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EN AW-2024 WROUGHT ALUMINUM ALLOY PROCESSED BY CASTING WITH CRYSTALLIZATION UNDER PRESSURE

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Abstract: By using the wrought aluminum alloys can be created castings with higher mechanical properties than the castings made of standard foundry aluminum alloys, but it is necessary to handle the process of making sound castings without any defects such as hot tears and shrinkage porosity. In experiments, we have been studied of wrought aluminum alloy EN AW-2024 which has been processed by the casting with crystallization under pressure with forced flow. Castings were heat treated by standard T6 heat treatment.

KEYWORDS: wrought aluminum alloy, EN AW-2024, casting with crystallization under pressure, mechanical properties

1 Introduction

Although aluminum alloys do not belong to the latest breakthrough materials [1], they are currently at the top in terms of their use in worldwide practice. Castings made of foundry aluminum alloys has probably reached its top in terms of mechanical properties and probably neither on-coming casting technology does not produce castings with higher mechanical properties. Therefore, in order to take advantage of casting technology in comparison with forming technology, for example higher shape complexity of the products, came a time of examination of wrought aluminum alloys usability in the production of castings. It has been already engaged of all unconventional technologies to the research such as casting with crystallization pressure (direct and indirect) [2,3] or semi-solid metals casting [4-6]. Investigated are the alloys of 2xxx, 6xxx and 7xxx series because they offer the highest mechanical properties [7,8]. One of the difficulties in casting of these alloys is a wide solidification range that cause higher tendency to the formation of defects during solidification, for example shrinkage porosity and hot tears [9,10]. The aim of this research is to investigate the effects of casting parameters (pouring temperature and die temperature) in the casting with crystallization under pressure with forced flow [11] on the mechanical properties and microstructure of castings made of wrought aluminum alloy EN AW-2024 in the as-cast state and after heat treatment.

2 Material and methods

Experimental material was prepared using four different ways of casting with crystallization under pressure with forced flow (Tab. 1). Castings were cup-shaped (Fig. 1) with a height of approximately 130 mm, a wall thickness of 15 mm and bottom thickness of about 20 mm (depending on the height of casting).

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Chemical composition of the EN AW-2024 wrought aluminum alloy was 92.783 % Al, 4.264 % Cu, 1.446 % Mg, 0.8 % Mn, 0.356 % Fe, 0.22 % Si, 0.06 % Zn, 0.025 % Ti, 0.013 % Cr, and the rest were other elements contained only in trace amounts. Melting charge was treated with covering flux. Melt was not degassed prior to the casting. The die was made of hot working tool steel (X40CrMoV5-1) heated for 90 minutes to 100, 200 or 250 °C (Tab. 1). Die cavity was not covered with any protect agent. When the melt reached required pouring temperature (Tab. 1), preheated die was opened and melt was dosed into the lower die mounted on chucking table of the hydraulic press. Within few seconds the lower die was closed with upper die mounted on the ram and the value of pressing force reached the preset maximum which corresponds to die cavity pressure of 100 MPa. After 30 seconds of pressing the die was opened and casting was ejected. Measured and evaluated were following quantities: melt temperature T, die temperature T_D, punch displacement h, and pressing pressure p_h (measured in hydraulic system).

Tab. 1 Casting parameters.

Casting number	**No. 1**	**No. 2**	**No. 3**	**No. 4**
Pouring temperature [°C]	650	700	650	700
Die temperature [°C]	100	100	200	250
Pressure [MPa]	100	100	100	100
Pressing time [s]	30	30	30	30

