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Quality of automotive sand casting with different wall thickness from progressive secondary alloy

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Abstract
This paperwork is focused on the quality of AlSi6Cu4 casting with different wall thicknesses cast into the metal mold. Investigated are structural changes (the morphology, size, and distribution of structural components). The quantitative analysis is used to numerically evaluate the size and area fraction of structural parameters (α-phase, eutectic Si, intermetallic phases) between delivered experimental material and cast with different wall thicknesses. Additionally, the Brinell hardness is performed to obtain the mechanical property benefits of the thin-walled alloys. This research leads to the conclusion, that the AlSi6Cu4 alloy from metal mold has finer structural components, especially in small wall thicknesses, and thus has better mechanical properties (Brinell hardness). These secondary Al-castings have a high potential for use in the automotive industry, due to the thin thicknesses and thus lightweight of the construction.

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1. Introduction

Aluminum cast alloys are a widely used material in the engineering industry, mainly due to their excellent combination of mechanical, tribological, and corrosion resistance properties. The dominant type in the production of automotive castings is Al-Si-Cu alloy, with various combinations of silicon, copper, and other alloying elements including magnesium and zinc. The alloys are hypoeutectic (exceptionally eutectic) with a content of 6 to 13% Si and 1 to 5% Cu. The addition of silicon maintains lower melting temperature and at the same time increases the melt fluidity. This is the most important factor in ensuring high-pressure die casting (HPDC) productivity. The presence of copper in these alloys contributes to better strength, hardness, and improves machinability and thermal conductivity. It also significantly increases heat strength up to 200 °C by the Al_2Cu intermetallic phase or the eutectic (Al + Al_2Cu) phase. The alloy has a very low tendency to shrink and heat crack. The corrosion resistance is affected by the Cu phase (inter-crystalline corrosion tendency) but is sufficient for castings in the automotive industry (Fiocchi, 2020; Kaufman, 2004; Kasińska, 2020; Reyes, 2020; Roučka, 2004; Tillová, 2004).

Moreover, in many countries, is research focused on making wrought aluminum alloys using scrap aluminum recycling technologies, as recycling has become a very important part of the sustainable development of an advanced industrial society from an economic, technical, and ecological point of view. Recycling of aluminum scrap is characterized by a great benefit in electricity consumption, where up to 95% of the electricity needed to produce primary alloys is saved. The main purpose is to save a significant amount of energy, which is an important aspect of environmental management. With regard to electrical power, it takes approximately 750 kWh to melt aluminum scrap to produce one metric ton of aluminum, which is nearly 20 times less energy than it takes to make primary aluminum. Not only saving energy consumption but also 85% less CO_2 emissions are produced and also can save up the usage of chemical products in comparison to primary aluminum production. The result of recycling is possible contamination of secondary alloys with impurities and trace amounts of chemical elements. During recycling resp. remelting some elements such as Fe, Cu, Mg, Mn, Zr, Cr coexist as unwanted impurities causing segregation and intermetallics, the morphology of which affects the casting quality and strength properties of cast alloys (Kasala, 2011; Reyes, 2020; Tillová, 2004).

The presence of iron content, even in a small content leads to degradation of mechanical properties such as strength, ductility, fatigue, etc. Although iron is highly soluble in liquid Al- and its alloys, the solubility of iron in solid α-phase is very low. Therefore, most of them form intermetallic phases. The effect of Fe-rich phases on the mechanical properties of aluminum alloys is usually determined by their type, size, and quantity in the microstructure. The iron content usually causes so-called Chinesescript α-$Al_{15}(Fe.Mn)_3Fe_2$ and the plate-like ß-Al_5FeSi intermetallic phases. The most common Fe-phase is the β-Al_5FeSi in a plate-like morphology and needle-like in cross-section. This phase is characterized by a very high tendency to corrosion, is very brittle but hard. Moreover, the plate-like β-Al5FeSi cause an expansion in pore sizes, even though the platelets also limit pore growth (Bacaicoa, 2019; Castro-Sastre, 2021; Ji, 2013; Kasala, 2011; Kuchariková, 2018; Mahta, 2008).

