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Study of Susceptibility to Tearing of AlSi5Cu2Mg Alloy with Addition of Zr and Ti

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Abstract

The current trend of continuous improvement of various components constantly pushes the development of new materials forward. The basic goal of research into new and better materials is to improve their properties compared to the original material. One of the essential properties of the newly developed aluminum alloys is their resistance to the formation of tearing. Tears appear during the solidification of the casting and break the integrity due to tension arising while cooling. Several factors influence the susceptibility to tearing, but they can be minimized and reduce the chance of their occurrence. As part of the experiment, the AlSi5Cu2Mg alloy was evaluated in four material variants, without additives (in the reference state), with the addition of transition elements Zr, Ti and their combination Zr + Ti. Susceptibility to the formation of teras was assessed using a qualitative method supplemented by microscopic analysis of the tear profile and determination of the dendritic coherence temperature. The evaluation shows that the addition of Zr increased the susceptibility to tear formation. On the contrary, the addition of Ti had a positive effect and reduced the susceptibility to the formation of tears. The effect of the addition of Zr and Ti in the AlSi5Cu2Mg alloy showed a similar values as without the addition of alloys (reference condition). Microstructural analysis of the tear profile pointed to the negative influence of phases rich in Zr. The subsequent evaluation of the dendritic coherence temperature of individual AlSi5Cu2Mg alloys did not show a correlation with the results of a quantitative evaluation of susceptibility to tears.

Keywords: Al-Si-Cu-Mg alloy, Hot tears, Curve of load force, Dendrite coherency point

1. Introduction

The formation of tears is influenced by several factors, and they mainly arise during the cooling of the casting, when the individual parts are cooled at different speeds, which causes different shrinkage [1]. The material of the casting, the shape and construction of the casting have a fundamental influence on the formation of tears [2].

For tear susceptibility, the chemical composition of the alloy is an important aspect, but especially the width of the solidification interval. In general, the wider the solidification interval is, the longer the time for tears to form in the alloy and thus the susceptibility is higher [3,4]. In silicon, the width of the interval is not directly proportional to the susceptibility to tear formation. For this reason, it is important to consider other factors affecting the susceptibility of the alloy to tears [5]. Copper has a significant effect on the formation of tears, mainly due to the influence of the solidification interval. The greater the concentration of copper in the alloy, the greater the interval in the alloy and the susceptibility to tear formation increases in direct proportion to the copper content [6,7].

The influence of the cooling rate during solidification is one of the factors affecting the formation of tears. Therefore, the mold must be preheated to a certain temperature so that the alloy during casting has the ability to better settle in critical places and reduce the tendency to form tears [8]. As the mold temperature increases, the tendency to tear is reduced, the mechanical properties are improved, and the macrostructure is finer and more uniform throughout the alloy [9].

The temperature of the dendritic coherence point (DCP) can be equally important for the formation of hot tears. The solidification of an aluminum alloy begins at the temperature of the liquid with the formation of small crystal nuclei in the melt. Further cooling leads to more pronounced precipitation of the primary dendritic network of α-phase crystals. A primary dendrite and subsequently a secondary dendrite laterally arise from one active nucleus [10]. Growth continues until the primary dendrite meets another dendrite. The temperature at which this occurs is defined as the dendrite coherence temperature. Further, secondary to tertiary arms grow with gradual thickening of the secondary dendritic arms. After the melt reaches the dendrite coherence temperature, the mass replenishment of the liquid component of the alloy is already greatly limited. Limiting the addition of the liquid component of the alloy to the interdendritic spaces increases the sensitivity to the formation of tears [11].

The main goal of the experimental work was to evaluate the susceptibility of the AlSi5Cu2Mg alloy to tear formation in the reference state (without additives), with the addition of Zr, but also with the addition of Ti (above the defined limited titanium content of 0.03 wt.%) and their mutual combination.

