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EFFECT OF STRONTIUM INOCULATION ON HOT TEARING IN ALUMINIUM ALLOYS

Main aim of submitted work is evaluation and experimental verification of inoculation effect on Al alloys hot-tear sensitivity. Submitted work consists of two parts. The first part introduces the reader to the hot tearing in general and provides theoretical analysis of hot tearing phenomenon. The second part describes strontium effect on hot tearing susceptibility, and gives the results on hot tearing for various aluminium alloys. During the test, the effect of alloy chemical composition on hot tearing susceptibility was also analyzed. Two different Al-based alloys were examined. Conclusions deals with effect of strontium on hot tearing susceptibility and confirms that main objective was achieved.

Keywords: hot tearing, aluminium alloys, strontium

1. Introduction

Hot tears are integrity defects forming on a semi-solid alloy prior to its complete solidification. Generally, there are two main categories of factors responsible for hot tearing in castings: metallurgical factors and mechanical factors. The metallurgical aspects, such as alloy grain size and morphology of intermetallic phases, influence both the semi-solid mechanical properties (i.e. strength and ductility) of the alloy as well as the ability of the liquid metal to feed the solidifying alloy. Such factors are directly affected by the alloy's solidification characteristics. The mechanical factors, on the other hand, are due to the casting deformation caused by thermal contraction within a rigid steel mold. The rigidity of the mold restricts contraction of the casting during cooling, thereby inducing tensile strain and stress and promoting the formation of hot tears in the casting. The major hindrance in hot tearing analysis is the absence of a method to quantitatively measure the stress and strain causing hot tears in castings. In the case of the remaining factors (i.e. solidification and microstructure), numerous techniques are readily available for characterization [1,2].

2. Effect of strontium on hot tearing susceptibility

In 2012, Qinxin Wu presented work focused on hot tearing of aluminum alloys. One of the work objectives was to compare the susceptibility of A380.1 alloy in the unmodified state and after addition of 0.03 wt. % Sr. The susceptibility was measured by the load force, temperature and the first derivation of the force.

By using the software to determine the change of phase during solidification, it was found that the modified alloy had earlier formation of the eutectic phase (at a higher temperature). The strontium effect did not manifest clearly on the force curve, but the visible change occurred on the curve of the first derivation (Fig. 1). For modified alloys, load velocity during the initial tears is significantly smaller than in the unmodified state [3].

The changes occurred also in linear shrinkage analysis, where the unmodified alloy had a higher value than the alloy modified by Sr (Fig. 2). Wu explains that the presence of strontium can slightly reduce the density and thereby increase the volume, which consequently reduces the value of linear shrinkage. By reducing linear shrinkage, hot tear resistance increases [3,4].

3. Effect of Cu and Ti on hot tearing susceptibility

In aluminium-copper alloys, during Al–Cu eutectic transformation, tearing or cracking can form. Hence, hot tearing formation is seen widely in aluminum alloys which include copper. This was first recorded and proved by Clyne and Davies by correlating the susceptibility-composition relationship in binary systems based on the concept of the existence of critical time periods during the solidification process when the structure is most vulnerable to tearing. Clyne and Davies also created a graph by experimental works, which describes the extent of the hot tearing susceptibility depending on the amount of Ti in the Al alloys (Figure 3). It can be clearly seen that in the range of 0.15 to 0.2 wt. % Ti the hot tear susceptibility significantly increases [5].