To sum up, the Al-Si-Cu alloys are among the most frequently applied non-ferrous HDPC alloys. As mentioned, these alloys have wide application in the automotive industry, especially used for engine components, motor mounts, gearbox housings, cylinder heads, filter housings, generator housings, etc. The properties of all the aforesaid castings are different. In the production of castings, it is necessary to take into account the metal composition, casting quality, initial mold temperature, mold shape and size, mold wall thickness, and the material from which the mold is made. This also affects the structure in which can change: fineness, silicon morphology, matrix content (DAS, SDAS-factor), amount and shape of intermetallic phases, and the occurrence of defects. Unfortunately, these alloys are susceptible to extensive porosity, especially in castings with decreasing solidification rates in sand molds. In contrast to casts from sand molds, alloys cast into metal molds can quickly solidify and refine dendritic cells due to their excellent heat dissipation ability. The disadvantage is that cast components produced in metal molds are usually more ductile than those made in sand molds (Davor, 2019; Fiocchi, 2020; Kasala, 2018; Mae, 2008; Reyes, 2020).

Additionally, the usage of structural castings with thinner walls, which also are known to resist filling and feeding during the casting, is required for the lightweighting of components. While thin-walled aluminum castings can be made using die-casting or low-pressure casting all larger and complex thin-walled castings of high-temperature alloys still require gravity casting. To achieve excellent thin-walled castings the features must be completely filled and sufficiently fed during solidification. Thin-walled structures are exposed to severe rates of cooling and dendritic growth during the casting process. Because of the fast formation of the dendritic structure, the flow of the melted alloy in these features is prohibited shortly after pouring. If the interdendritic melt's solidification shrinkage is not supplemented, micropores will form. The mentioned process is relevant to features such as dendritic morphology and the density of the dendritic network, and also solute distribution (Li, 2015).

Therefore the aim of this work is to study the quality of thin-walled castings made from secondary AlSi9Cu4 alloy with higher Fe content cast into the metal mold.

2. Experimental material and procedures

As an experimental material was used hypouetectic casting secondary alloy AlSi6Cu4, supplied by company Confal Ltd., delivered in the form of ingots and weight from 5 to 7 kg with dimensions 610 x 85 mm – Fig. 1. The chemical composition according to the delivery list is shown in Table1.

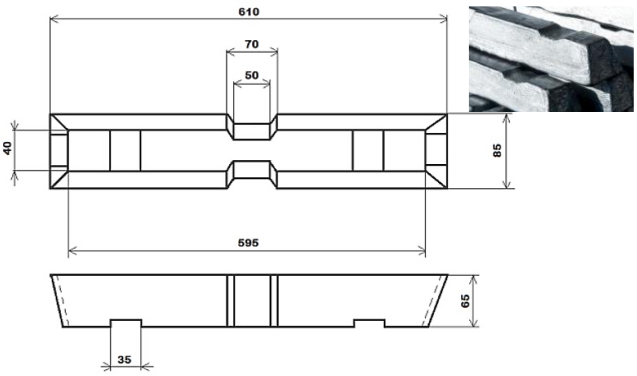


Fig. 1. Supplied experimental material in form of ingots

Table 1. The chemical composition according to the delivery list from Confal Ltd. [wt. %]

Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti
6.34	0.449	3.21	0.490	0.219	0.0249	0.0283	0.610	0.180

The delivered ingots were cast into a metal mold by gravity casting method from which castings with different wall thicknesses were cast, see Fig. 2.

Fig. 2. AlSi6Cu4 step-casting from the metal mold

In general, ingots were melted in an electric resistance furnace in the graphite melting-pot with a protective coating. The molten metal temperature was measured with a DMT 1550 thermometer using a NiCr-Ni thermocouple. The melt was refined with AlCuAB6 refining salt before casting and then were cast into metal molds at a temperature of 720 ± 5°C. The size of the individual casting steps for the metal mold was given on the basis of the use of a standardized metal mold (sorted from the smallest to the largest): 2 mm, 3 mm, 5 mm, 6 mm, 8 mm, and 15 mm.

3. Experimental procedures

Samples for metallography evaluation were cut from the middle part of each individual casting step using an MTH MICRON 3000 automatic saw. The samples preparation was followed by wet grinding on rough and soft grit sandpaper on a Tegra System from Struers. After grinding, polishing was performed to obtain a flat surface without the presence of scratches from previous operations. After each operation, the samples were rinsed with water, ethanol and then dried with hot air. Prepared samples were etched with Dix-Keller of 0.5 % HF etchant to produce a black and white contrast.