2. Experimental process

As part of the experimental work, the hypoeutectic aluminum alloy AlSi5Cu2Mg was used. This alloy is used in the production of complex castings for the automotive industry. It is a non-standardized alloy and there are no data regarding the required chemical composition. For the AlSi5Cu2Mg alloy, the chemical composition is defined directly from the customer (Tab. 1).

An AlSi5Cu2Mg alloy was prepared without additives (reference alloy) with an addition of 0.2 wt. % Zr (Zr alloy), with the addition of 0.1 wt. % Ti (Ti alloy) and their mutual combination 0.2 wt. % Zr together with 0.1 wt. % Ti (Zr+Ti alloy). The reason for adding Zr to the melt is to refine the structure or its replacement Ti, which according to the customer's request is limited to 0.03 wt. %. The amount of 0.2 wt. % Zr was chosen based on previous research, which showed that the grain refinement effect was most effective at the given amount [12,13]. Despite the limited Ti content (max. 0.03 wt.%), the addition of 0.1 wt.% Ti was evaluated for the needs of the experiment.

A resistance melting furnace was used to melt the alloys. Before casting, additive elements were added at a temperature of 760 ± 5 °C in the form of AlZr10 and AlTi5B master alloys. After the charge was completely dissolved, the melt was stirred and the oxide films were mechanically removed before casting, the alloy was intentionally degassed. From each melt, 5 test samples for tearing susceptibility and 3 samples for DCP evaluation were cast. The chemical composition of the experimental AlSi5Cu2Mg alloys is given in Tab. 1.

A metal form was used as a measuring device, which allows simultaneous quantitative as well as qualitative evaluation of the susceptibility to the formation of tears. The form consists of an inlet channel from which five arms of different lengths emerge (Fig. 1a). The experimental part is devoted to qualitative evaluation and therefore the fifth longest arm was used. The fifth arm ends with an anchoring screw (Fig. 1b - blue ellipse). When filling the mold, the front conical part of the screw was filled with melt and the rear part was fixed with a force sensor. The force transducer (S9M Force Transcuder) ensured the measurement of the tensile force of the shrinking casting along with the K-type thermocouple (NiCr-Ni) and sent the data via the measurement card (NATIONAL INSTRUMENTS Hi-Speed USB Carrier NI USB – 9162) to the computer. Measured load and temperature values over time were displayed by LabView software. The diagram of the experimental casting with the marking of the fifth arm intended for qualitative evaluation is shown in Fig. 1a and the diagram of the connected measuring system is in Fig. 1b. The casting temperature of each alloy was 750 ± 5 °C and the metal mold temperature was 150 ± 5 °C.

