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Influence of Cooling Rate on the Structure and Damping Properties of the AlSi6Cu4 Alloy

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Abstract

The investigated alloy was cast as a shaft into seven casting molds. Casting molds made of different materials were characterized by different abilities to conduct heat from the sample. This property significantly influenced the cooling rate of the sample casting from the AlSi6Cu4 alloy. The highest cooling rate was achieved in a steel mold at 25°C and the lowest in a mold made of insulating mass. Different cooling rates significantly influenced the structure of the alloy. Different grain sizes were obtained and the morphology of the microstructure components changed. At the highest cooling rate of 16.63 $K \cdot s^{-1}$, a grain with an average size of 0.58 mm was obtained. However, in the mold with the lowest cooling rate of 0.36 $K \cdot s^{-1}$, the average grain size was 3.76 mm. Changes in the structure of the alloy also influenced its damping properties. The tested values *f* the vibration damping coefficient α indicated that the AlSi6Cu4 alloy cooling with the highest cooling rate has the highest value of damping coefficient. This is influenced by the grain size and shape of the silicon precipitates. The refinement structure and fragmented components effectively disperse the vibration wave in the structure of the casting alloy.

Keywords:
aluminum alloys, damping coefficient, cooling rate, ultrasound testing, Al-Si alloys, grain size

1. INTRODUCTION

The type of alloy for a particular application is selected for its range of specific properties. In materials with high damping properties (Hidamets materials), the main factor influencing these properties is the structure of the alloy [1–5]. The properties of alloys can be controlled mainly by influencing its structure and this is usually done by one of two methods. The first is the introduction of foreign particles that create an increased number of crystallization nuclei. This leads to a larger number of grains being obtained, which determines their smaller size, which in turn causes the refinement of the structure. The second way to influence the structure of the alloy is to control the cooling rate. Very slow cooling leads to large grains. As the cooling rate increases, the grain size decreases, which leads to a refinement of the structure [6–8]. At extremely high cooling rates, an amorphous state is already achieved [9]. The simplest way to control the cooling rate during casting is by selecting appropriate materials for the casting mold. Foundry mold materials exhibit a wide range of properties, among which the most important are typically measured and defined using specific coefficients. These properties include thermal conductivity and heat capacity.

The article presents the results of research on the influence of cooling rate on the structure of the AlSi6Cu4 alloy and its ability to dampen vibrations. Different cooling rates were achieved by using various mold materials with differing thermal properties. The tested rolls-castings were cast in a metal mold made of structural steel grade S235 of initial temperatures 25°C, 100°C and 180°C, as well as in a green sand mold cast immediately after forming, or cast into its dry state (drying process: 120°C/24 hours). The final group of molds consisted of materials with low thermal conductivity, such as molding plaster and compressed Al_2O_3 fiber insulation mass.

2. MATERIALS AND METHODOLOGY

The subject of the research was the AlSi6Cu4 alloy with the composition as measured through spark emission spectroscopy shown in Table 1. The alloy was melted in an electric resistance furnace in an amount of 3.5 kg. The alloy was cast at a temperature of 680°C. The liquid metal was poured into seven molds: a metal mold at temperatures of 25°C, 100°C and 180°C, a green sand mold and a dried sand mold, a mold made of molding plaster and a mold made of Al_2O_3 insulating mass (Fig. 1). The mold cavity reproducing the shape of the casting had a diameter of 42 mm and a depth of 100 mm.

Table 1
Chemical composition of the investigated alloy

Element	Si	Cu	Mg	Mn	Ni	Sn	Pb	Ti	Fe	Zn	Al
Analysis [wt.%]	6.21	4.08	0.51	0.43	0.2	0.09	0.10	0.11	0.61	0.52	the rest

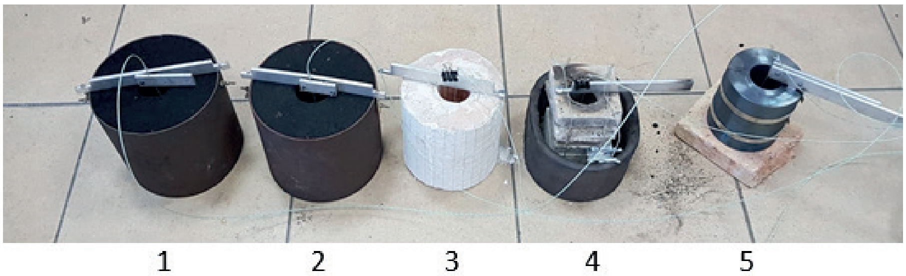

Fig. 1. Types of foundry mold used in the studies: 1 – green sand mold, 2 – dried sand mold (drying process: 120°C/24 hours), 3 – plaster mold, 4 – compressed Al_2O_3 fiber insulation mass, 5 – metal mold made of structural steel grade S235

During the cooling of the liquid alloy, as well as the crystallization and subsequent cooling of the solidified casting, the temperature was recorded. The temperature was measured with K-type thermocouples placed in the sample axis, at the midpoint of the sample's height. After cooling, the castings were removed from the molds and subjected to machining. Samples with a diameter of 40 mm were cut from the places under the thermocouple. The diagram of the thermocouple location and the area from which samples were taken for further tests are shown in Figure 2. The samples were then sanded with 350–1200-grit sandpaper. The final grinding step was 2000-grit sandpaper.