Quantitative analysis was performed by using image analyzer NIS Elements to evaluate structural components numerically connected on the NEOPHOT 32 optical microscope. The evaluation consisted of measuring the average distance of the dendritic arms of the α-phase, the average area size of the eutectic Si particles, and the average area of the intermetallic phases. The resulting average values were calculated from a minimum of 40 measurements.

Metallographic evaluation of the microstructure was also performed on the VEGA LMU II scanning electron microscope (SEM) due to better identification of structural components. The individual structural components were identified on the basis of their morphology, followed by the use of EDX analysis (energy dispersive analysis), which is a chemical microanalysis used to determine the qualitative composition of the sample (Reyes, 2020).

After metallographic evaluation, the Brinell hardness test (STN EN ISO 6506-1) was performed on the experimental material and measured six times on each wall thickness of the casting. The resulting values were averaged. For measuring was used: load at 62,5 kp = 612.916 N, dwell ball with diameter 2.5 mm and time 10 s.

4. Results and discussion

Microstructure observation on NEOPHOT 32 light microscope confirmed that the delivered (Fig. 1) experimental material is a hypoeutectic AlSi6Cu4 cast alloy. The metallography evaluation of delivered ingots shows that the microstructure consists of α-phase, eutectic Si, and intermetallic phases on the bases Fe and Cu (Fig. 3). The eutectic Si was excreted in the form of platelets, which in the plane of the metallographic cut took on the shapes of short needles distributed in various ways (Fig. 3). The dominant Fe-rich phases were in skeleton-like form and Cu-rich phases were excreted as ternary eutectic phase (Fig. 3). The EDX analysis (point, line, and mapping) demonstrated that the skeleton-like Fe-rich phase is $Al_{15}(FeMn)_3Si_2$ and Cu-rich phases are Al_2Cu and Al-Al_2Cu-Si phase (Fig. 4). Despite that delivered material is secondary Al alloy the presence of Fe-rich phases in form plate (needles) were in ingots only in a small amount.

For a better understanding of the quality of experimental material before and after casting, the structural components of the delivered material were firstly compared to AlSi6Cu4 step-casting. This comparison shows that in step-castings were observed the same structural component.

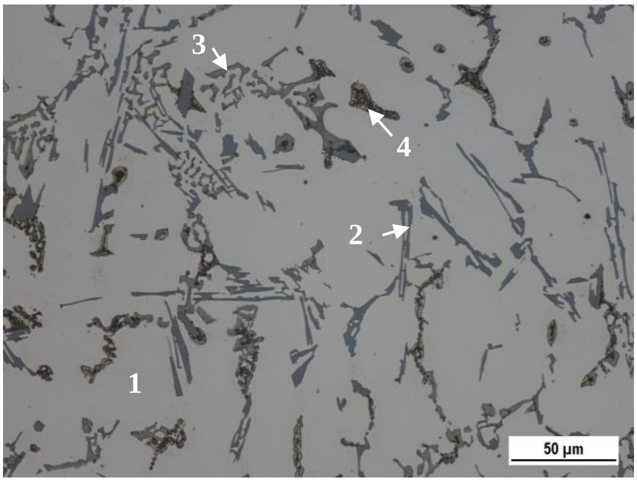


Fig. 3. Microstructure of delivered ingots from AlSi6Cu4, etch. Dix-Keller.
1 – α-phase; 2 – eutectic Si; 3 – Fe-rich phase; 4 – Cu-rich phase

