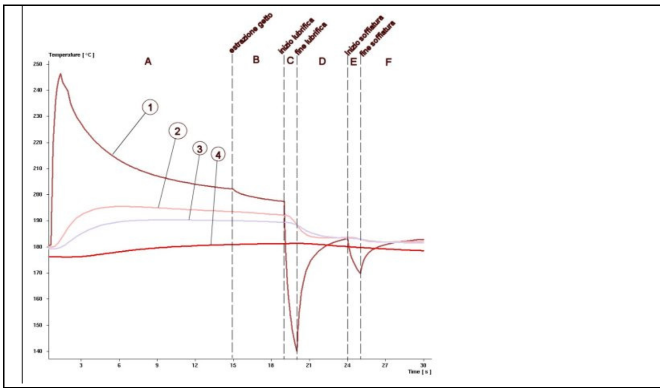

Fig. 6 The evolution of the temperature acquired by thermocouples located closet o the die surface

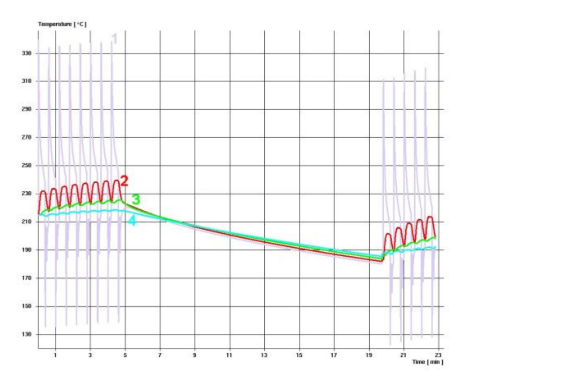

Fig. 7 Effect due to production interruption

The application of the lubricant implies a considerable thermal loss due to the difference in temperature between the active part of the die and the lubricant working fluid.
From the thermal point of view, several are the factors determining the flux of lost heat during spraying with the lubricant: vector temperature, mould temperature, air pressure, medium

pressure, distance from the surface, angle of impact with the surface, application time, concentration and chemical composition of the lubricant.

Practically, once the system and the kind of lubricant have been chosen, the main remaining variables are the time and the angle of impact; while the first can be managed by the operator, the suitable angle of impact (90°) is not easy to be achieved, in case of complex geometries formed by very deep cores and die "holes".
Different local temperatures on the die surface suggest a diversified application to better control, if using the most common water lubricant, the four cooling conditions, experimentally identified as functions of higher and higher thermal gradients between the die and the lubricant:

- For ΔT low values between die and liquid, the lubricant drops adhering to the die surfaces generate a limited heat loss for convection.
- If ΔT increases, the working vector generates a higher thermal loss, when it hits the die hot surface and tends to evaporate.
- The evaporation phase becomes more and more important if the ΔT is even higher; the convection is reduced implying a reduction of lost heat.
- When the temperature ratio between the mould and the lubricant is considerable, the working vector instantly evaporate and the heat loss increases.

The four above-mentioned situations analyse this phenomenon only from a thermal point of view, neglecting the thermo-chemical elements influencing the stratification of the protective deposit and therefore the lubricant and release properties of the application.

The following figure (fig. 8) shows the temperature distribution on a high pressure die-casting mould, before and after the release agent application: the thermal effect is not visible in depth and it is different according to the initial surface temperature.