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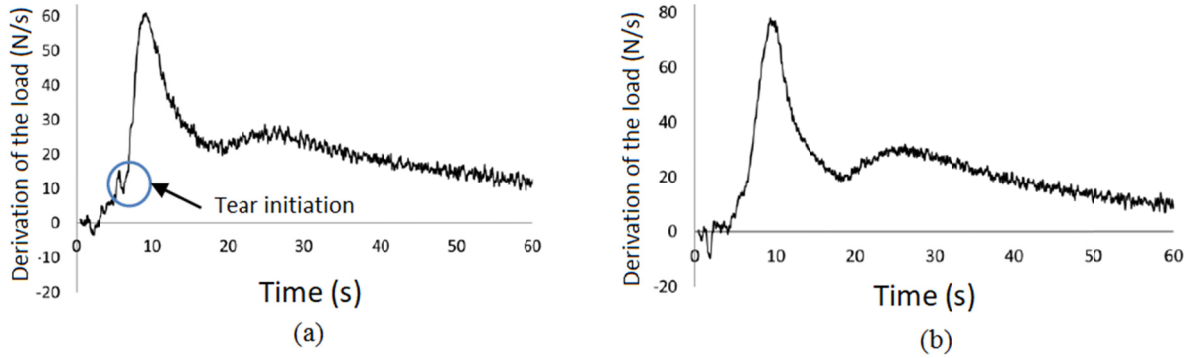#   Corresponding author: marek.bruna@fstroj.uniza.sk

Fig. 1. First derivation of the force (a) non-modified alloy (b) modified alloy [3]
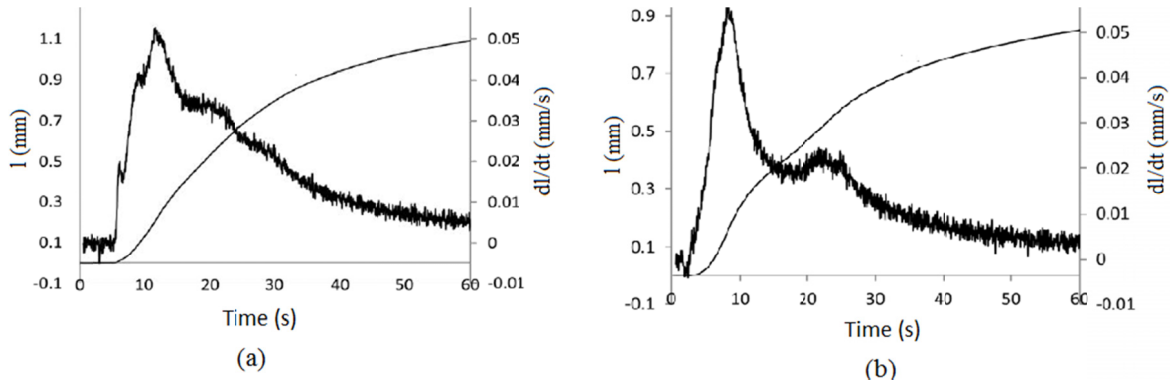

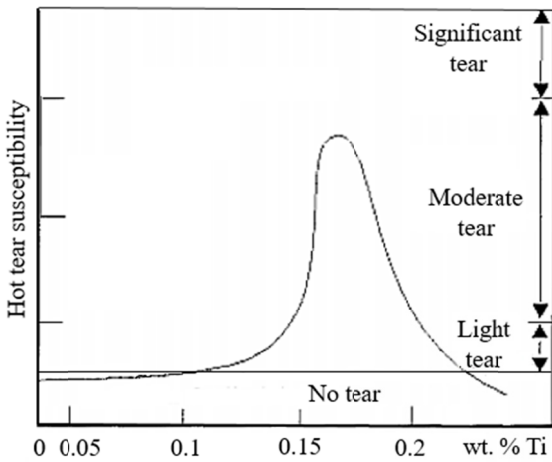Fig. 2. Linear shrinkage (a) non-modified alloy (b) modified alloy [3]

Fig. 3. Hot tear susceptibility dependent on wt. % Ti [5]

4. Objectives

Hot tearing is influenced by many factors. Previous studies have developed various theories to clarify the mechanism of hot tearing but there has been no consensus. Past conventional hot tearing tests have provided a qualitative index by measuring the cracks on the castings. It is more difficult to set up a quantitative experiment, and such a test is limited as to repeatability.