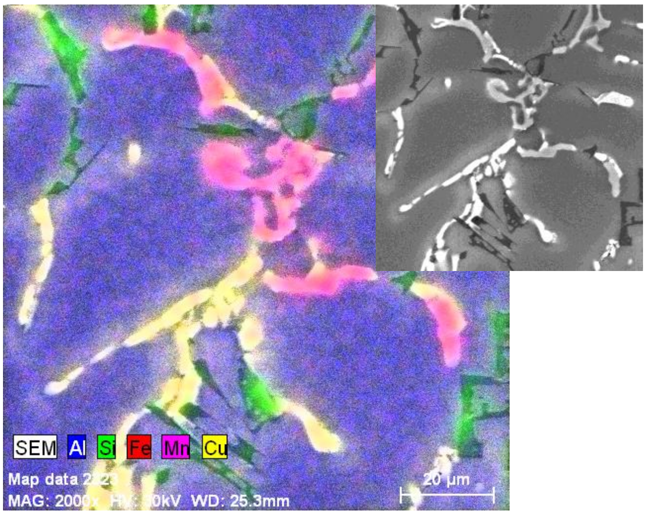


Fig. 4. EDX analysis of structural components in delivered ingots of AlSi6Cu4 cast alloy, etch. Dix-Keller.

The different wall thickness does not lead to the formation of another structural component. So the different cooling rate does not cause the formation of needles Fe-rich phases. The differences were only in their size and distribution (Fig. 5).

The next experimental work was focused on the quantitative evaluation of all structural components in delivered ingots and step-casting. At first, the α-phase was evaluated in the experimental material (Fig. 6). The results show that the average dendritic distance of α-phase in ingots is 33.83 μm. The measurements of dendritic distance in step-castings shows, that thickness of the casting affects the distance of the dendrites (Fig. 6, Fig. 7). The distance of the dendrites varies with the different wall thicknesses. As the wall thickness increases, the distance of the dendrites increases too. These result corelate with results of author Qi (2019). Their results show that as the wall thickness increases, the distance between the dendrites of the α-phase increases.

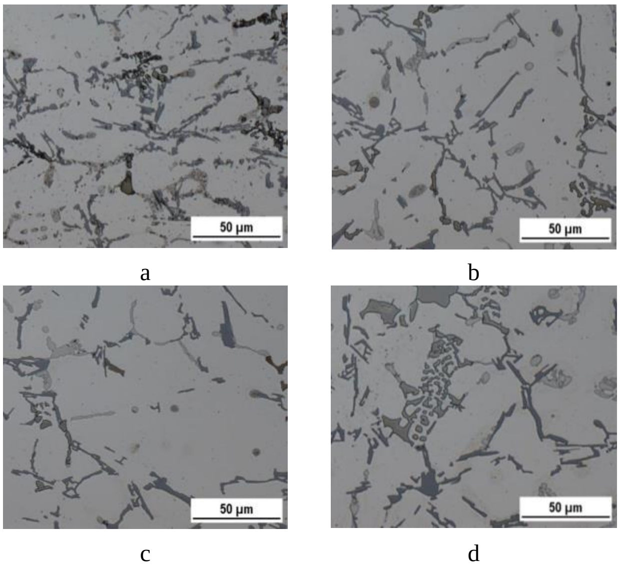


Fig. 5. The microstructure changes in step-casting, etch. Dix-Keller
a) 2mm, b) 3 mm, c) 8 mm, d) 15 mm

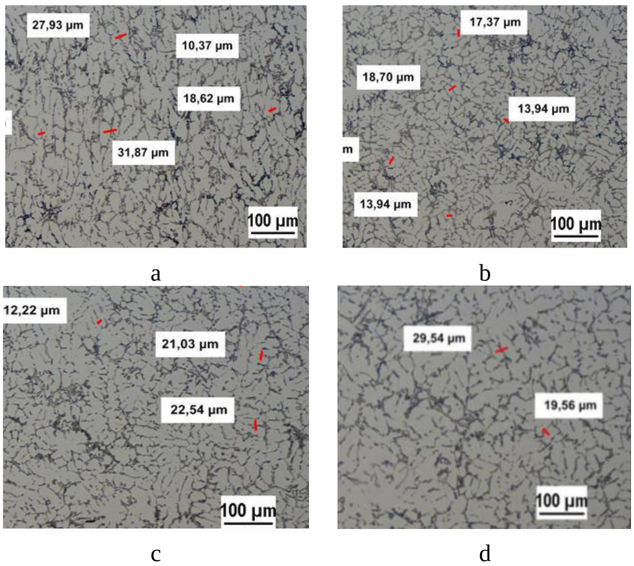


Fig. 6. Quantitative analysis of α-phase in step-casting, etch. Dix Keller
a) 2 mm, b) 3 mm, c) 8 mm, d) 15 mm