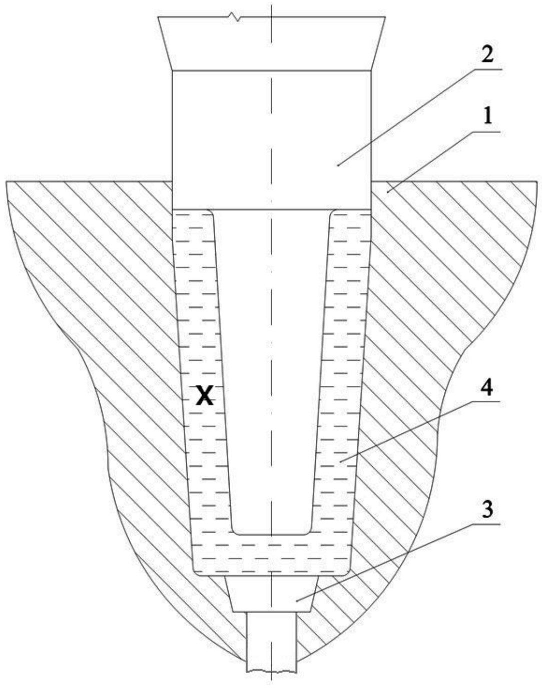

Fig. 1 Experimental tool (1 – lower die, 2 – upper die, 3 – ejector, 4 – casting, X – point of recording of the alloy temperature).

The tensile specimens (Fig. 2) for the tensile testing were made by milling axial sections of castings. Some of them were heat treated in the thermocouple controlled electric resistance muffle furnace. Temperature was at 495 °C, and the time of solution annealing was set at 3 hours. After removal from the furnace the specimens were quenched into water with a temperature of 20 °C. Artificial aging was made in the same furnace at a temperature of 190 °C during 12 hours. Cooling down of specimens after aging was carried out in the open air.

Tensile testing was carried out in accordance with the standard STN EN ISO 6892-1 at ambient room temperature on the universal electromechanical testing machine with the crosshead separation rate of 0.5 mm.min^{-1}. The tensile strength R_m, yield strength $R_{p0.2}$, as well as the percentage elongation to fracture A (further only elongation) was determined.

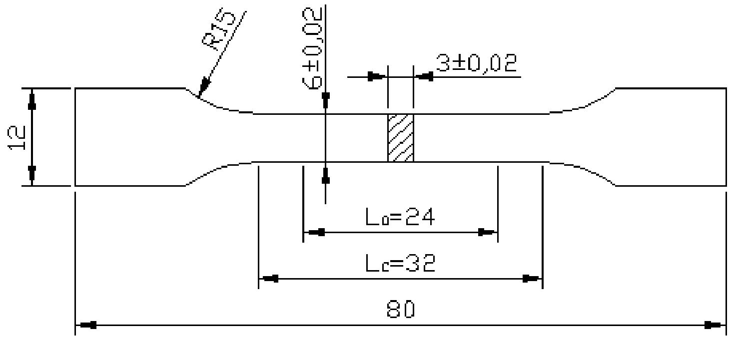

Fig. 2 Specimen for tensile test made in accordance with the standard STN EN ISO 6892-1.

3 Results and discussion

Influence of the pouring temperature and the die temperature on mechanical properties of castings was investigated in the experiment. For determining the conditions of solidification were evaluated next parameters: melt temperature at the pressing start, solidification time in the middle of the casting wall (interval between the melt temperature at the pressing start and the equilibrium temperature of solidus 503 °C), initial and average cooling rate during solidification in the middle of the casting wall, punch movement and average punch speed during solidification (Tab. 2). These parameters exactly classify the production process of each casting. On the basis of these parameters it is possible during repeated cycles detect deviations in the casting (solidifying) and cannot come to an error in reproducibility of castings.

Tab. 2 Evaluated casting parameters.