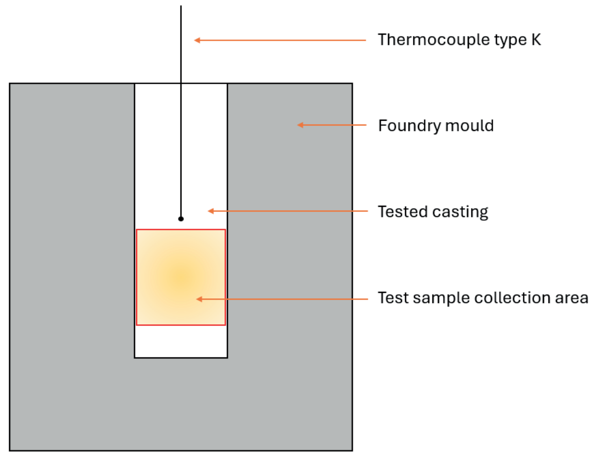

Fig. 2. Schematic diagram of the mold structure, location of the thermocouple and the area where the sample is taken for testing

The samples prepared in this way were subjected to ultrasonic tests to determine the vibration damping coefficient α. The ultrasonic vibrations generated by the head had a frequency of 1 MHz. To reduce signal losses at the sample-measuring head interface, a coupling liquid (paraffin oil) was used. The tests were carried out using a dedicated, portable ultrasonic examination set, the Krautkramer 2000. The set consists of a control and recording computer, a transducer and a measuring head (Fig. 3).

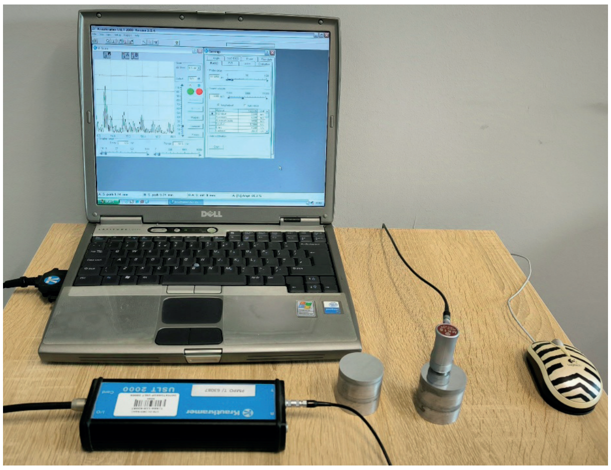

Fig. 3. Stand for testing the vibration damping coefficient α

Fig. 4. Location of the transmitting-receiving head on the tested sample

The signal passes through the sample, is reflected from its lower surface and returns to the transmitting and receiving head. The values of the vibration damping coefficient α are obtained in $dB \cdot m^{-1}$. The measurement principle consists in applying the measuring head to the upper surface of the sample (Fig. 4). Due to the method of measurement, the generated signal is reflected multiple times between the flat surfaces of the sample. An echo of the signal is created, hence the name of the measurement method – the pulse echo method. The transmitting-receiving head records signals and sends them to the computer. In the computer, appropriate software interprets the received signals and presents them as peaks of subsequent signal echoes. An example image of the signal for one of the tested samples is shown in Figure 5. Using the markers available in the software, it is possible to read the difference in values between subsequent signal echoes.

