FORMATION OF HOT TEARS IN HIGH STRENGTH Al-Cu ALLOYS

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ABSTRACT

The authors studied the high strength Al\textsubscript{5}Cu alloy to establish the parameters deciding the high crack sensitivity and analyse the possibility of decreasing this sensitivity. The results have proved that the region of very high plasticity below BDTT is very narrow and the region of the secondary brittleness appears. This phenomena is caused by the typical microporosity resulted from the difficult feeding of areas between the coarse dendrites formed during the solidification of Al-Cu alloy. The high plasticity region can be enlarged by modification of the alloy with a low addition of boron and titanium.

Keywords: Al-Cu alloys, hot cracking, simulation

1. INTRODUCTION

The aluminium alloys with about 5\% of Cu are characterised by high tensile strength and yield strength. In form of castings they are frequently applied in motorcraft industry as well as in construction of engines. Unfortunately they are very sensible to the formation of cracks during solidification. The aim of this work was to establish the parameters deciding the high crack sensitivity and analyse the possibility of decreasing this sensitivity.

2. METHODS ADOPTED IN INVESTIGATION AND RESULTS

For the programmed study the test bars were cast in metal moulds. The chemical composition of the alloy was: Si-0,53 \%, Cu-4, 58 \%, Mg- 0,022 \%, Fe-0,076 \%,

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Zn-0.14 %, Ti+Zr-0.093 %, Ni-0.022 %, Al – rest. (AlCu01). In the second heat (AlCu02) the alloy was modified with 1 % of the TiB alloy addition to obtain 1 % Ti in alloy. The method of casting is presented in Figure 1.

Fig. 1. Casting of the test bars from AlCu alloy

Rys.1 Odlew próbek do badania właściwości mechanicznych stopów AlCu

The solidification curves of the alloy were recorded by the thermocouple installed in the bar. The results were processed to obtain the derivatives of the curves (ATD curves). The results are presented in Figure 2.

Fig. 2. Solidification curves of non modified (1) and modified Al-Cu5 alloy and their

Rys.2 Krzywe stygnięcia niemodyfikowanego i modyfikowanego stopu AlCu5 oraz ich pochodne.

It can be concluded that the liquidus temperature of the alloy is about 660 °C. The modification reduced it by about 3-4 K. The end of solidification was observed to fall to 528 K for standard as well as modified alloy. The temperature of the start of linear contraction and its development with the alloy temperature decreasing were measured and the coefficient of the linear contraction was then calculated.

The formation of hot tears was observed using a test casting, cast in metal mould. In this casting a hot spot was created by the sand inserts. During solidification the temperature
in hot and cold zone has been measured and the moment of the tear formation was registered by camera.

From the test bars presented on the Figure 1, the samples φ 8 mm were cut out and tested on an Instron testing machine with heating attachment. The testing temperature varied from 460 to 550 °C. The applied tension rate was 0.1 mm/s. Figure 3 presents the reduction of area in the deformation tests.

When raising the test temperature, the alloy attains a zone of superplasticity. The reduction of area is about 100 pct. For non-modified alloy it is between 510-517 C, for a modified alloy this zone is situated a little below 473 –492 C but is markedly larger. Below the superplasticity zone the reduction of area decreases, above - the failure without plastic deformation is observed. The BDTT is about 525 °C. It is corresponding to the recorded temperature of the end of solidification. Results explains the susceptibility of AlCu alloys to hot crack formation. It is interesting to note that in the cooling process the superplasticity range is much narrower than in ferrous alloys [1,2]. Below 500 C the fall of plasticity is observed.

After the modification of alloy, the BDTT is difficult to establish because no rapid change of plasticity is observed but the alloy preserves its plasticity even at higher temperatures, i.e. up to 535 deg. It may be explained by finer dendrite structure resulting from the modification process. The results of the mechanical test have been confirmed by examination of samples fractures after the test.

It should be emphasized that the elongation of samples is very difficult to establish because during the tests at high temperatures the samples were “yielding” in the jaws of the machine, which affected the calculated value of elongation. Due to this, it was difficult to calculate Young’s modulus, necessary for simulation of the field of stresses created in a solidifying casting.

Contrary to plastic properties, the tensile strength reveals a linear drop with increasing temperature, and even at 550 °C it still reaches 8 MPa.
The authors observed the fractures formed at different temperatures, using a scanning microscope. Below the superplasticity region, i.e. at 500°C the view of fracture indicates that the failure process was preceded by a macroscopic plastic deformation (a cone-hemisphere type of fracture). Under magnification, the fragments of fracture indicate the presence of heavy micro-deformations, too. At 517°C the fracture is characterized by a 100% reduction of area. In the central part of the necking, a cylindrical pore, formed probably due to a coalescence of micro-voids along the sample axis, is noted. The enlarged fragments of the place where the sample has failed reveal the presence of numerous, wavy steps which mark the traces where the slip bands have criss-crossed the sample free plane. The examined fracture was formed due to the material carried away from the zone of the reduced area as a consequence of local, directional plastic deformation.

The morphology of fracture formed at a temperature above BDTT is quite different. Under low magnification, no plastic deformation preceding the failure has been noted to occur. The fracture is of a rocky-candy type, indicating the intercrystalline route of crack. The enlarged sections reveal the presence on the surface of smooth fragments with delicate wavy lines. This suggests in an obvious way that the grain boundaries were coated with a thin film of the liquid phase. The decohesion occurred at low stresses along the surface of crystals enveloped with liquid. Similar results of fractographic examinations were obtained for samples after modification.