Casting number	No. 1	No. 2	No. 3	No. 4
Melt temperature at the pressing start [°C]	596	600	619	631
Solidification time [s]	2.2	2	4	7.8
Initial cooling rate [°C.s^{-1}]	300	313	565	390
Average cooling rate during solidification [°C.s^{-1}]	42.3	48.5	29	16.4
Punch movement during solidification [mm]	3.8	3.9	4.3	5.3
Average punch speed during solidification [mm.s^{-1}]	1.8	2	1.1	0.7

The melt has at each casting a different temperature at the pressing start (Tab. 2) and thus different initial ratio of the liquid and solid phase (Tab. 3). Fraction of solid or liquid phase was determined approximately on curve of DSC analysis [12]. A different amount of solid phase during the die closure and initial phase of pressing can provide differences in the efficiency of utilization of punch movement to fragmentation of dendrites and their spheroidization through shear stresses according to the Newton's law of viscosity. Achieved as-cast microstructures are presented in Fig. 3 and mechanical properties in the as-cast and heat treated state are presented in Tab. 4 and shown in Fig. 4.

Tab. 3 Initial ratio of the solid and liquid phase at the pressing start.

Casting number	No. 1	No. 2	No. 3	No. 4
Initial fraction of solid phase [%]	68	64	47	32
Initial fraction of liquid phase [%]	32	36	53	68

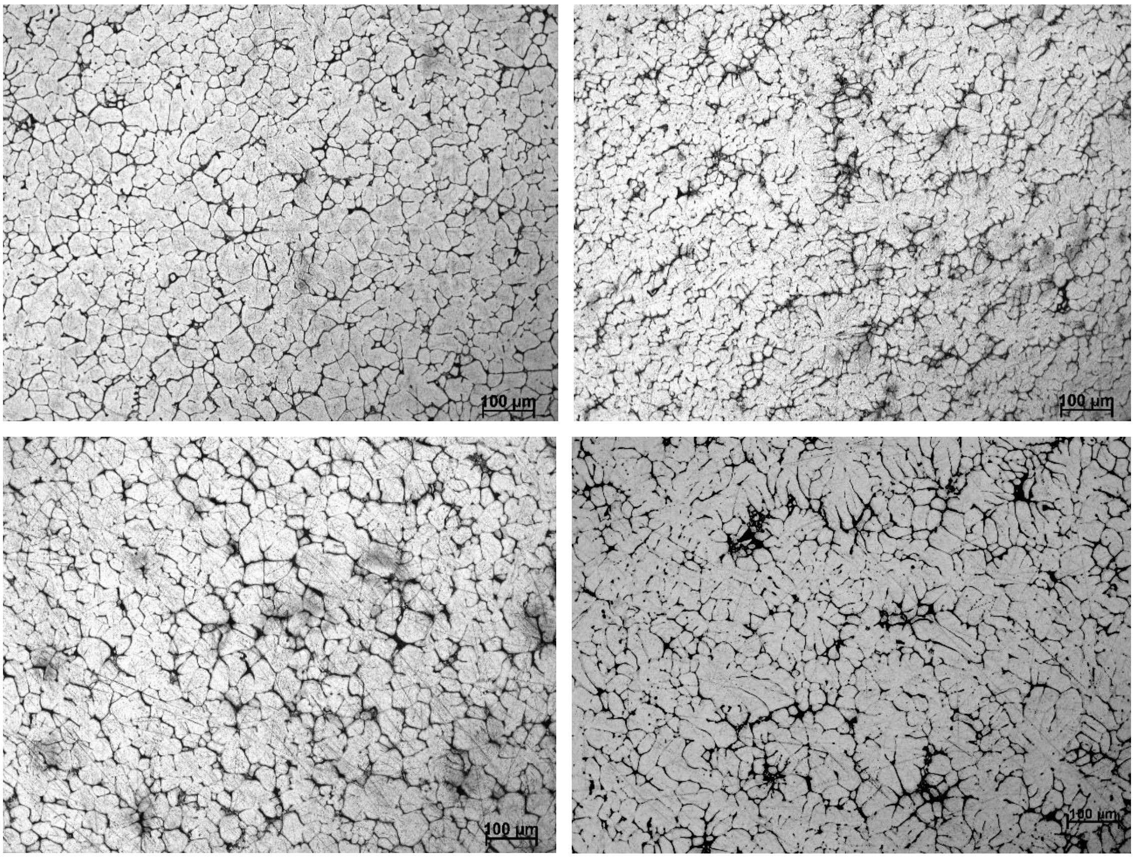

Fig. 3 As-cast microstructures in the middle of the casting walls (top left – casting No. 1, top right – casting No. 2, bottom left – casting No. 3, bottom right – casting No. 4).

