AN ANALYSIS AND COMPARISON OF PROPERTIES OF AL-SI ALLOY AUTOMOTIVE CASTINGS MADE BY RAPID PROTOTYPING AND STANDARD LOT PRODUCTION

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Summary: The use of rapid prototyping for the manufacture of prototype castings assumes that the properties of a prototype will be similar to the properties of parts obtained in standard lot production. This refers to both gravity and pressure die casting processes. However, different conditions of metal treatment, pouring and solidification, specifically related with the piece production of castings by rapid prototyping as compared to the lot production, generate different final properties of the cast elements. This is of particular importance in pressure die casting. In this process, the effect of an additional parameter, i.e. pressure, acting on the solidifying metal changes in a fundamental way the solidification conditions due to changes in the Al-Si equilibrium diagram. The article presents the results of comparative studies made on selected castings manufactured in lot production and by the methods of rapid prototyping.

Key words: prototype castings, additional parameter, lot production, rapid prototyping.

INTRODUCTION.

Casting is a technological process by which various objects are formed in liquid metal, poured into a foundry mould, which reproduces the shape of the manufactured object. When the liquid metal undergoes the process of cooling and solidification, the casting properties are formed. The use of aluminium castings in modern industry means always more stringent requirements regarding final casting properties, dictated by the thin-wall or "lean" casting design, introduced mainly to reduce the casting weight to an indispensable minimum. The automotive industry tries by all posible means to reduce the weight of vehicles, since lower weight means less of CO, emissions escaping to the atmosphere [1]. It is estimated that 50% of the fabricated aluminium castings are used by automotive industry, and so they form an important cost component in the overall process of the manufacture and operation of both civil and military mechanical vehicles. To develop new designs, it is necessary to make prototypes (pilot patterns) of castings, including also parts usually manufactured by piece production. The typical parameters in the production of prototypes are small lots, intricate shapes, and short lead times. To comply with these requirements, special manufacturing methods are developed [2]. The lot production of castings on a die casting machine requires the use of very expensive tooling. Making a die is profitable only when the annual production amounts to approximately 20,000 pieces [3], while in the manufacture of prototypes the required number of castings hardly ever exceeds 100 pieces. For this reason, the technologies of making prototype castings must differ from those commonly used in lot production, and in most cases they are based on the techniques of rapid prototyping. Rapid prototyping is also suitable for the production of pattern tooling. A review of technologies used nowadays by the leading world companies to make prototype castings shows the three processes that seem to be most popular in this respect :

- investment casting;
- casting into sand moulds;
- casting into plaster moulds.

In the majority of cases, large lots of aluminium alloy castings for automotive applications are poured in metal moulds. Generally speaking, there are two techniques of making castings in metal moulds. The first process consists in free, gravity-induced flow of metal through the previously designed gating system (gravity die casting), while in the second process, the metal is forced into a die under high pressure, which enables a very precise reproduction of the casting configuration and making thin-walled elements of the wall cross-sections amounting to, e.g., 1 mm (pressure die casting). The time necessary for a mould to be filled with molten metal differs in both cases quite considerably. While in the case of gravity die casting, it is from 3 to 20 seconds and depends on the casting size, in pressure die casting it takes only 0,05 second to fill the die cavity completely. So great difference in the mould filling time must influence the casting solidification and cooling process. This is important, since final properties of a casting will greatly depend on the solidification rate. The casting regions solidifying for a longer time are characterised by a coarse-grain microstructure, which results in reduced mechanical properties. Additionally, in gravity die casting, the specific solidification regime creates some regions in the cast object that are particularly susceptible to the occurrence of shrinkage porosity defects (the hot spots mainly). To eliminate these defects, risers prolonging the time of solidification are commonly used, and this also tends to reduce the casting strength in this particular area.

On a selected example, this article shows differences in the final properties of castings manufactured by lot production and rapid prototyping (piece production).

THE RESEARCH.

Studies to determine and compare the properties of castings manufactured in lot production and by rapid prototyping were carried out on selected specimens made by two variations of the die casting process. Figure 1 shows the casting of a cover, the process of its manufacture, and the die design.