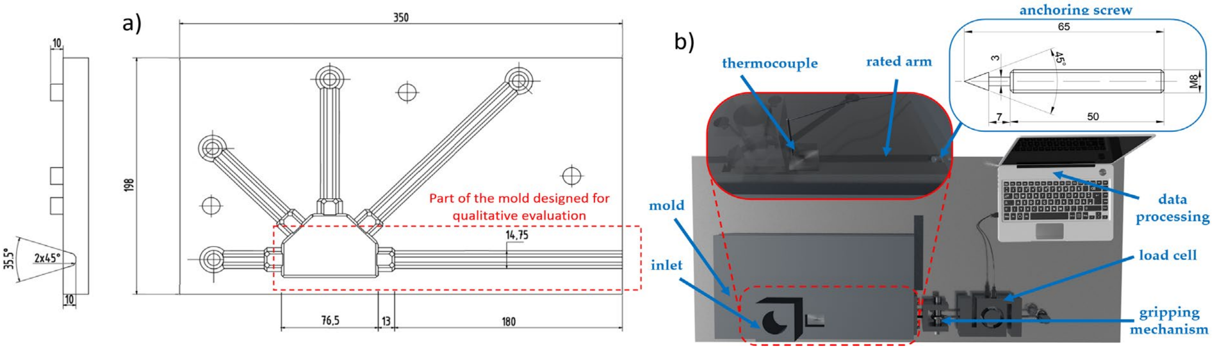

Fig. 1. Scheme of the measuring apparatus

Tear profiles of the experimental material were evaluated using a scanning electron microscope (SEM) observations with EDX analysis using a VEGA LMU II scanning electron microscope connected to energy dispersive X-ray spectroscopy (Brucker Quantax EDX analyzer) and NEOPHOT 32 optical microscope (OM). Sample preparation consisted of coarse and fine wet grinding and polishing using diamond emulsion. Finally, the samples were etched in 0.5% HF solution.

The point of dendritic coherence was determined through the method of two thermocouples and to determine the minimum temperature difference.

Table 1.
Chemical composition of the AlSi5Cu2Mg alloys [wt.%]

	Si	Fe	Cu	Mn	Mg	Ti	Zr
Required	5.0 6.5	max. 0.20	1.6 2.5	1.6 2.5	max. 0,03	max. 0,03	-
Ref.	5.91	0.209	1.97	0.014	0.286	0.014	0.002
Zr	5.57	0.218	2.00	0.016	0.977	0.013	0.243
Ti	5.65	0.210	1.95	0.015	0.293	0.066	0.002
Zr+Ti	5.73	0.241	1.95	0.017	0.285	0.078	0.17

3. Results

3.1. Qualitative evaluation of susceptibility to tearing

Susceptibility to the formation of tears was evaluated qualitatively with the help of curves of temperature, force and rate of load increase. The curves were created based on the values obtained from the thermocouple and the force meter. Breach of integrity violation of the arm and the formation of tears were detected from the force curve.

Reference alloy AlSi5Cu2Mg (without the addition of alloys)

In Tab. 2, the measurements from five samples and the results of strength growth and tear initiation for the reference alloy are recorded. In the measured samples, a complete rupture of the arm occurred in two samples. The highest increase in force, at which the sample did not break, was recorded by the first sample with an increase of 14.9 N/s. The fifth sample had the highest measured force with a maximum force of 1106 N.

On the graph you can see the course of force, temperature and the increase in load rate for sample no. 2 (Fig. 2). A sharp increase in force is visible from the force curve. After approximately 20 seconds from the start of the increase in force, there was stabilization and gradual growth up to a maximum value of 987 N. It is clear from the curve that there was no violation of the transition arm.

AlSi5Cu2Mg alloy with an addition of 0.2 wt. % Zr

After adding 0.2 wt. % Zr into the AlSi5Cu2Mg alloy can be from Tab. 3 observe that the tear occurred in three cases with one immediate tear-off (sample no. 4). The maximum values of the load increase rate were measured for sample no. 3 with a maximum value of 12.22 N/s and with a maximum force of 1195 N. From the quantitative evaluation, the alloy is included among alloys with a very high susceptibility to tear formation.

The graph in Fig. 3 shows the course of sample no. 5, which was not immediately broken. The tear appeared after 20 seconds of force and then spread. After 8 seconds of propagation, there was a stop by adding liquid metal to the tear zone and a repeated increase in force. The red ellipse marks the tear that caused the interruption of the increase in strength. The hairline tear was not severe enough to break the arm and the force reached a maximum value of 413 N. Arrows on the graph indicate the points of tear initiation and termination of tear propagation.

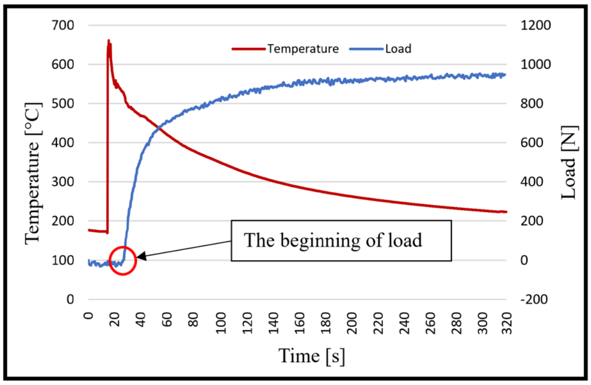

Fig. 2. Course of force and temperature for reference alloy AlSi5Cu2Mg, sample no. 2