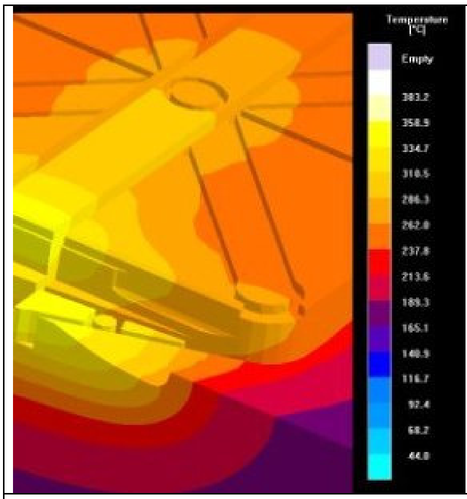

Fig. 8 Surface temperature before die lubrication

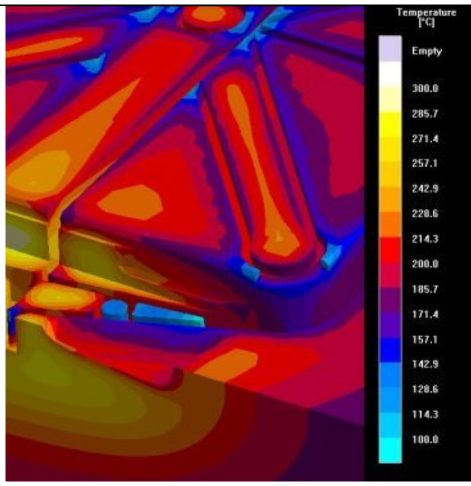

Fig. 9 Surface temperature after die lubrication

The thermal effect of the following blow phase is similar: the air that flows in pressure towards the die surfaces generates a softer heat loss than the lubrication.
It is therefore clear that the mould heat balance strongly depends on the surface lubrication phase and the strong heat loss is the main reason for surface cracks.

Through a little variation of the lubrication time (for instance, from 4 to 1 second, on average), as shown in the following figures (Fig. 10 and Fig. 11), it is possible to change the average working temperature of the die but, above all, the thermal oscillation, which could be critical in view of the fatigue strength is reduced (a 50% reduction going from 74 to 38 °C).

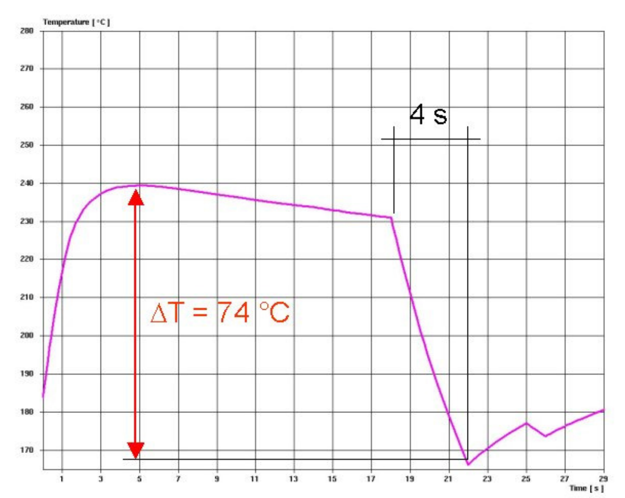

Fig. 10 Surface thermal drop due to di lubrication

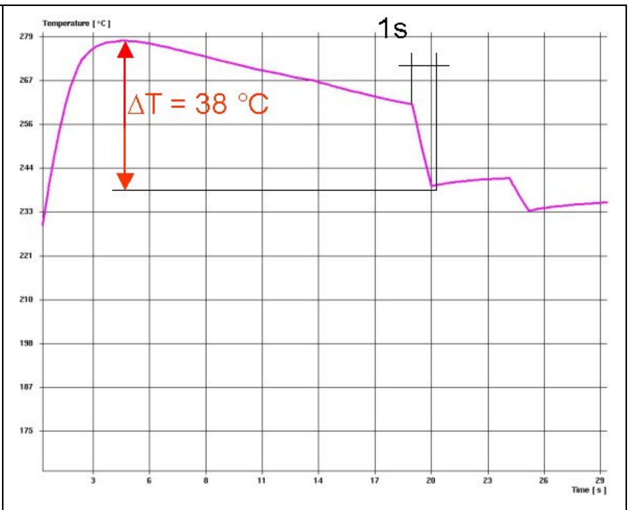

Fig. 11 Surface thermal drop due to die lubrication with reduction of time application

As previously mentioned, the inner thermal regulation channels (Fig. 12 and Fig. 13) are charged with the thermal regulation of the die, making the temperature distribution stable and uniform. Water remains the cheapest and more widely used means, when a stronger cooling of the casting is required (Fig. 13).