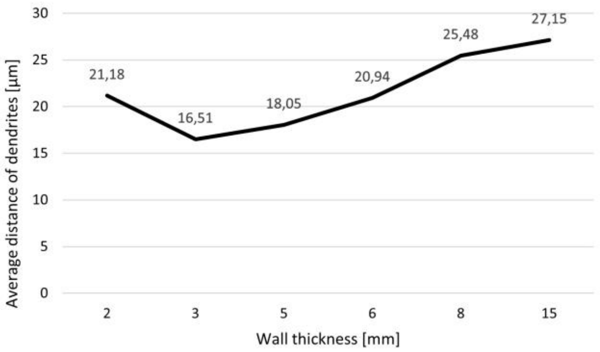


Fig. 7. Results of the average distance of α-phase considering wall thickness from NIS Elements

After the evaluation of the α-phase, the average area of eutectic Si was determined (Fig. 8). Their average area in ingots was 113.2 µm². The effect of wall thickness was also observed in the eutectic Si. The average area of eutectic Si increases with increasing wall thickness (Fig. 9).

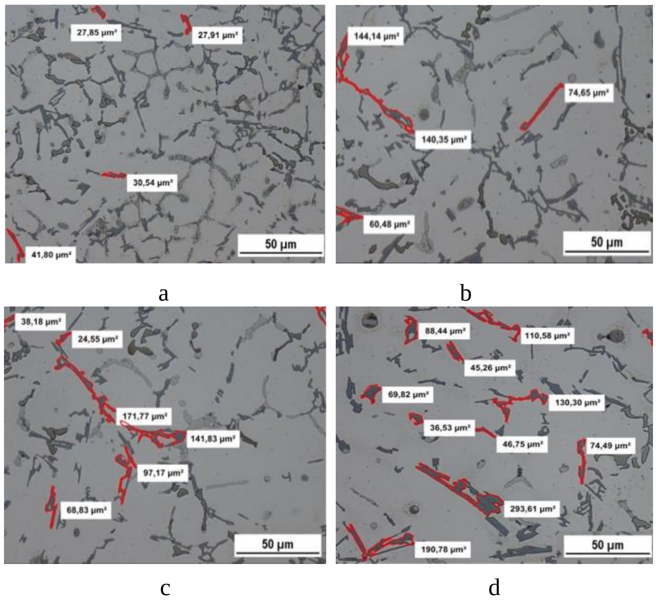


Fig. 8. Quantitative analysis of eutectic Si in step-casting, etch. Dix-Keller
a) 2 mm, b) 3 mm, c) 8 mm, d) 15 mm

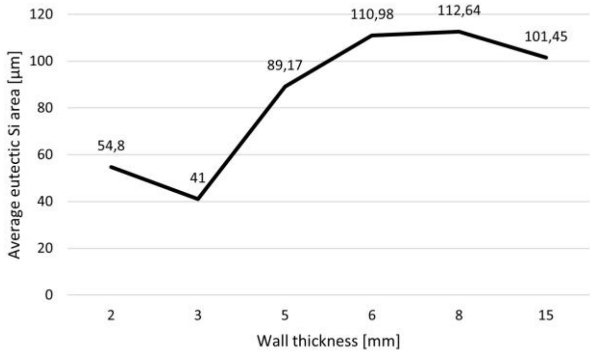


Fig. 9. Results of the average area of eutectic Si considering wall thickness from NIS Elements

Its area is settling in the roughest steps, see Fig. 9. Comparison to results of Kuchariková (2019) the size of eutectic Si is smaller in experimental material (casted into the metallic mould) as in sand mould.

The average area of the Cu-rich phases in delivered ingots was 82.2 µm² and Fe-rich phases 106.32 µm². The image analysis results also confirmed the effect of thickness on the area of the intermetallic phases, see Fig. 10. The average area of the Cu phase decreased with increasing wall thickness. The biggest difference is in the tinner parts of the casting between 2 mm and 3 mm (Fig. 10, 11). In the case of the Fe phase, its average area increased and can be observed especially at thicknesses of 8 mm to 15 mm where the difference in area is the greatest (Fig. 10, 12).