The primary objective of this work is to design, optimize and manufacture a new simple and reliable methodology to analyze hot tearing in aluminum alloy castings. Further imple-ment the experimental melts to investigate the impact of various factors on cracking.

The second objective is to investigate the hot tearing ten-dency of various aluminum alloys. The main goal will be to evaluate effect of chemical composition on hot tearing tendency.

5. Experimental procedure

The experimental section is divided into 4 parts: (1) measur-ing apparatus, (2) alloys, (3) hot tearing index and (4) qualitative evaluation.

Measuring apparatus

Fig. 4 shows the schematic drawing of the whole measur-ing apparatus.

Used alloys

As the first we used aluminium alloy AlSi6Cu4 and Al-Cu4Ti alloy. Table 1 shows the chemical composition of the analyzed alloys.

TABLE 1

Chemical composition of used alloys

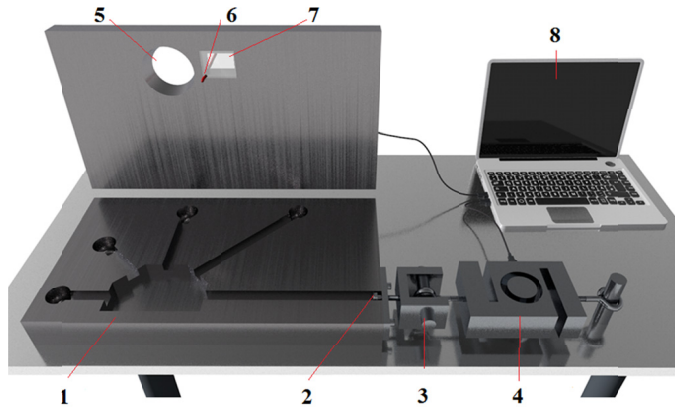| Alloy	Chemical composition [%]							
	Si	Fe	Cu	Mn	Mg	Zn	Ti	Ni
AlSi6Cu4	6.75	0.43	4.84	0.47	0.25	2.0	0.15	0.01
AlCu4Ti	0.05	0.13	4.61	0.456	0.25	—	0.17	0.006

Fig. 4. Measuring apparatus, 1 – Mold, 2 – Anchoring screw, 3 – gripping mechanism, 4 – load cell, 5 – inlet, 6 – thermocouple, 7 – refractory glass, 8 – data processing

Hot tearing index

The evaluated criteria is "Hot tears index" (HTI). Criterion is determined by character and amount of tears in four arms with different length. From each alloy was casted three samples, the sample was removed from the mold after five minutes for the visual evaluation. The melt temperature was $720 \pm 5°C$ and the mold was preheated to $150 \pm 10°C$. The HTI equation was defined as:

$$HTI = \frac{NOT \times \Sigma WF}{NOF}$$

Where:

NOT: number of tears,

NOF: amount of casted samples,

WF: weighting factor.

The value of the weighting factor depend on the nature and size of the individual hot tear. Fig. 5 represents coefficient values for different types of hot tears.

The resulting HTI values can be characterized as a measure of susceptibility to tearing so called "Hot Tears Susceptibility" (HTS). Five levels of severity were set for hot tearing that are identified with intervals shown at Table 2.

From the above values it is clear that with increasing value of HTS, the tendency to hot tearing increases as well. Tab. 3 shows the results of quantitative evaluation together with details of casting parameters.

TABLE 2

HTS intervals

HT index	HTS
<0,5	Minimal susceptibility
0,5-1,25	Low susceptibility
1,25-2,25	Moderate susceptibility
2,25-3,5	High susceptibility
>3,5	Very high susceptibility

The AlSi6Cu4 and AlCu4Ti have been modified by AlSr10 master alloy to reach 0.1; 0.2 and 0.3 wt. % Sr in the final chemical composition before casting. For every value of wt. % Sr four test samples were casted. Three samples for hot tearing evaluation and one sample for chemical composition verification. The measured values are shown in tab. 3 and tab. 4. All samples were cast at a melt temperature of $730 \pm 5°C$ and the preheating temperature of the mold was $150 \pm 10°C$. The process conditions were maintained at a constant value so that the different hot tearing susceptibility will be caused by different chemical composition of the individual alloys.