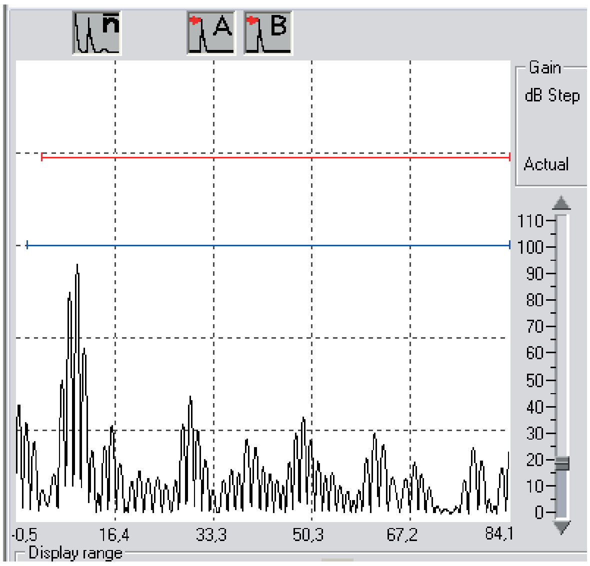

Fig. 5. Image of subsequent signal echoes for one of the tested samples

After ultrasonic measurements, the samples were ground again on 1200 and 2000 sandpaper. Then, the samples were polished with a 3 mm diamond suspension. After polishing, the samples were etched alternately in 10% HNO_3 and 10% HF to reveal the macrostructure until satisfactory results were obtained (approximately 3 seconds in one solution and 3 seconds in the other, repeated several times). This procedure revealed grains in the structure of the casting alloy. The average grain size in the tested samples was determined using the intercept method. To observe the microstructure, the samples were ground and polished again. Then samples were etched with Keller's reagent at room temperature for approximately 5 seconds [10]. The microstructure was observed in reflected white light on a Zeiss Axio Imager M2m microscope with a magnification 100×.

3. RESULTS OF INVESTIGATIONS

While the liquid alloy and the already solidified castings were cooling, temperature changes were recorded over time. The determined cooling curves of the AlSi6Cu4 alloy cast into molds from various mold materials are shown in Figure 6.

As expected, the steeper slope of the cooling curve was obtained in the metal mold at 25°C. The curve recorded in the mold made of Al_2O_3 insulating mass has the flatter course. The cooling curves show the transformations occurring in the AlSi6Cu4 alloy in the form of thermal arrests and breaks. Table 2 lists the determined cooling rate and the average grain size and the damping coefficient α of the alloy depending on the mold materials.

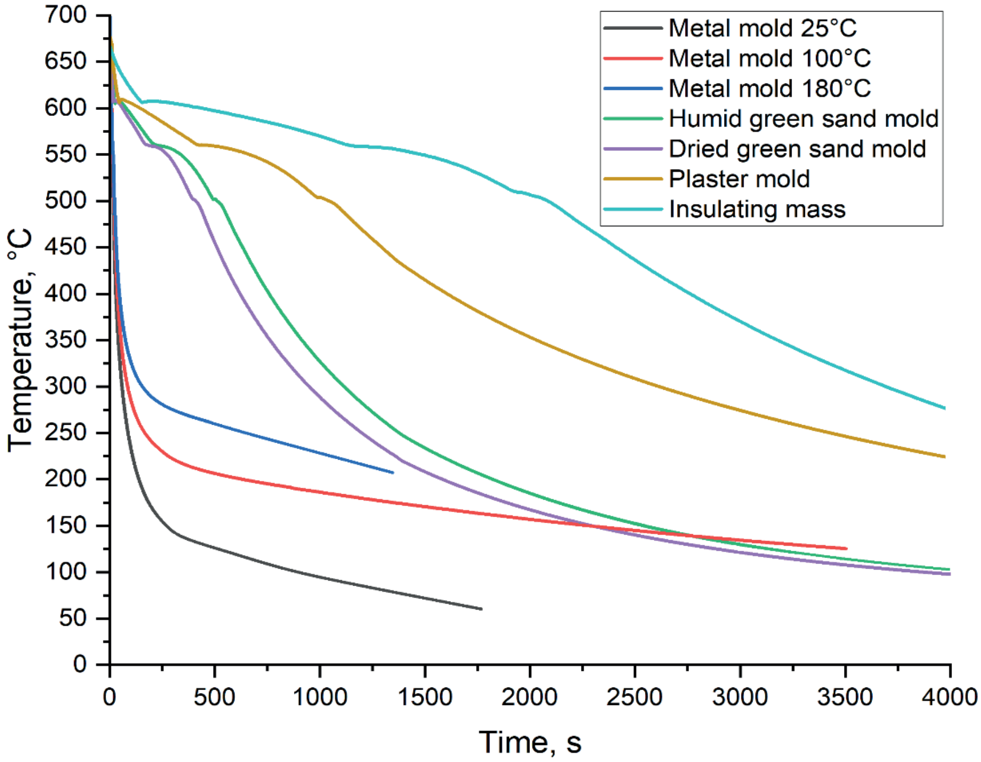

Fig. 6. Cooling curves of the AlSi6Cu4 alloy cast into molds made from various materials

Table 2
Melt cooling rates and average grain size in the tested casting alloy depending on the type of material used to build the mold

Mold material	Metal mold 25°C	Metal mold 100°C	Metal mold 180°C	Wet green sand mold	Dried green sand mold	Plaster mold	Insulating mass
Cooling rate, $K \cdot s^{-1}$	16.63	13.86	11.24	4.67	3.83	1.51	0.36
Grain size, mm	0.58	0.73	0.84	2.76	3.16	3.34	3.76
Damping coefficient α, $dB \cdot m^{-1}$	215.73	198.67	187.52	138.19	139.24	132.46	129.31