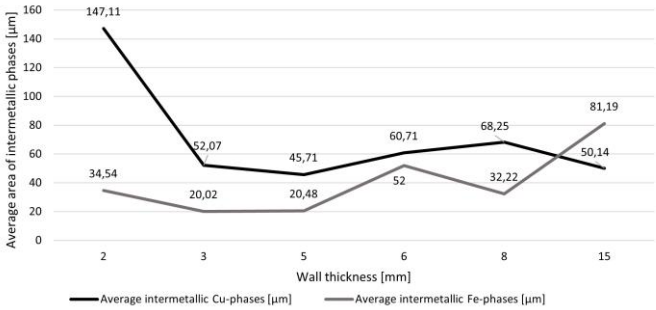
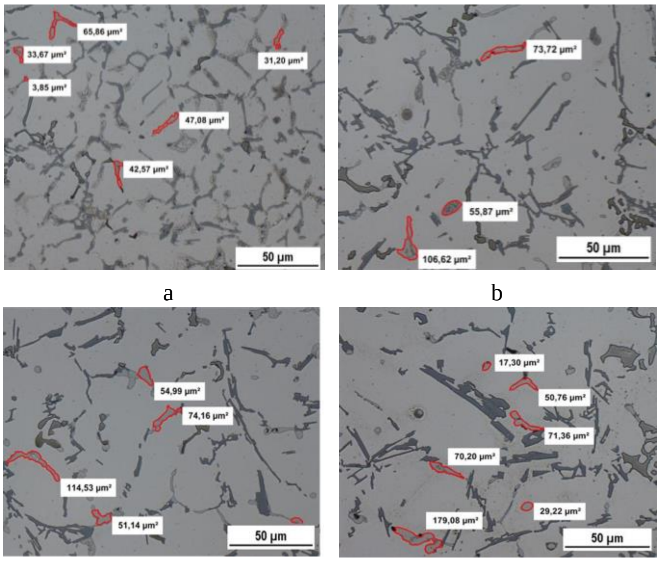


Fig. 10. Results of the average area of intermetallic phases considering wall thickness from NIS Elements



a b

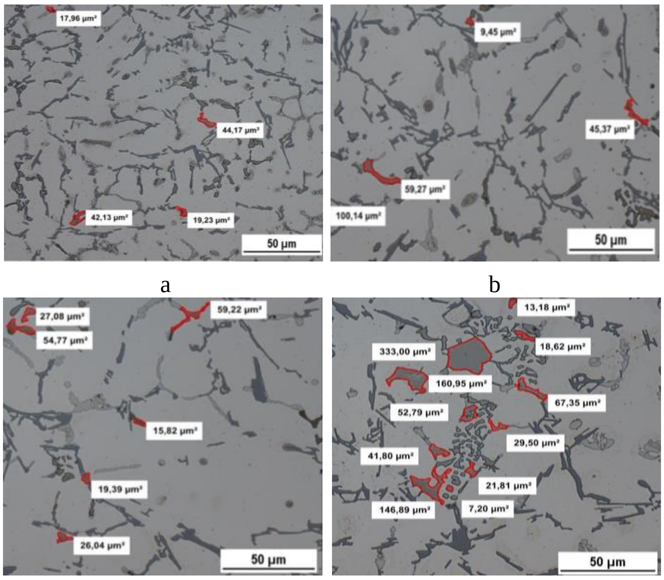
c d

Fig. 11. Quantitative analysis of Cu-rich phases in step-casting, etch. 0.5% HF
a) 2 mm, b) 3 mm, c) 8 mm, d) 15 mm

The results of different wall thickness effect on intermetallic phases in sand castings shows the same results as authors Kuchariková (2019). The results of author Qi (2019) show that size of the other structural components also increases with increasing wall thickness, which presents the possibility of crack initiation as hard-brittle Fe particles or long eutectic Si needles accumulate the crack.

To determine the hardness of the individual thicknesses of the casting, a Brinell hardness test was performed according to EN ISO 6506-1. The hardness measured on the delivered ingots was 103 HBW (2.5/62/10). From the hardness measurements shown in Fig. 13, the cast of the thinnest thickness has the greatest hardness. The measured values further indicate an increase in hardness with decreasing wall thickness, which also confirmed the effect of the wall thickness of the casting on the hardness.