AlSi6Cu4

Generally, the AlSi6Cu4 alloy has a silicon content of 6.75 wt. %, which exceeds the critical silicon value and thus the alloy is capable of compensating for eventual tearing occurrence. The presence of copper in the given quantity can increase the susceptibility to tear formation due to the extending the solidification interval. Table 3 shows the casting parameters and the HT index and HTS values for the gradual increase of wt. % Sr.

TABLE 3

HTI index a HTS for AlSi6Cu4

wt. % Sr	Mold temperature [°C]	Pouring temperature [°C]	HTI	HTS
0,1 (0,13)	150 ± 10	730 ± 5	1,08	Low susceptibility
0,2 (0,21)	150 ± 10	730 ± 5	0,66	Low susceptibility
0,3 (0,35)	150 ± 10	730 ± 5	1,67	Moderate susceptibility

The first measurement was carried out with the addition of 0.13 wt. % Sr and the resulting HT index was 1.08, which corresponds with low susceptibility to hot tearing. The result
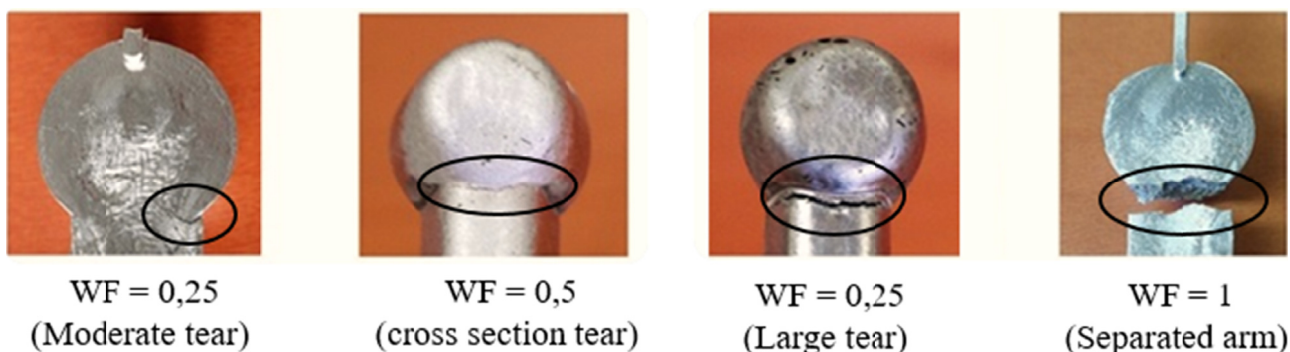

Fig. 5. Weighting factor categories

of the second experimental measurement (Sr content of 0.21 wt. %) Showed that the HT index was 0.66 (low susceptibility). Improvement can be attributed to a better modifying effect of Sr that led to the earlier eutectic phase initiation. The earlier eutectic phase, as stated by Wu in its research, reduces can increase a tearing resistance. The third set of samples with 0.3 wt. % Sr reached value of 1.67 for HT index, which represent moderate susceptibility. Compared with previous measurements, the alloy exhibits the worst results. At 0.3 wt. % Sr the alloy was pre-modified and fragile phase, eliminating the positive effect of strontium can be found in the structure. The content of Ti (0.159 wt. %) In the alloy as well as the above mentioned elements plays an important role in assessing the alloy susceptibility to tearing formation as mentioned in introduction (Fig. 3).

AlCu4Ti

The AlCu4Ti alloy is an alloy with a wide solidification interval (as mentioned above), the copper content (4.612 wt. % Cu) extends this interval. Low Si content (0.05 wt. % Si) increases alloy hot tear susceptibility. Table 4 shows the resulting values of HTI and HTS for the gradual increase in wt. % Sr for the AlCu4Ti alloy.