Fig. 1. The casting of a cover, its manufacturing technology and die design



Fig. 2. The successive steps of metal injection into a die

For this system, the simulation covered the metal injection stage and casting solidification, allowing for the final casting properties, strength included. Investigations have proved that the values of strength were distributed evenly within the whole casting volume in a range of up to 230 MPa (Fig. 4 a). The even distribution of properties is a characteristic feature of the pressure die cast parts. In this process, the metal is injected into the die (Figure 2) at a velocity of 2000 cm/sec. The very short time of the die filling with metal (in the case under discussion amounting to 0.05 sec) makes casting solidify rapidly within the whole of its volume. Due to this, the primary nuclei of the solidifying metal have no time to grow, and casting has a fine-grained structure. This type of structure has a significant effect on the casting properties. The strength of a fine-grained structure is higher than the strength of the structure in which the grains are free to grow. The grain boundaries are of nearly rounded shapes, which promotes uniform stress distribution and helps to avoid local stress concentrations.



Fig. 3. Effect of casting cooling rate on the severity of microporosity defects in castings [4]

The examined solidification rate affects the size of the gas-induced microporosity, if it happens to occur in the casting structure. The high rate of casting solidification blocks the passages by which the free gas bubbles can escape from casting. In a similar way, the high rate of the casting cooling promotes the growth of dendrites, inside which the gas bubbles may get locked. Higher cooling rate increases the percent share of porosity in casting microstructure [4]. The currently done investigations interrelating the casting solidification rate with gas porosity occurrence in aluminium alloys [5] enable the gas microporosity size and distribution in casting to be determined from the solidification rate in a given casting region. In the numerical analysis of microporosity distribution in pressure die castings, the adverse effect of solidification rate on the microporosity level is well visible. The results of the simulation indicate that in the middle part of casting the severity of microporosity can reach even 5 % (Figure 4 b).



Fig. 4. Properties of pressure die castings a) strength, b) microporosity



Fig. 5. Microstructure of the examined pressure die casting (200x, unetched)

The metallographic examinations of the pressure die casting shown in Figure 5 confirm the presence of a fine-grained structure with very fine (acicular) silicon precipitates visible against the background of eutectic. The photograph also shows the presence of gas microporosity. The microporosity assumes the shape of rounded nodules, which mitigates to some extent its adverse effect on the casting strength properties, reducing the risk of occurrence of the micro-notches, i.e. of the regions that are acting as potential crack-initiating sites.

At further stage of the investigations, the cover was made as a prototype casting. The process of casting in a ceramic mould was chosen. The operation of mould preparation for the investment casting of prototype element consisted of several stages. Using a model drawn in 3D system, a physical pattern of the casting was made from an ABS material on a prototype device. The examined pattern was made by an FDM (Fused Deposition Modeling) technique at the Designing and Prototyping Centre of the Foundry Research Institute in Cracow. It was next used as a master pattern for the silicone resin mould, into which the wax was poured to form after solidification the proper pattern of a casting. The wax patterns were next joined together into a cluster and coated with several layers of the ceramic slurry. After melting out the wax in a high-pressure autoclave, the cluster was baked at a temperature of 900°C for about 8 hours. Figure 6 shows individual stages of the ceramic mould making process for the manufacture of prototype castings by a rapid prototyping technique.

Model 3D w systemie	Budowanie przyrostowe	Wykonanie formy
CAD	modelu na urządzeniu	silikonowej z
	RPS	zbudowanego modelu
Wykonywanie modeli	Wykonanie zestawu z	Wykonanie formy
woskowych	modeli woskowych	ceramicznej i jej
		wypalenie

Fig. 6. Schematic diagram of the ceramic mould manufacturing process by rapid prototyping system

While using ceramic moulds it was decided to keep the shell thickness at the level of 8 mm. The simulation allows for the heat radiation effect from mould surface. This effect is important since, contrary to sand moulds, it is not possible to assume in calculations an unlimited mould wall thickness and neglect the effect of environment on the casting solidification process. For pouring, moulds of the self-supported type were prepared. The following parameters of the process of making a prototype casting of the cover were assumed: pouring temperature -740° C, initial mould temperature $- 450^{\circ}$ C, pouring time - 5 seconds, heat transfer coefficient HTC (dependent on temperature) - from 400 to 1000 W/m²K.