Tab. 4 Mechanical properties of the castings in the as-cast and heat treated state.

Casting state	**Casting number**	**No. 1**	**No. 2**	**No. 3**	**No. 4**
As-cast	**$R_{p0.2}$ [MPa]**	123	124	120	115
	R_m [MPa]	283	310	293	309
	A [%]	2	2	2	2.5
Heat treated	**$R_{p0.2}$ [MPa]**	194	197	211	378
	R_m [MPa]	305	318	356	418
	A [%]	1.5	1.5	2	2.5

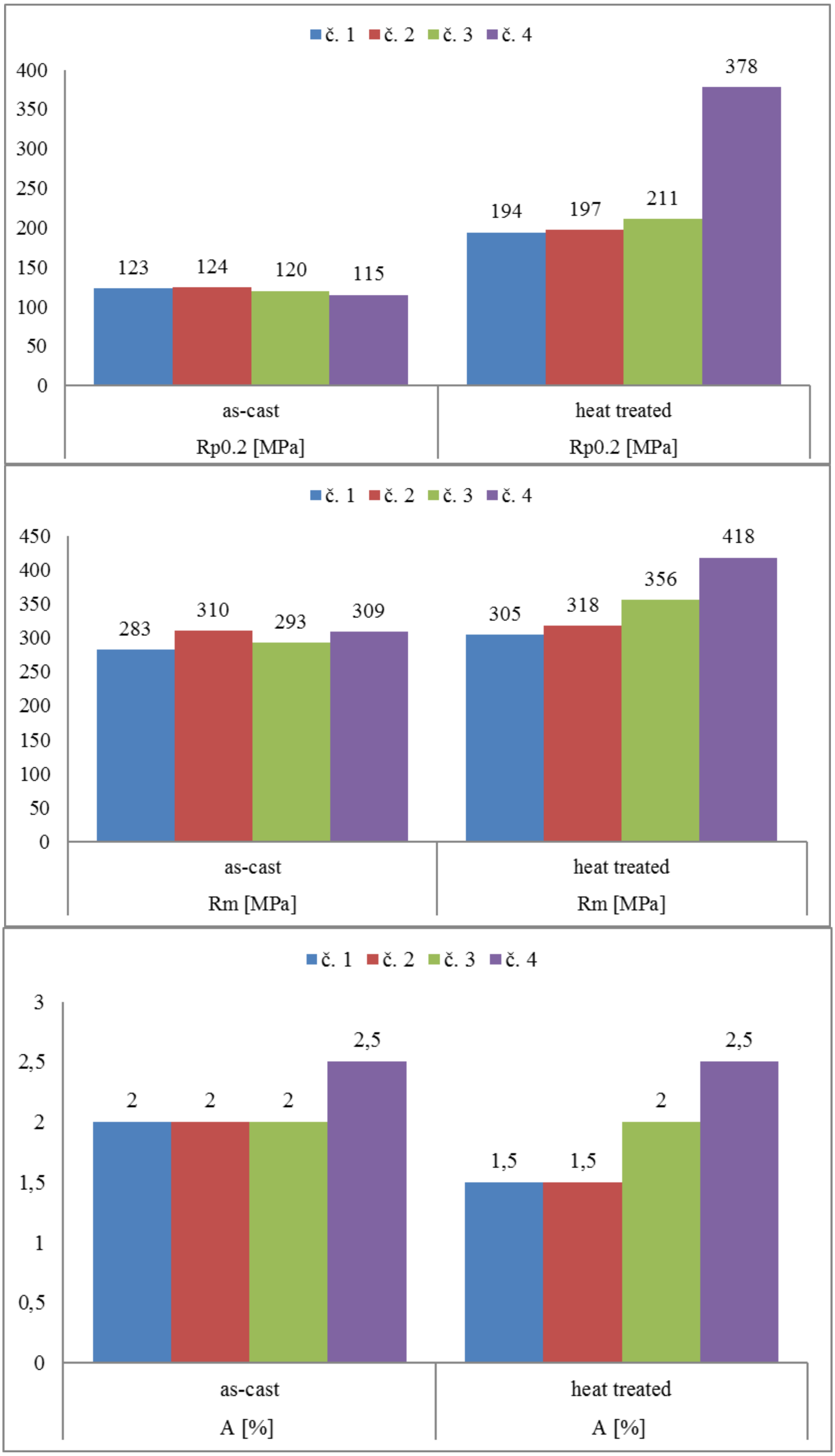

Fig. 4 Mechanical properties of the castings in the as-cast and heat treated state.

The effect of the pouring temperature and the die temperature on mechanical properties of the castings in the as-cast state is not clear. Differences in measured values are negligible, so it is not possible to determine their impact. However, it is possible to determine the impact of the casting parameters on the formation of microstructures. From the comparison of microstructures result that the initial fraction of solid phase at the pressing start has no effect on formation of non-dendritic microstructure. At high initial fraction of solid phase about 68 or 64 % in the castings No. 1 and No. 2 (Tab. 3) once a non-dendritic and once a dendritic microstructure was created. At the lower initial fraction of solid phase about 47 % in the casting No. 3 a non-dendritic microstructure was created and at the lowest initial fraction of solid phase about 32 % in the casting No. 4 again a dendritic microstructure was created. Therefore, it can be thoroughly evaluated only the impact of pouring temperature and die temperature.

The effect of pouring temperature on microstructure can be seen on the castings No. 1 and No. 2, which has been cast into a die with the temperature of 100 °C. The higher pouring temperature of 700 °C in casting No. 2 caused formation of dendritic microstructure. The lower pouring temperature of 650 °C in casting No. 1 is suitable for the formation of a spheroidal microstructure, as was confirmed also at higher die temperature of 200 °C in casting No. 3. There was achieved the highest quality spheroidization of the solid solution in casting No. 3. According to the results of mechanical properties of castings in the as-cast state it can be written that the desired