TABLE 4

HTI index and HTS for AlCu4Ti

wt. % Sr	Mold temperature [°C]	Pouring temperature [°C]	HTI	HTS
0,1 (0,11)	150 ± 10	730 ± 5	2,9	High susceptibility
0,2 (0,18)	150 ± 10	730 ± 5	1,67	Moderate susceptibility
0,3 (0,27)	150 ± 10	730 ± 5	2,08	Moderate susceptibility

From Tab. 4 it can be seen that the best results were achieved with 0.2 wt. % Sr. The HT index is 1.67 and the hot tear susceptibility is moderate. At 0.3 wt. % Sr alloy has a slight increase in HTS (2.08). The worst results were seen with an alloy with the smallest modifier (0.1 wt. % Sr), where the HTI index value is 2.9. It can be stated that the optimal inoculation in our conditions is with 0.2 wt. % Sr due to the earlier creation and a significant transformation of the eutectic silicon shape (thick plates are changed to soft rounded sticks), which increases the resistance to hot tearing. Amount 0.1 wt. % Sr has been clearly insufficient to effectively alter the shape of eutectic silicon, so the HTS is high. Also alloy AlCu4Ti has 0.171 wt. % Ti. The amount of Ti falls within the critical value range (fig. 5), which was reflected in the resulting HT index and HTS.

Qualitative evaluation of test samples

The chapter deals with the evaluation of two alloys from a qualitative point of view. The evaluation was performed by analysis of the load force and temperature curves recorded during the casting process via the thermocouple and load force sensor that was attached to test sample arm. Using the first derivation, we were able to analyze a force load rate. The experiment is aimed to evaluate the effect of the strontium, which amount was

gradually increased (0.1, 0.2, 0.3 wt. % Sr). For every strontium amount, three samples were evaluated but due to scope of the article, only one representative graph for each category will be presented.

AlSi6Cu4 – 0.1 wt. % Sr

From the load development for the alloy modified by 0.1 % wt. (Fig. 6) it can be stated, that the load started to increase at 30.5 seconds ($T = 461$°C), and a tear occurred at 35.5 seconds ($T = 440$°C, $F = 269, 4$ N). Initial tear started to spread, but there has been no complete separation of the arm. In 42.5 seconds load started to increase again, so the tear was partially healed, the force reached a maximum value of 510.5 N. The significant load rate occurred in 21.25 seconds and in 32.75 second ($dS/dt = 28.84$ N/s).
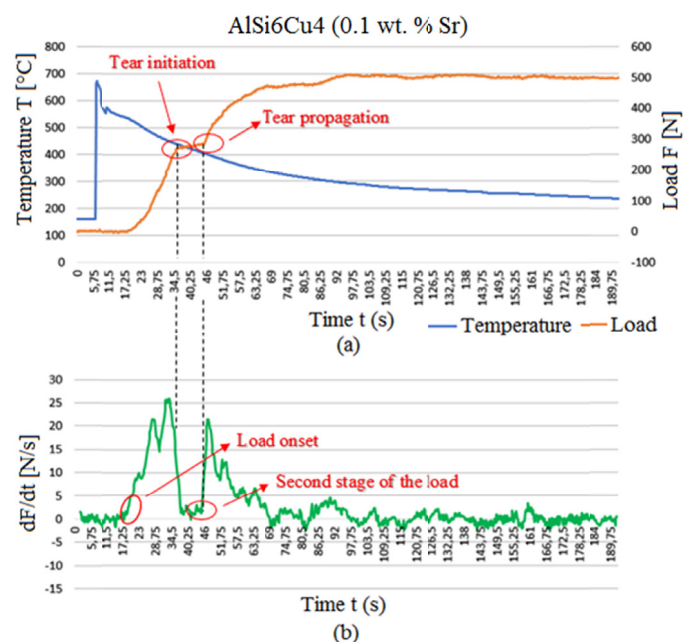