The finest structure caused by high cooling rates was obtained in metal molds (Fig. 7–9). Slight differences in grain size are observed depending on the degree of heating of the mold before pouring. The average grain sizes do not exceed one millimeter and are respectively 0.58 mm for a steel mold at 25°C, 0.73 mm for a steel mold heated to 100°C and 0.84 mm for a steel mold at 180°C. A coarse-grained structure was obtained in sand molds, where the cooling rates were 4.67 $K \cdot s^{-1}$ for the wet mold (Fig. 10) and 3.83 $K \cdot s^{-1}$ for the dried mold (Fig. 11). The grain size in this case was 2.76 mm and 3.16 mm, respectively. A slight porosity is observed here. The lowest cooling rate was achieved in the insulating mass mold, that of 0.36 $K \cdot s^{-1}$. Such a low cooling rate results in a coarse-grained structure (Fig. 12). The average grain size in this case is 3.76 mm. In addition to the coarse-grained structure, porosity is observed in castings cast into molds from insulating mass and molding plaster (Fig. 12 and Fig. 13). It can be seen that the significant reduction in the cooling rate observed between the dried sand mold and the insulating mass does not result in a proportional increase in grain size.

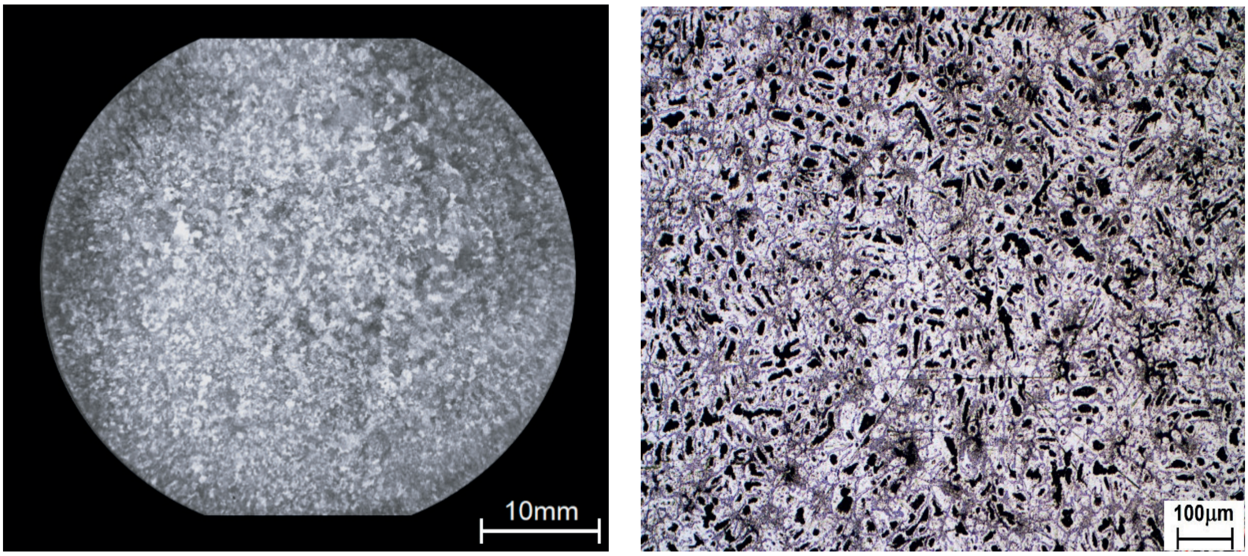

Fig. 7. Macrostructure and microstructure of the AlSi6Cu4 alloy cast into a steel mold at a temperature of 25°C