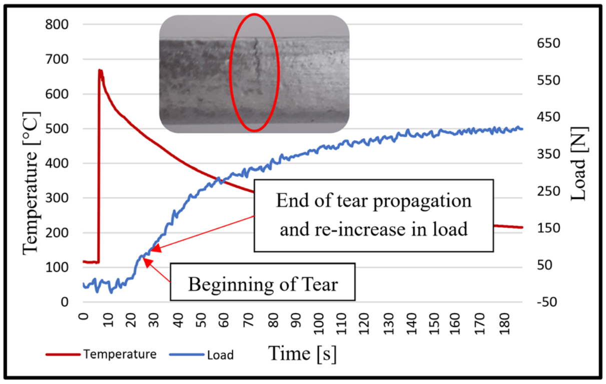

Fig. 3. Course of force and temperature for AlSi5Cu2Mg alloy with addition of wt. % 0.2 Zr, sample no. 5

AlSi5Cu2Mg alloy with added wt. % 0.1 Ti

Titanium promotes resistance to tear formation, but from the five specimens tested, there was one complete arm separation and a severe tear across the entire cross-section of the arm. Tab. 4 shows the values of the samples, where the best values were recorded by sample no. 4 with a maximum value of 1033 N and with the highest rate of force increase with a value of 15.2 N/s.

For sample no. 5, a significant tear appeared in almost the entire cross-section of the arm already at the beginning of the measurement, which, however, did not lead to a complete tearing of the arm (Fig. 4). A slight rise can be observed on the force curve up to a value of 194 N and the resulting tear is shown in the figure (Fig. 4 – red ellipse).

AlSi5Cu2Mg alloy with an addition of 0.2 wt. % Zr+0.1 wt. % Ti

In the last alloy with an addition of 0.2 wt. % Zr and 0.1 wt.% Ti, arm breakage occurred immediately in only one case (Tab. 5). The highest values were recorded by sample no. 3, in which the maximum force reached 1179 N and the maximum load increase with 19.41 N/s.

For sample no. 2, a small tear was formed in the initial phase of the measurement, which propagated simultaneously with the increase in force (Fig. 5). As a evidence of the tear presence, the visual inspection was performed, but also a gradual growth in strength versus immediate growth. The maximum force also reached a reduced value of around 680 N.

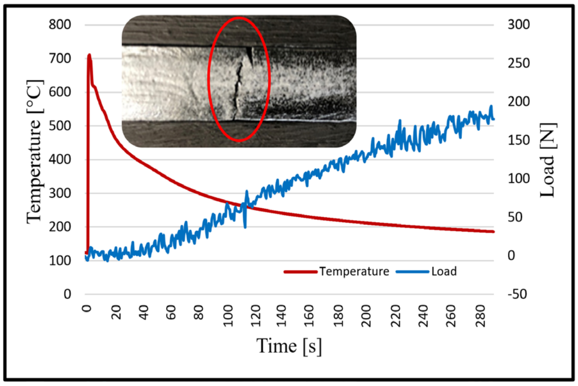

Fig. 4. Course of force and temperature for AlSi5Cu2Mg alloy with addition of wt. % 0.1 Ti, sample no. 5