change in morphology of solid solution from dendritic to non-dendritic (spheroidal) may not always have a positive effect on mechanical properties as presented in the literature [6, 13]. This statement was confirmed by casting No. 4, which has been cast at pouring temperature of 700 °C and at the highest tested die temperature of 250 °C. Microstructure of casting No. 4 was in the whole volume dendritic and mechanical properties in the as-cast state correspond to the values of other castings. The effect of die temperature on microstructure is not clear and have not been evaluated.

After heat treatment can be observed the effect of casting parameters on mechanical properties. Castings No. 1 and No. 2 produced with low temperature die of 100 °C answer to the selected standard (non-optimized) T6 heat treatment very slightly. There was increased only the yield strength (about 70 MPa). Tensile strength and elongation remained virtually unchanged. Small changes are insignificant due to variations in measurements. There was not seen an effect of pouring temperature on mechanical properties. Casting No. 3 which has been cast into the die with the temperature of 200 °C answer to the selected heat treatment slightly better. There was not only a change in yield strength (enhanced about 90 MPa), but also in tensile strength increased about 63 MPa, from 293 MPa in the as-cast state to 356 MPa after heat treatment. Confirmation of the positive impact of higher temperatures on mechanical properties after heat treatment can be done on the casting No. 4, which has been cast at pouring temperature of 700 °C and a die temperature of 250 °C. Yield strength has increased markedly, about 260 MPa (from 115 MPa in the as-cast state to 378 MPa after heat treatment) and tensile strength has increased most of all observed castings of about 110 MPa (from 309 MPa in the as-cast state to 418 MPa after heat treatment). Elongation of all castings remained virtually unchanged at a low value around 2 %. The cause of the low elongation is probably the presence of intermetallic phases and shrinkage porosity in the interdendritic regions found in all castings (Fig. 5).