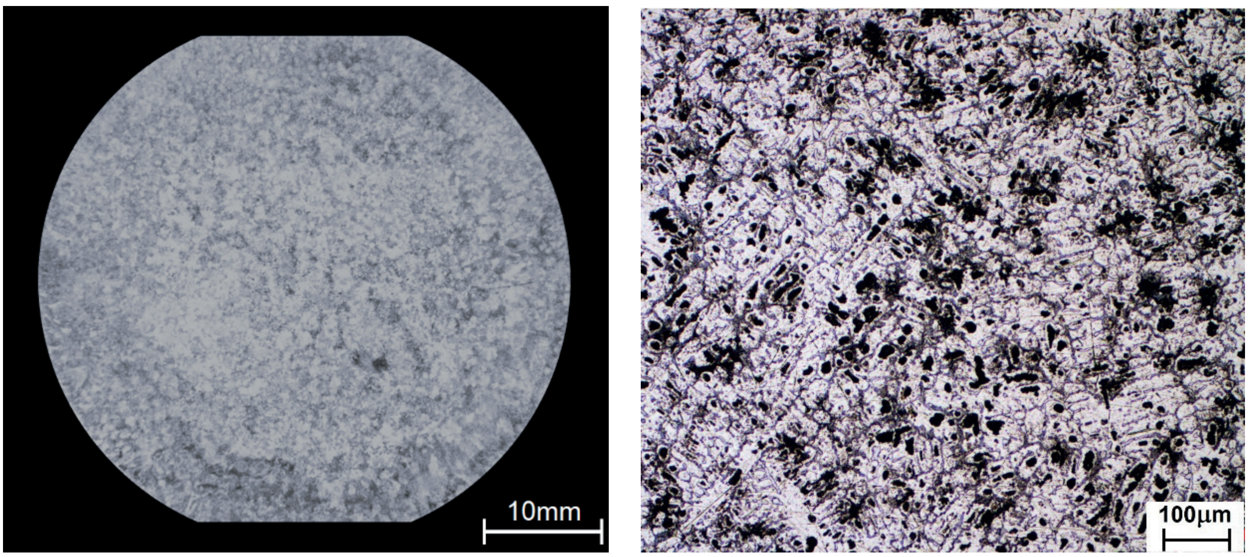

Fig. 8. Macrostructure and microstructure of the AlSi6Cu4 alloy cast into a steel mold at a temperature of 100°C

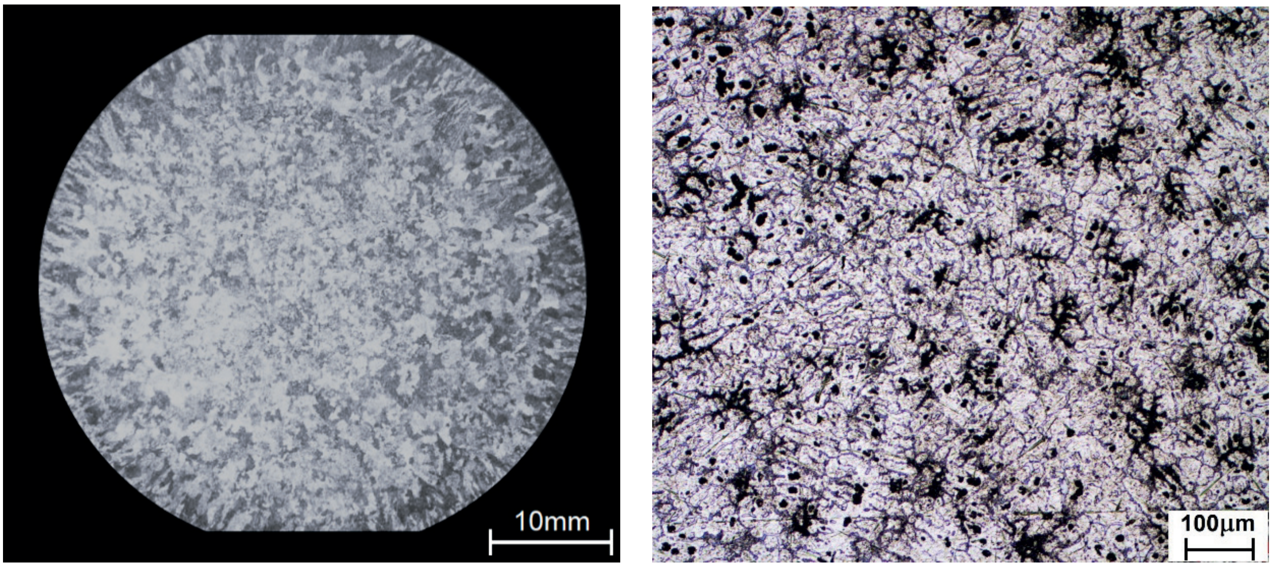

Fig. 9. Macrostructure and microstructure of the AlSi6Cu4 alloy cast into a steel mold at a temperature of 180°C