The highest hardness in thin wall thickness casting relates to the size and amount of structural components especially Cu-rich phases and eutectic Si. The presence of a large amount and size of Cu-rich phases was for wall thickness of 2 mm (Fig. 11). The same results are given for the size and amount of eutectic Si particles (Fig. 8). It has also been confirmed that as the size of the eutectic Si and Cu-rich phases increases, their amount decreases, and thus the hardness decreases (Fig. 8,11,13).



a b

c d

Fig. 12. Quantitative analysis of eutectic Si in step-casting, etch. Dix-Keller.
a) 2 mm, b) 3 mm, c) 8 mm, d) 15 mm

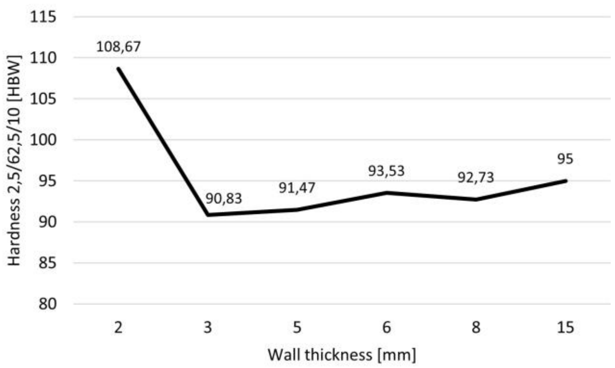


Fig. 13. Average Brinell hardness values for AlSi6Cu4 casting with different wall thickness

Results of Brinell hardness from Kucharikova (2019) also confirmed increasing hardness with decreasing wall thickness in the cast from the sand mold. The Brinell hardness measured in 3 mm was 90 HBW (2.5/62.5/10) which is almost the same as in the cast from the metal mold. According to the finer structure of the casting from metal mold, the casting from sand mold should have a lower hardness in all wall thicknesses.

The effect of wall thickness on hardness and structure was also investigated by the author Qi (2019). The author's results confirmed that the hardness of the alloy decreases in the casting with increasing wall thickness.

5. Summary and conclusion

The aim of this work was to investigate the effect of different wall thicknesses on the quality of AlSi6Cu4 alloy casting. The work is focused mainly on the changes of structure, the morphology of structural components, and the hardness of castings due to wall thickness in the metal mold. The structural parameters were evaluated on metallographically prepared samples at each wall thickness of the metal mold casting, also at the supplied experimental material by NIS-Elements image analysis.

Based on the theoretical and experimental results can be concluded that increasing wall thickness affect the hardness and size of the structural components as follows:

- The α-phase is about 27 % smaller, and also the size of the eutectic Si is about 85 % smaller in the thinnest wall thickness than in the roughest wall thickness. The size of Cu-rich phases is about 65 % smaller, and Fe-rich phases are about 135 % larger in the thinnest wall thickness than in the roughest wall thickness.
- Brinell hardness is about 12 % higher in the thinnest thickness and decreases with increasing wall thickness. These changes relate to the size and amount of structural components (especially Cu-rich phases and eutectic Si)

All these results lead to the conclusion that the cast from the metal mold has a finer structure and finer structural components in the thinner wall thicknesses which lead to better Brinell hardness and is assumed for other mechanical properties as well.

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渐进二次合金不同壁厚汽车砂型铸造质量

關鍵詞
铸件质量
二次铝合金
室壁厚度
定量分析
较高的铁含量

摘要

本文重点关注铸入金属模具的不同壁厚的 AlSi6Cu4 铸件的质量。研究的是结构变化（结构成分的形态、大小和分布）。定量分析用于数值评估交付的实验材料和具有不同壁厚的铸件之间的结构参数（α 相、共晶硅、金属间相）的尺寸和面积分数。此外，执行布氏硬度以获得薄壁合金的机械性能优势。本研究得出结论，金属型AlSi6Cu4合金具有更精细的结构成分，特别是在小壁厚处，因此具有更好的机械性能（布氏硬度）。由于厚度薄，结构轻巧，这些二次铝铸件在汽车工业中具有很大的应用潜力