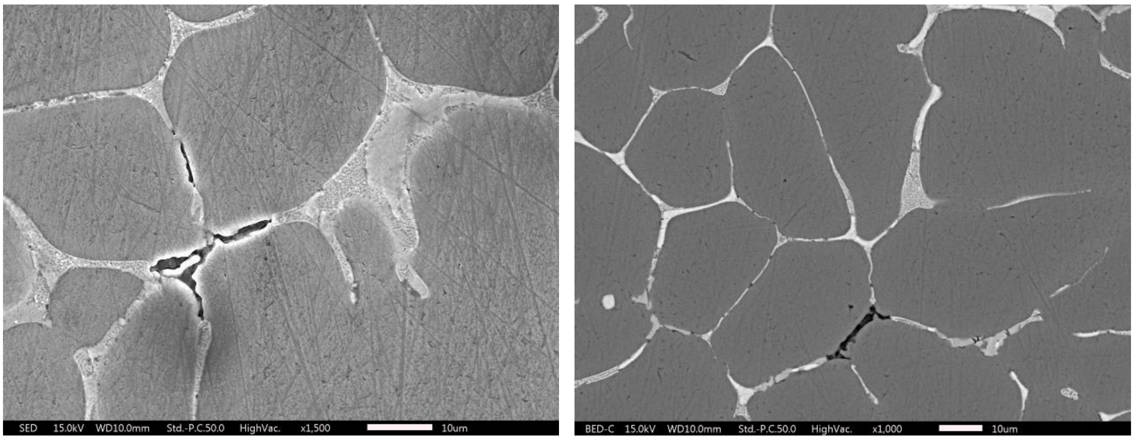

Fig. 5 Interdendritic shrinkage porosity in the castings (REM: left – casting No. 1, right – casting No. 3).

Mechanical properties (tensile and yield strength) of the castings in the as-cast state are comparable to the results of other laboratories [6, 13]. For example, tensile strength of the castings No. 2 and No. 4 in the as-cast state is about the same level as the highest tensile strength achieved in the experiment [6], and the tensile strength of the heat treated casting No. 4 is only 10 MPa lower than the highest tensile strength achieved in the same experiments. Yield strength of the castings in the as-cast state (about 120 MPa) is approximately 80 MPa below the maximum value of the experiment [6], but the yield strength of heat treated casting No. 4 is about 60 MPa higher than the highest yield strength achieved in those experiments. Compared with the results of other laboratories the elongation about 2 % is very low. Typical elongation of castings made of EN AW-2024 alloy in the as-cast state is within the range about 6.5 to 10.5 % [6] and after heat treatment about 8 to 13 % [6, 13].

4 CONCLUSION

Wrought aluminum alloy EN AW-2024 was successfully cast by casting with crystallization under pressure with forced flow. All castings achieved in as-cast state tensile strength about 300 MPa, yield strength about 120 MPa and elongation about 2 %. After the standard (non-optimized) heat treatment T6 the highest mechanical properties were achieved in the casting No. 4, which has been cast at higher pouring temperature of 700 °C and the highest die temperature of 250 °C. It was achieved tensile strength 418 MPa, yield strength 378 MPa, and elongation 2.5 %. Values of the tensile and yield strength of all observed castings are comparable with other laboratories, but elongations are very low due to interdendritic shrinkage porosity and intermetallic phases.

The non-dendritic microstructure was achieved in castings No. 1 and No. 3, which were cast at lower pouring temperature of 650 °C. Castings No. 2 and No. 4 produced at higher pouring temperature of 700 °C had a dendritic microstructure. However, the morphology of the solid solution had not effect on mechanical properties in the as-cast state. After heat treatment, the highest mechanical properties were obtained in the casting No. 4, which microstructure was dendritic.

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