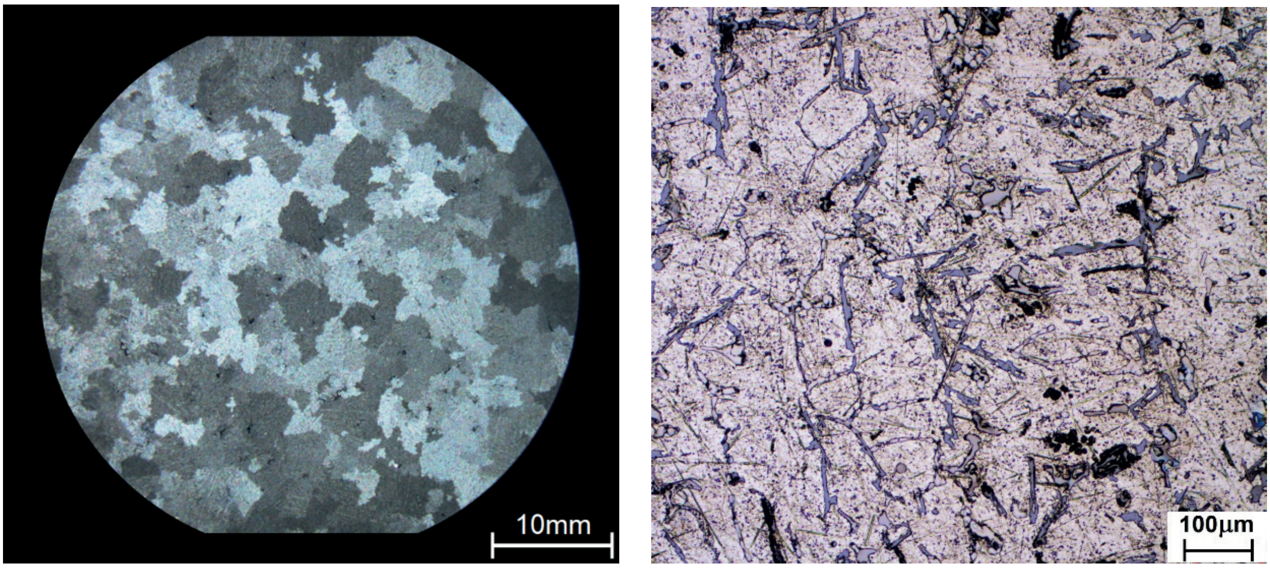

Fig. 10. Macrostructure and microstructure of the AlSi6Cu4 alloy cast into a wet sand mold

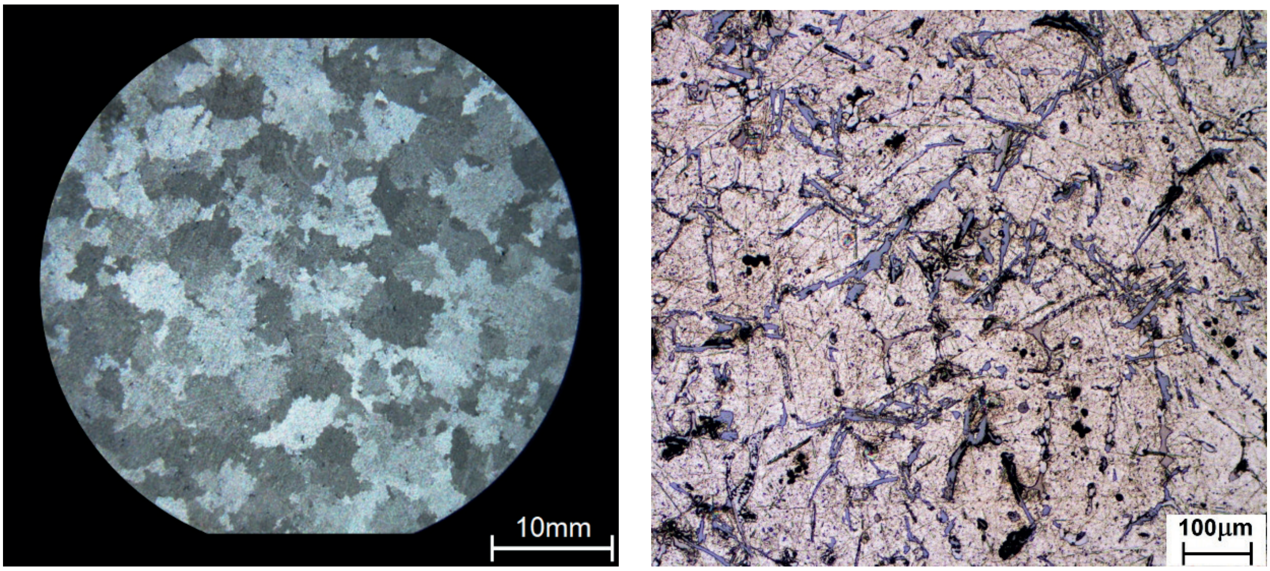

Fig. 11. Macrostructure and microstructure of the AlSi6Cu4 alloy cast into a dried sand mold