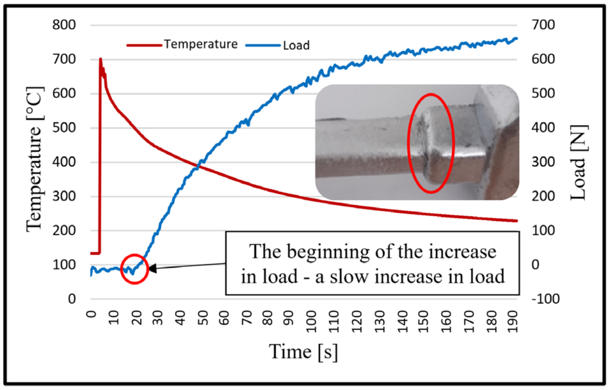

Fig. 5. Course of force and temperature for the AlSi5Cu2Mg alloy with an addition of 0.2 wt. % Zr + 0.1 wt. % Ti, sample no. 2

Table 2.
Results of the qualitative evaluation for the reference alloy AlSi5Cu2Mg

Sample no.	Hot Tear Initiation				End Hot Tear Propagation		
	Temperature (°C)	**Time (s)**	**Load (N)**	**Load Force Ratio (N/s)**	**Temperature (°C)**	**Time (s)**	**Type of End Hot Tear Propagation**
1.	No hot tear		Max. 934	Max. 14.9		No hot tear	
2.	No hot tear		Max. 987	Max. 9.62		No hot tear	
3.			Arm separation			Arm separation	
4.			Arm separation			Arm separation	
5.	No hot tear		Max. 1106	Max. 14.72		No hot tear	

Table 3.
Results of the qualitative evaluation for AlSi5Cu2Mg alloy with addition of wt. % 0.2 Zr

Sample no.	Hot Tear Initiation				End Hot Tear Propagation		
	Temperature (°C)	**Time (s)**	**Load (N)**	**Load Force Ratio (N/s)**	**Temperature (°C)**	**Time (s)**	**Type of End Hot Tear Propagation**
1.	433	32	131	4.7	416	39	Increase of load
2.	No hot tear		Max. 944	Max. 11.37		No hot tear	
3.	No hot tear		Max. 1195	Max. 12.22		No hot tear	
4.			Arm separation			Arm separation	
5.	515	20	64	4.3	471	28	Increase of load

Table 4.
The results of the qualitative evaluation for the alloy with the addition of 0.1 wt. % Ti

Sample no.	Hot Tear Initiation				End Hot Tear Propagation		
	Temperature (°C)	**Time (s)**	**Load (N)**	**Load Force Ratio (N/s)**	**Temperature (°C)**	**Time (s)**	**Type of End Hot Tear Propagation**
1.			Arm separation			Arm separation	
2.	No hot tear		Max. 800	Max. 7.62		No hot tear	
3.	No hot tear		Max. 796	Max. 6.9		No hot tear	
4.	No hot tear		Max. 1033	Max. 15.2		No hot tear	
5.	584	2	11	-		Increase of load	

Table 5.
The results of the qualitative evaluation for the alloy with an addition of 0.2 wt. % Zr + 0.1 wt. % Ti

Sample no.	Hot Tear Initiation				End Hot Tear Propagation		
	Temperature (°C)	Time (s)	Load (N)	Load Force Ratio (N/s)	Temperature (°C)	Time (s)	Type of End Hot Tear Propagation
1.	Arm separation				Arm separation		
2.	460	25	28	4.1	Hot tear is formed in parallel with the growth of load		
3.	No hot tear		Max. 1179	Max. 19.1	No hot tear		
4.	No hot tear		Max. 957	Max. 13.15	No hot tear		
5.	482	24	5.8	16.8	629	56	Increase of load

3.2. Evaluation of the tear profile

Microstructural evaluation was performed in the arm tear occurrence area. By observing the microstructure of the tear profile of the reference alloy (Fig. 6), it was found that the fracture occurred due to the failure along the dendrite boundaries of the α-Al phase. Areas were also observed on the profile in which a violation occurred due to the presence of intermetallic phases based on Cu and Fe (Fig. 6 - mapping). At the same time, it was found that one of the initiation sites for the formation of tears was contractions occurring in the inter-dendritic areas of the material.