The computer simulation of the process of making castings of a cover in ceramic moulds shows that the properties of raw prototype castings, i.e. of castings without heat treatment, differ considerably from the die casting properties. This statement is particularly true in the case of strength, which in castings poured in ceramic moulds does not exceed 150 MPa, as shown in Fig. 8c.



Fig. 7. The successive operations of the gravity pouring of ceramic mould



Fig. 8. Properties of castings made in ceramic moulds at a starting mould temperature of 450° C : a – porosity, b – SDAS, c – yield strength R₀₂, d – microporosity, e –temperature distribution in castings

Lower strength of castings made in ceramic moulds reflects the type of structure formed in the cast element. The characteristic parameter determining the structure refinement degree, i.e. the secondary dendrite arm spacing (SDAS), is at the level of 43 to 50 micrometers, as shown in Figure 8 b. The structural examinations of the prototype casting fracture confirm the presence of large eutectic grains and silicon precipitates (Fig. 9), absent in the structure of pressure die castings (Fig. 5). Because of the lower rate of mould cooling, and hence lower rate of casting solidification, a reduced level of microporosity is observed, in accordance with the relationship shown in Figure 3. The microporosity shown in Figure 8d does not exceed 1 %. In pressure die castings it was at the level of 5 to 7 %. The same investigations were also made for the initial mould temperature reduced to 150° C.



Fig. 9. Microstructure of the examined prototype casting made in ceramic mould (200x, unetched)



Fig. 10. Properties of castings made in ceramic moulds at the starting mould temperature reduced to 150° C: a – porosity, b – SDAS, c – yield strength R₀₂, d – microporosity, e – temperature distribution in castings

The results of the simulation shown in Figure 10 indicate the strength values increased to the level of 190 MPa (Fig. 10 c). On the other hand, the casting also shows an increased level of porosity and microporosity (Figs. 10 a and 10 d, respectively). In spite of the satisfactory strength levels, the increased porosity may cause a lack of tightness in casting during its performance.

SUMMARY AND CONCLUSIONS.

1. A comparative analysis of the properties of prototype castings made in ceramic moulds and pressure die castings made by lot production enabled the technological process parameters on which the casting properties depend to be determined.

2. In the ceramic mould technology, the important parameters of the ceramic mould pouring process are the temperature of pouring and the initial mould temperature.

3. The high temperature of the ceramic mould reduces casting strength, but it also reduces the shrinkage porosity and microporosity, including the gas-induced porosity.

4. The strength of aluminium castings made in ceramic moulds can be improved by heat treatment (solutioning and ageing).

5. The use of numerical computations in an analysis of the prototype casting technology enables a more precise determination of the final casting properties and shaping the technological parameters in such a way as to obtain the required casting parameters.

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ANALIZA WŁAŚCIWOŚCI ODLEWÓW ZE STOPU AL-SI PRZEZNACZONYCH DLA PRZEMYSŁU MOTORYZACYJNEGO WYKONYWANYCH METODAMI SZYBKIEGO PROTOTYPOWANIA W PORÓWNANIU Z ODLEWAMI OTRZYMA-NYMI W PRODUKCJI SERYJNEJ

Streszczenie. Stosowanie różnych metod szybkiego prototypowania do wykonywania odlewów prototypowych zakłada, iż właściwości takiego odlewu są zbliżone do odlewu otrzymanego w produkcji seryjnej. Dotyczy to zarówno odlewania kokilowego jak i ciśnieniowego. Jednak inne warunki przygotowania metalu, zalewania, procesu krzepnięcia, związane z specyfika wykonania odlewu jednostkowego z zastosowaniem metod szybkiego prototypowania, w porównaniu z produkcją seryjną generują odmienne, końcowe właściwości. Ma to duże znaczenie szczególnie w odlewach ciśnieniowych, w których proces krzepnięcie ze względu na dodatkowy parametr - ciśnienie jakim poddawany jest metal w sposób zasadniczy zmienia warunki krzepnięcia. Zmienia się bowiem wtedy układ równowagi stopów Al.-Si. Poniższy artykuł przedstawia wyniki badań porównawczych wybranych odlewów wykonywanych w produkcji seryjnej i otrzymanych z zastosowaniem metod szybkiego prototypowania.

Slowa kluczowe: odlewy prototypowe, dodatkowy parametr, produkcja masowa, szybkie prototypowanie.