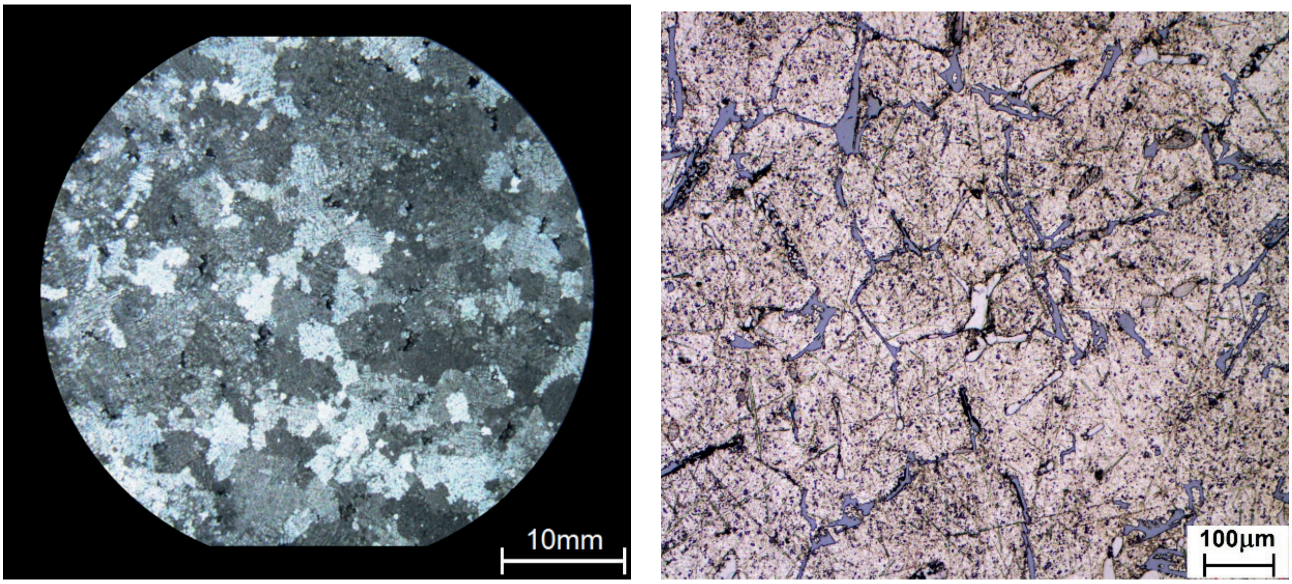

Fig. 12. Macrostructure and microstructure of the AlSi6Cu4 alloy cast into a mold from Al_2O_3 insulating mass

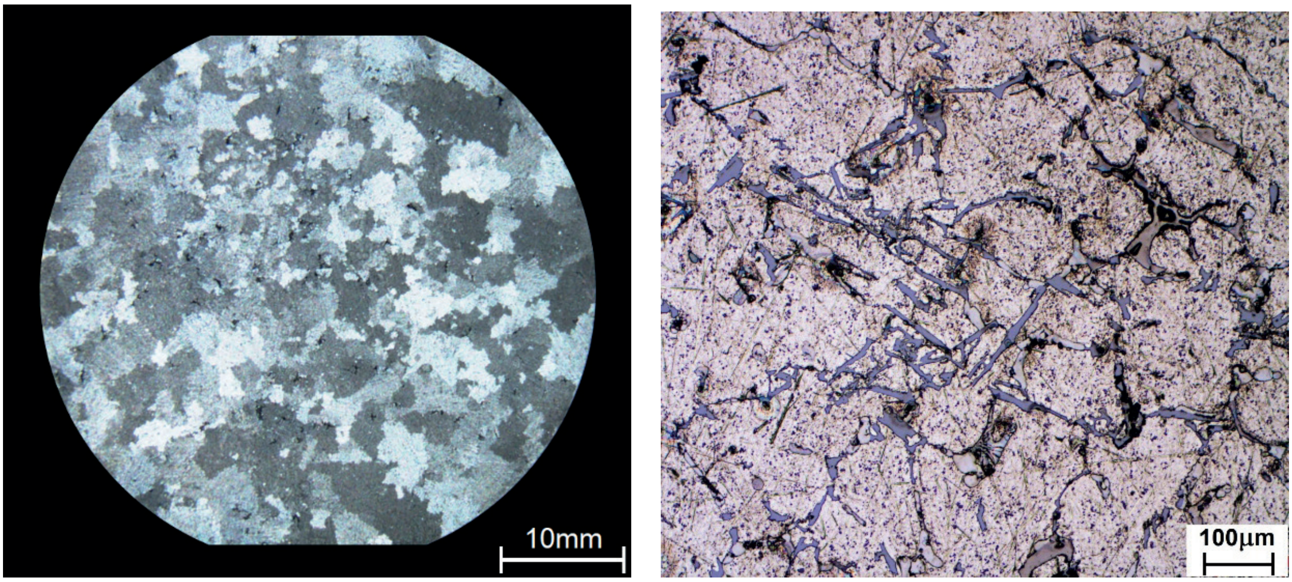

Fig. 13. Macrostructure and microstructure of the AlSi6Cu4 alloy cast into a plaster mold