As in the case of the reference alloy, the tear initiation mechanism was characterized by intercrystalline propagation along the dendrite boundaries of the α-Al phase. Locally, it was also possible to observe the occurrence of intercrystalline propagation on the tear profile as a result of the failure of the material through intermetallic phases based on Cu and Fe (Fig. 7 - EDX analysis). The increased susceptibility to the formation of tears after the addition of Zr was related to the occurrence and nature of intermetallic phases based on Zr. These were present in the structure of the alloy in the form of hard and brittle plates (in the plane of the metallographic cut of the needle - Fig. 7 - optical microscope OM). The sharp ends of the needles increased the voltage potential at the interface between the intermetallic phase and the aluminum matrix.

For the purpose of evaluating the microstructure of the alloy with the addition of 0.1 wt. % Ti was selected a sample in which a tear occurred during solidification without breaking the integrity of the arm by tearing off. The tear on the observed arm was created by the mechanism of ductile failure along the boundaries of the dendrites of the α-Al phase (Fig. 8) with the local appearance of fission areas due to the failure of the material through intermetallic phases based on Cu and Fe (Fig. 8 - EDX analysis).

In the alloy with the addition of zirconium and titanium, an increased amount of microshrinkage and fracture along the grain boundaries can be observed (Fig. 9). Further observation of the tear profile showed that the zirconium phases were split into several parts due to solidification and the resulting tension between the α-phase grains (Fig. 9 - optical microscope OM).