Examining the results of the tensile test and basing on the macroscopic images of the fractured samples and fractographic analysis, it can be stated that the drastic drop of plasticity is noted in sample of AlCu4 alloy at a temperature of 520°C, and so lower by about 10 K than the determined solidus point. This is probably due to a heavy interdendritic segregation. Within the range of 510 - 517°C, the samples are characterised by a very high plasticity, manifested by an almost 100% reduction of area effectively obtained (99.2%, 99.7%).

In the case of alloy samples after modification, the temperature range within which the alloy is characterised by a very high plasticity is much broader and comprises the values of 473-492°C. With further increase of temperature the drop in the reduction of area is gradual; still at 517°C the reduction of area is over 38 %, while at 540°C, and so obviously above the solidus point, it is 3.58 %.

Alloys from the Al-Cu system are characterised by a relatively wide range of solidification temperatures, amounting to about 130 K. Due to this, the rate of contraction during solidification is high, since it results from both the phase transformation and a considerable drop of temperature. Quite typical is the very narrow range of superplasticity, reaching in non-modified alloys a few dozen degrees only. The propagation of little tears formed in the brittle solid-liquid zone is very probable in the solid state below the superplasticity range. Modification of alloy causes that already at a temperature above the solidus point the material is capable of undergoing some small deformation, and the range of superplasticity is much broader. This explains beneficial effect of AlCu alloys modification with master alloys containing titanium and boron.
3. MODELLING OF CRACK FORMATION IN PILOT CASTING MADE FROM AlCu4 ALLOY

For modelling a ProCast programme was used. Changes in the field of temperature and stresses were determined in a pilot castings. The following conditions of unequivocality, determined in the experiments, were adopted for calculations:

- Liquidus temperature: 660°C
- Temperature of the beginning of linear contraction: 605°C
- Temperature of the end of solidification: 529°C
- Coefficient of linear contraction within the solidification range: 0.02 1/K

Figure 4 shows the test casting with generated computation lattice created by the finite element method. Figures 5 and 6 present fraction of solid phase and field of the main stresses respectively. The stress $\sigma_2$ and $\sigma_3$ are negligible and the main stress is nearly the same as the reduced stress.

Fig. 4 Test casting with generated computation lattice created by the finite element method.
Rys. 4. Próbny odlew z siatką obliczeniową generowaną metodą elementów skończonych.

Fig. 5. Computed fraction of the solid phase at the points shown in Figure 4.
Rys. 5. Wyliczony udział fazy stałej w punktach pokazanych na rys.4)
The highest stress is at the centre of the hot spot. It attains 25 MPa after 70 seconds of solidification. The experiment proves that the failure appears after about 60. At this moment the solid fraction is above 0.85 (figure 16). That confirms the results of the calculation. It was also confirmed that the condition indispensable for the crack formation is the presence of liquid phase on the grain surface.

4. CONCLUSIONS

The conducted studies have proved that Al-Cu alloys are characterised by a wide range of solidification temperatures amounting to about 130 K. The result is an almost 75 K wide section on the solidification curve within which the linear contraction appears. The contraction starts already when the fraction of the solid phase exceeds 50%. An immediate effect are the critical stresses easily formed in castings and breaking the cast material continuity. An analysis of the alloy suffering failure within the material brittle range confirms that the development of brittle fractures occurs in the presence of a residual liquid phase. This has also been confirmed by simulation of the process of temperature and stress field formation. A maximum axial tensile stress occurs in the presence of less than 5% of the liquid phase, when the material has not achieved its plastic state yet, thus indicating that cracks can be expected within this range of temperatures. The results of simulation confirm the measurements of the time necessary for crack formation in pilot casting. In practice, cracks appear after about 60 s when the solid fraction attains more than 0.9; according to the results obtained in simulation tests - after 57 s. Basing on the results obtained in a high-temperature tensile test it is difficult to determine the Young’s modulus of alloy because the deformation is in most part of a plastic nature. Introducing to numerical computations a value estimated with great approximation the calculated stress accords with measured in high temperature tests. The conducted experiments reveal significant effect of alloy modification on its crack formation susceptibility.
The simulation tests were performed on a straight pilot castings with one hot spot. And yet, the obtained results confirm that it is possible to use the numerical method in determination of a probability of crack formation in each casting, providing that alloy properties within the range of solidification range are known.

REFERENCES


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POWSTAWANIE PĘKNIEĆ NA GORĄCO W WYSOKO WYTRZYMALNYCH STOPACH Al-Cu

STRESZCZENIE

Badano parametry decydujące o wysokiej skłonności do tworzenia pęknięć wysokowytrzymających odlewniczych stopów Al-Cu. Analizowano możliwości zmniejszenia tej skłonności, między innymi poprzez modyfikacje. Stwierdzono, że badane stopy charakteryzują się bardzo wąskim zakresem nadplastyczności w temperaturach niższych od temperatury końca krzepnięcia. Zaobserwowano występowanie wtórnej kruchości, związanej z występowaniem makroporowatości będącej wynikiem trudnego zasilania tych stopów. Modelowano pole naprężeń w prostym odlewie zakładając właściwości stopu określone w badaniach empirycznych.

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