The cooling rate also significantly affects the microstructure of the alloy. This is especially visible in the appearance and size of the eutectic. At high cooling rates, large refinement of the eutectic and a change in its shape are observed in castings cast into a steel mold. Increasing the cooling rate causes the irregular lamellar eutectic to transform into a more compacted form. This is the so-called granular structure, consisting of silicon eutectic crystals in the form of plates and primary silicon precipitates in the form of compact precipitates against the background of the α(Al) phase. All these changes in the structure of the tested alloy affect its damping properties. The measured data were used to calculate the vibration damping coefficient α for each sample. The main difference in the values of the vibration damping coefficient α measured in the AlSi6Cu4 alloy compared to Al-Zn or Zn-Al alloys can be observed here [3, 8]. The highest values of the vibration damping coefficient α, and therefore the best ability to damping vibrations, are the samples with the finest structure. For the sample with the smallest grain and the highest cooling rate, an attenuation value of 215.73 $dB\cdot m^{-1}$ was obtained. This is influenced by grain refinement and changes in the morphology of the microstructure components. For the tested alloy, a linear dependence of the reduction of damping properties with increasing grain size of the structure is observed. The value of the vibration damping coefficient α depending on the type of material of the casting mold is summarized in Table 2. A summary of all measured parameters depending on the type of material of the casting mold is additionally presented in Figure 14.

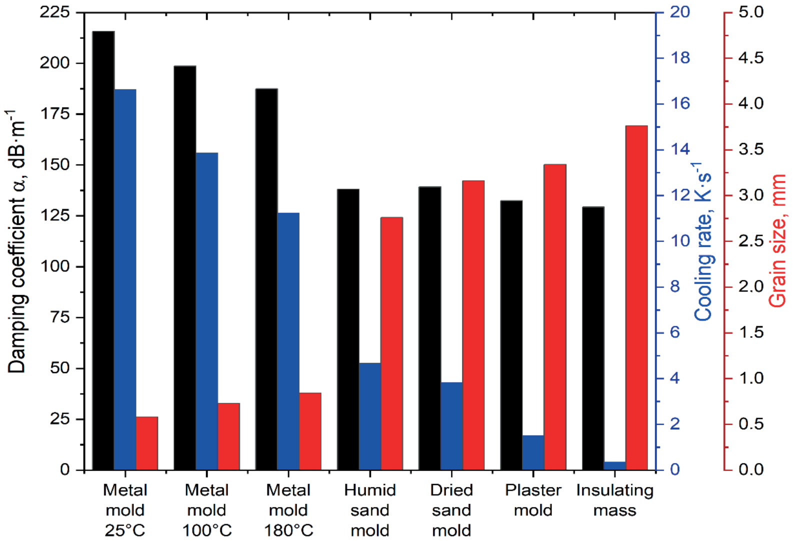

Fig. 14. Summary of measurement results

4. CONCLUSIONS

The structure of the AlSi6Cu4 alloy is susceptible to shaping by changing the cooling rate. The high cooling rates of 11–16 $K \cdot s^{-1}$ obtained in metal molds cause the refinement of the structure. Grains with an average diameter of 0.58 mm, 0.73 mm, 0.84 mm were obtained, depending on how much the steel mold was heated. High cooling rates also affect the microstructure. Both the α(Al) phase and the silicon eutectic are refinement. Additionally, in addition to refinement plates, more compact structures appear in eutectics. Cooling rates obtained in sand molds: dried 2.76 $K \cdot s^{-1}$ and wet 3.16 $K \cdot s^{-1}$ provide time for the grains of the structure to grow. The grains here have an average size of about 3 mm. The eutectic takes the shape typical of hypoeutectic aluminium-silicon alloys in the form of chaotically arranged plates with sharp edges. Casting the tested alloy into a mold made of Al_2O_3 insulating mass resulted in the reduction of the cooling rate by more than ten times compared to a wet sand mold. The cooling rate reached 0.36 $K \cdot s^{-1}$. The average grain size increased by 1 mm compared to the wet sand mold to a value of 3.76 mm. Lowering the cooling rate to low values does not result in such a rapid increase in grain size and has its limitations. It is easier to break down the structure by increasing the cooling rate. All changes in the structure of the AlSi6Cu4 alloy caused by changes in the cooling rate affect its ability to dampen vibrations. Unlike the case of aluminium-zinc alloys, where the refinement of the structure compromises the damping properties, in the tested alloy the highest refinement of the structure resulted in the highest value of the vibration damping coefficient α. Its value gradually decreases as the grain size increases. The lowest damping properties were observed for the sample cooling at the lowest cooling rate in the insulating mass mold.

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