Fig. 6. AlSi6Cu4 with 0.1 wt.% Sr (a) Curve of load force and temperature (b) Load force ratio

AlSi6Cu4 – 0.2 wt. % Sr

The load graph for alloy with 0.2 wt. % Sr (Fig. 7), is smooth without any tear detection. A rapid increase in load force was recorded at 45.75 seconds ($T = 429$°C) and the maximum load force value reached $F = 784.6$ N. The graph in Fig. 7b shows that the maximum value of load rate is $dS/dt = 24.7$ N/s was at 63.5 seconds at 362°C.

AlSi6Cu4 – 0.3 wt. % Sr

The process of load development for AlSi6Cu4 with 0.3 wt. % Sr can be seen at fig. 8. The load began to raise in 27 seconds ($T = 492$°C) and continued to grow, but at 31.75 seconds ($F = 125$ N and $T = 464$°C) attenuation occurred due to tear initiation. This can be observed also on the first derivation curve (Fig. 8b), where after a rapid increase in the force load rate there was a sudden change to $dS/dt = 0$ N/s in approximately 36.5 sec-
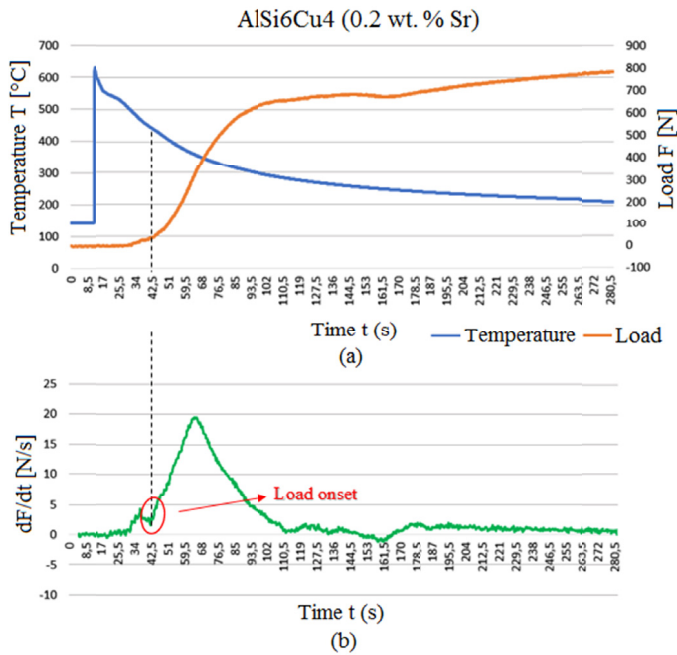
Fig. 7. AlSi6Cu4 with 0.2 wt.% Sr (a) Curve of load force and temperature (b) Load force ratio

onds, representing tear formation. Another increase in the load force curve indicates incomplete tearing. Full separation occurred at 135.25 s ($T = 251$ C, $F = 205$ N). The tear is also visible on the first derivation curve, where at the same time ($t = 135.25$ s) significant drop in the force load rate occurred.
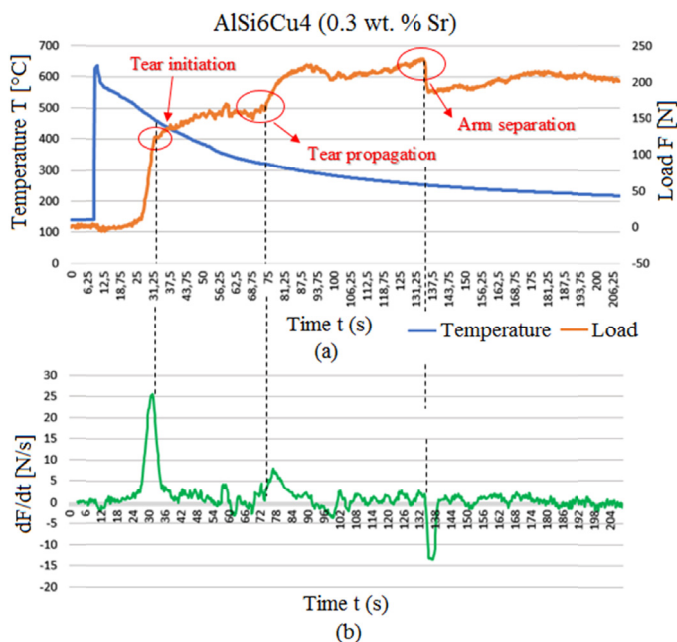