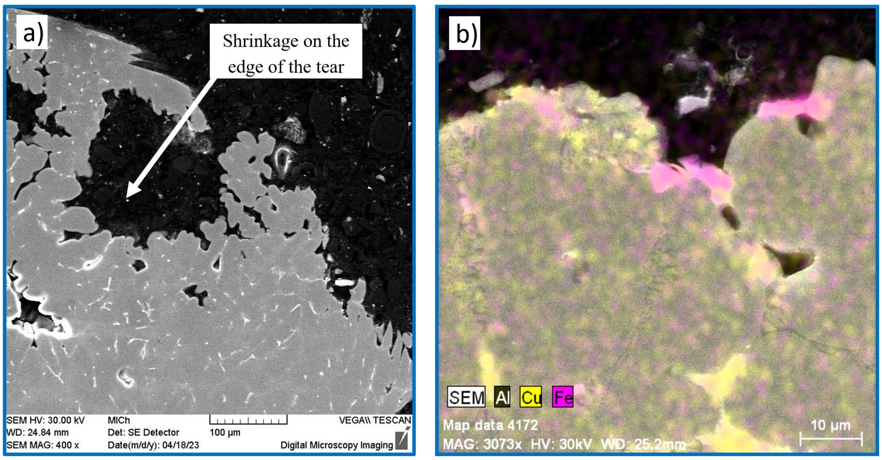

Fig. 6. Tear profile of the reference alloy: a) SEM, b) Mapping

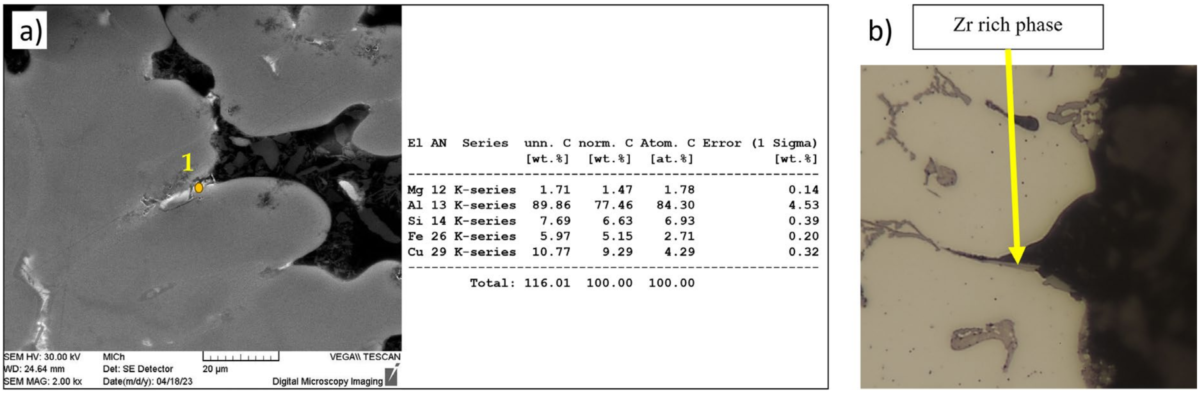

Fig. 7. Tear profile of Zr alloy: a) SEM - EDX point analysis; b) OM

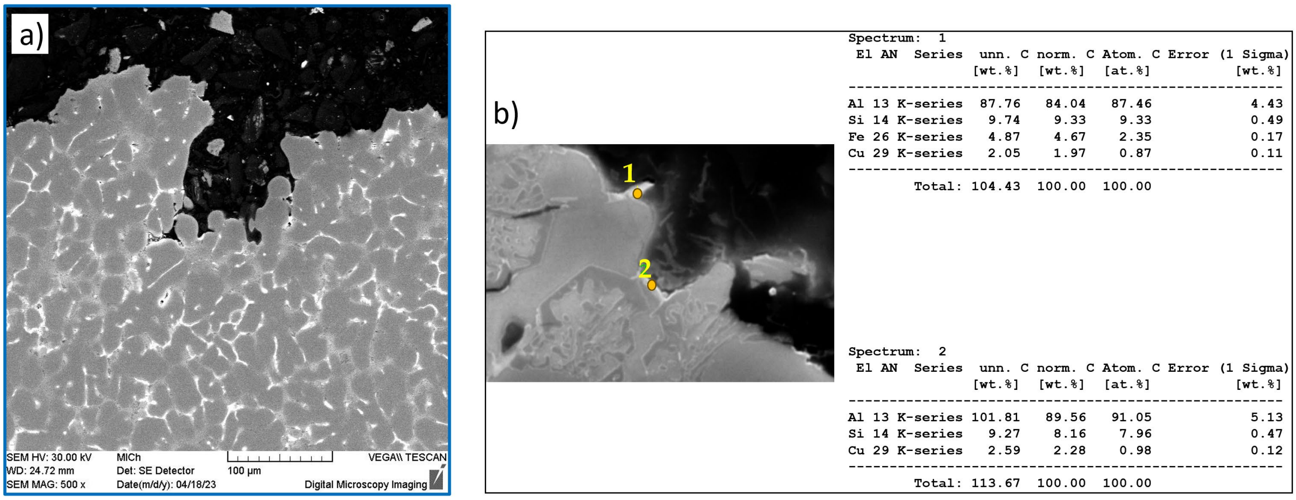

Fig. 8. Tear profile of Ti alloy: a) SEM; b) OM

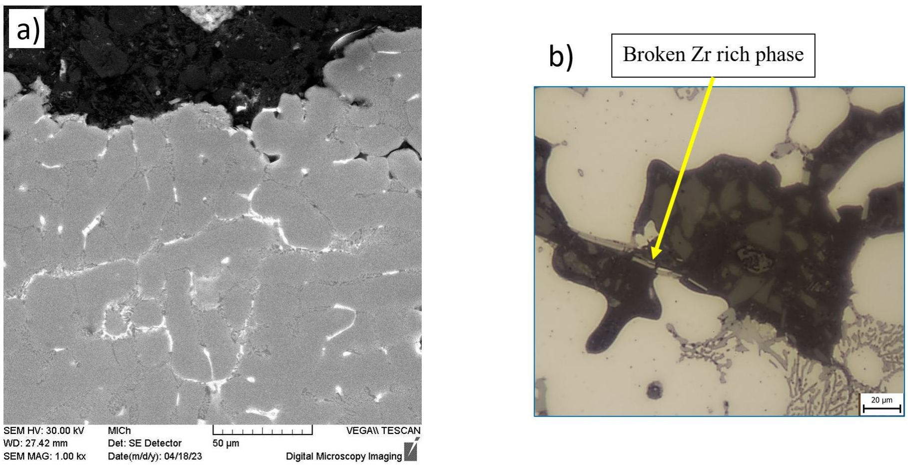

Fig. 9. Tear profile of Zr+Ti alloy: a) SEM; b) EDX point analysis

3.3. Dendrite coherency temperature (DCT)

In the initial stages of solidification of an aluminum alloy, the dendritic crystals separate and move freely in the melt. With further cooling, the dendritic arms of the growing crystals begin to bump into each other until a coherent dendritic network is formed. The temperature at which this occurs is called the dendritic coherence temperature (DCT). DCT temperature values for the studied alloys are shown in Tab. 6 and represent the average of three measurements. For the reference alloy, DCT = 608 °C. By adding 0.2 wt. % Zr, the temperature increased to 612 °C. After adding 0.1 wt. % Ti was DCT temperature = 616 °C. By combining the elements Zr and Ti, DCT = 612 °C was achieved.

Table 6.
Dendritic coherence temperatures of experimental alloys

Alloy	Ref.	Zr 0,2	Ti 0,1	Zr +Ti
DCT	608 °C	612 °C	616 °C	611 °C

4. Conclusions

The aim of the presented article was to evaluate the susceptibility to tears of the reference alloy AlSi5Cu2Mg and after the addition of transition elements Zr and Ti to the alloy. The resulting curves were used to determine the maximum tensile forces and the rate of increase in force that the alloy can achieve without breaking. In these measurements, the alloy with the addition of 0.1% Ti achieved the best results (3 times without breaking and once it was able to "heal" during tear propagation).

AlSi5Cu2Mg alloy without additions, according to qualitative assessment, has a high susceptibility to tear formation, which may be due to a wide solidification interval of the alloy and an increased occurrence of microporosity. By adding Zr to the melt, long needle-like (plates in 3D) phases based on Zr were formed in the structure, which increased the voltage potential and this was reflected in the reduction of the