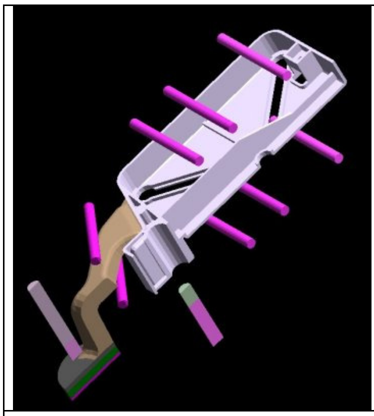

Fig. 12 Thermal regulation system scheme

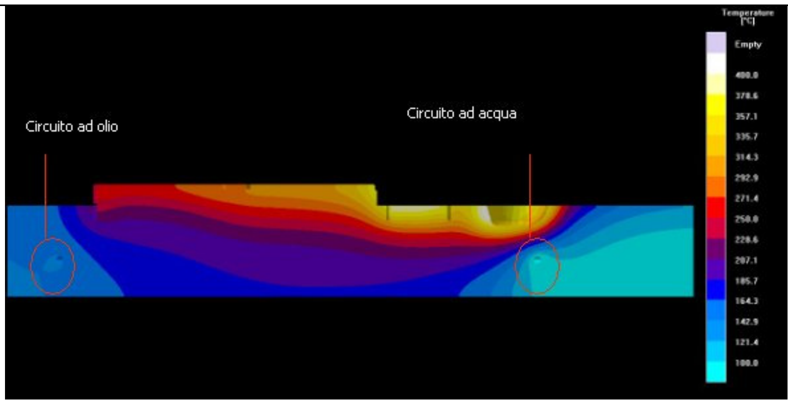

Fig. 13 Thermal effect of a water circuit and of a oil one

CONCLUSIONS

The list of the factors contributing to the die heat balance is well known, starting from the principal heat source (the cooling metal) to the main means for heat loss (mould and lubricant application).
It is not so easy to assign them a general contribution percentage to the heat balance, to be valid for any casting and any cycle time. The product-process-mould combination needs to be accurately analysed by the designer and requires an effective control in the production phase.

The monitoring of the working temperature of the steel permanent mould is an essential task to be performed for a suitable use of the tools and for their maintenance. Thermocameras or infrared sensors are practical and user-friendly tools in foundry. In order to obtain an ongoing and methodical detection, some fixed thermocouples may be placed in the most important points of the die and it would be possible to control the cooling channels switching on and off automatically, as well as the single phases of the productive process (filling, solidification, opening, ejection) establishing the limits that guarantee the casting quality.

In the design phase, when the tools haven't been physically produced yet, the process simulation by using the MAGMASOFT software [3-5], provides a useful help to analyse the heat balance. The numerical approach is already well-founded and allows to search for new solutions or to test new materials and methods for the release agent deposition/coating.

BIBLIOGRAPHY

1) C. BONACINA, A. CAVALLINI, L. MATTAROLO, " Trasmissione del calore" , Cleup editore
2) L. ANDREOLI, M. CASE', G. POMESANO, " Quaderni della colata a pressione delle leghe di alluminio" – Edimet
3) F. BONOLLO, N. GRAMEGNA, S.ODORIZZI, "La pressocolata delle leghe di alluminio: simulazione numerica del processo", Edimet
4) N. GRAMEGNA, C. MAGISTRETTI, "Tecniche di prototipazione virtuale applicate alla progettazione di componenti di design", High Tech Diecasting – 21-22 April 2004 – Montichiari (Brescia) – Italy
5) N. GRAMEGNA, "Aspetti operativi per lo svolgimento delle simulazioni di processo", ALUMOTIVE 2005, Modena