Fig. 8. AlSi6Cu4 with 0.3 wt.% Sr (a) Curve of load force and temperature (b) Load force ratio

AlCu4Ti – 0.1 wt. % Sr

The process of load development for AlCu4Ti with 0.1 wt. % Sr can be seen at fig. 9. The load force curve shows a slight initial force drop followed by an immediate crack and a tear-off.
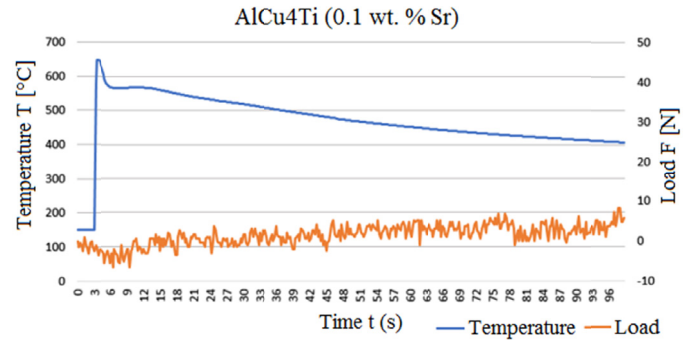

Fig. 9. AlCu4Ti with 0.1 wt.% Sr curve of load force and temperature

The increase in the load force took place in 34.5 seconds ($T = 523°C$) and the hot tear was recorded in 49.75 seconds ($T = 477°C$, $F = 364.2$ N). Tear propagation was completed by a „healing" process at 90.25 seconds, and the force began to rose again to a maximum value of $F = 607$ N (Fig. 10). The load rate at the time of tear formation was $dS/dt = 18.45$ N/s.
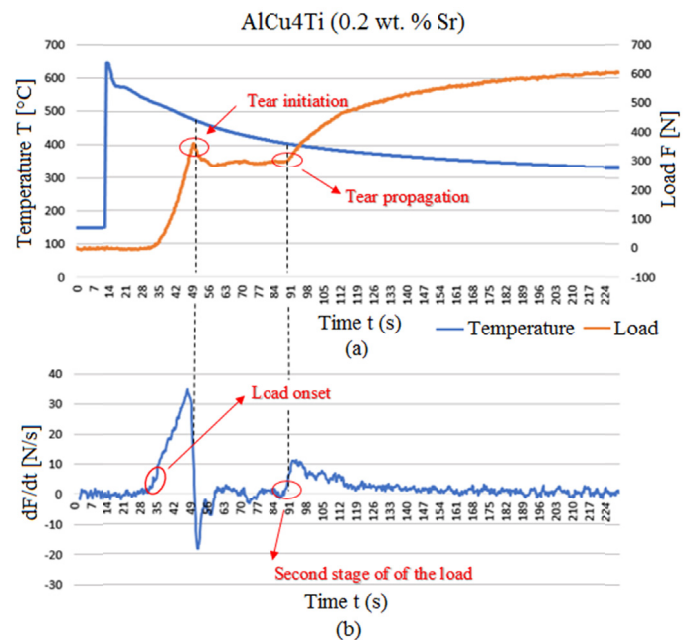

Fig. 10. AlCu4Ti with 0.2 wt.% Sr (a) Curve of load force and temperature (b) Load force ratio