material's resistance to tensile stresses during solidification and the subsequent breach of the integrity of the material. Another factor affecting the increased susceptibility to the formation of tears after the addition of Zr was also related to the formation of shrinkage. Zr-based intermetallic phases were excluded in the initial stages of solidification, when, due to their morphology and size, they could prevent the deposition of melt into the interdendritic regions, thereby promoting the formation of shrinkage / porosity. The influence of Zr on the increased susceptibility to the formation of tears was also confirmed by the analysis of the microstructure near the tears, where it was possible to observe material failure along the intermetallic Zr phase, or its splitting during tear propagation.

The addition of Ti to the AlSi5Cu2Mg alloy led to a grain refinement of the α-Al phase, which was one of the main factors influencing the reduction of tear susceptibility. By using the AlTi5B1 inoculant, the susceptibility to tears also decreased due to the change in grain morphology from columnar to equiaxed and the reduction of the size of equiaxed grains. This improved the overall homogeneity of the structure and enabled a better filling of the melt into the inter-dendritic spaces, which was also related to a higher resistance to the formation of tears.

The temperature of the dendritic coherence of individual alloys did not correspond with the results of tear evaluation. The AlSi5Cu2Mg alloy with the addition of 0.1 wt.% Ti showed the best resistance to tearing even when the DCT temperature was the highest (616 °C). It follows from this fact that even if the temperature of the formation of a complete network of α-phase crystals increased and thus the addition of the liquid component of the alloy to the interdendritic spaces was limited, the positive aspects of the addition of Ti prevailed - grain refinement and the formation of equiaxed grains. To produce castings from the AlSi5Cu2Mg alloy with more demanding shapes, the addition of Ti can be recommended, which improves the resistance of the alloy to the formation of hot tears.

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