AlSi6Cu4 – 0.3 wt. % Sr

The initial development of the load force occurred in 21 seconds ($T = 532°C$). The nucleation of the tear originated in 29.75 seconds ($T = 487°C$, F = 265.3 N), but consequently the propagation was stopped by the "healing" process (Fig. 11). Second tear formation was recorded at 54 seconds ($T = 392°C$, $F = 665.06$ N). As well as during the first tear, the alloy tried to "heal" by adding the liquid phase to the teared area but process has not been successful and load force started to drop to a value 344 N.
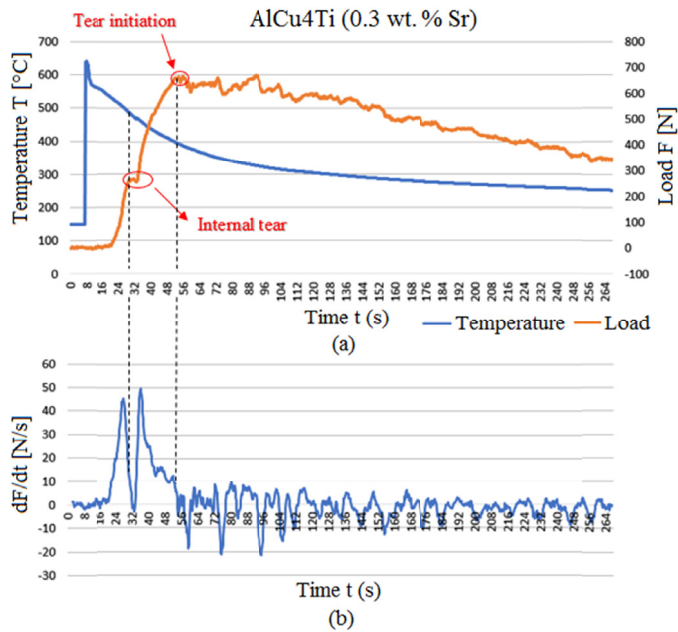
Fig. 11. AlCu4Ti with 0.3 wt.% Sr (a) Curve of load force and temperature (b) Load force ratio

6. Conclusion

The results of the HT index, respectively quantitative evaluation for AlSi6Cu4 and AlCu4Ti alloys are shown in Table 3 and in Table 4. In both cases the optimal amount of strontium (in terms of analyzed parameters) was 0.2 wt. % Sr, where the best modifying effect was demonstrated by the HTS analysis. The assumption is that by properly modified alloy, an earlier eutectic phase occurs, which reduces the force load rate of the resulting tear, thereby increasing hot tear resistance. The worst results for AlSi6Cu4 alloy occurred at 0.3 wt. % Sr due to pre-inoculation and nucleation of fragile phases. For the AlCu4Ti alloy, the highest tearing propagation rate was expressed at 0.1 wt. % Sr, which is likely insufficient amount to effectively change the shape of the eutectic silicon. Further microstructure analysis is required to confirm these assumptions.

In the quantitative evaluation, the force, temperature and load growth curves recorded during the solidification and cooling of the test castings were analyzed. As in the case of the HT Index, it was found to be the best value is 0.2 wt. % Sr. In the case of the AlSi6Cu4 alloy with 0.2 wt. % Sr, no tear was detected. Addition of 0.3 wt. % Sr in AlSi6Cu4 caused the biggest tear occurrence of the measuring arm and the load rate reached the highest value ($dS/dt = 17$ N / s). The AlCu4Ti alloy at 0.2 wt. % Sr achieved the best results within the alloy but, in comparison to AlSi6Cu4, the presence of tears in all three measurements was visible. The least optimal amount of Sr – 0.1 wt. % Sr in AlCu4Ti caused tearing of the measuring arm already in the initial phase. The best results obtained at 0.2 wt. % Sr can be attributed to the best modifying effect and to the fact that strontium also reduces alloy density, thereby increasing the volume and consequently decreasing the value of linear alloy shrinkage, thus decreasing the susceptibility to tearing.

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