Journal
of Achievements in Materials
and Manufacturing Engineering

VOLUME 35
ISSUE 1
July
2009

Structure and mechanical properties of Mg-Si alloys at elevated temperatures

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Received 22.04.2009; published in revised form 01.07.2009

Properties

ABSTRACT

Purpose: of this paper is to extend a complex evaluation of magnesium alloys which requires very often knowledge of structure and mechanical properties at elevated temperatures. These properties are connected with microstructure that is influenced by metallurgical and technological factors and exploitation conditions. Presented knowledge expresses very important information for design and exploitation of these alloys.

Design/methodology/approach: The optical and scanning electron microscopy methods were used for metallographic and fracture analyses of studied magnesium alloys after tensile test at elevated temperatures.

Findings: Objective of this work consisted in determination of structure and mechanical properties progressive magnesium alloys at elevated temperatures.

Research limitations/implications: Knowledge of alloys structure characteristics will be determined new research direction of scope.

Practical implications: The results may be utilized for a relation between structure and properties of the investigated material in process of manufacturing.

Originality/value: These results contribute to complex evaluation of magnesium alloys properties namely for explanation of structure developed new magnesium alloys. The results of this paper are determined for research workers deal by development new exploitations of magnesium alloys.

Keywords: Mechanical properties; Magnesium alloys; Tensile test at elevated temperatures; Structure and fracture analysis

Reference to this paper should be given in the following way:
L. Čížek, A. Hanus, O. Blahož, T. Tański, L.A. Dobrzański, M. Práźmowski, L. Pawlica, Structure and mechanical properties of Mg-Si alloys at elevated temperatures, Journal of Achievements in Materials and Manufacturing Engineering 35/1 (2009) 37-46.

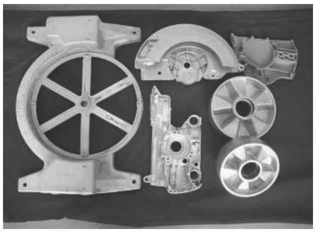
1. Introduction

Properties of magnesium alloys are connected with microstructure, which is influenced by metallurgical and technological aspects. The material selection is preceded by analysis of many factors like: mechanical, design, environmental, urbanization, recycling, cost, availability, and weight related issues, which may change the existing conditions and emerge the needs resulting from the supplier-customer relation [1-5].

Contemporary materials should be characterised with high mechanical, physical and chemical properties, as well as technological ones, to ensure the long time and reliable use. The above mentioned requirements and expectations regarding the contemporary materials are met by the non-ferrous metals alloys used nowadays, including also the magnesium alloys. Magnesium alloys and their derivatives, as materials from the lightweight and ultra-lightweight family are characteristic of low density (1.5-1.8 g/cm^3) and high strength in relation to their weight [1, 3].

A rising interest in exploitations of magnesium alloys which are an examination subject in many research and university centers in the country and abroad as well as in major manufacturers of mechanical engineering industry, chemical, power, textile, electronic, paper and aeronautic industries and in particular automotive, shipbuilding, aircraft, sports and even nuclear industries is observed (Fig. 1)

a) Camera body



b) Vehicle component

Fig. 1. Examples of magnesium alloys application

The interest in application of magnesium alloys in wide spectrum of industries rises from traditional used alloys, such as alloys with aluminium addition [6-12] as the main alloying component which is continuously improving and still new types are being developed [13,14]. The increasing use of magnesium alloys is caused by the manufacturing progress of new reliable alloys with the addition of Zr, Ce, Cd and very light alloys are made from Li [2-5].

Mg-Al-Si alloys are characterised by improved creep resistance at temperatures up to 150 ºC, they have good plasticity, ultimate strength and yield strength. They are used in crank cases of air-cooled automobile engines, for production of clutch pistons and blade stators.

Alloys containing silicon has an eutectic structure for example in case of the alloy with 1 – 1.5 wt. % silicon content. If the silicon contents are higher than the limit corresponding to eutectic concentration, the phase Mg2Si crystallises in form of needles and the alloy becomes brittle. Advantage of these alloys consists in their good cast- ability and resistance to corrosion [2,13].

2. Materials and experimental methods

The studied model alloy AS31 in as cast state was used for investigation of structure and properties at elevated temperatures in experimental part of the work. Chemical composition of alloy is given in the Table 1.

Testing of mechanical properties under elevated temperatures was made on tensile testing machine INOVA - TSM 20. Temperature range of the device was set up to 800°C. Samples for tensile test in as-cast state were in a form of bar with length of 115 mm, diameter 6 mm, in the middle the diameter was reduced down to 4 mm during a length of 30 mm.

Two crosshead rate levels - 0.6 mm/min and 6 mm/min were chosen for investigations will deliver a better understanding of the mechanical properties influence on deformation character.

In order to complete the obtained results the microstructure and fracture character was studied for the investigated samples.

Optical microscope of the NEOPHOT 2 type was used for microstructure investigation of the Mg alloys.

Macroscopic observation of the fracture surfaces was made on stereo microscope Olympus SZX 12.

For fracture investigation the scanning electron microscope JEOL JSM 6490LV was used.

3. Results and discussion

3.1. Tensile tests results

Temperature influence on tensile test results of the investigated AS31 alloy is presented in Figs. 2 to 6 or in Tables 2 and 3. The following values were measured during the test: tensile strength (R_m), contraction (Z), elongation to crack ratio and work to crack ratio – in comparison to the integral deformation energy (IDE). Dependence of sample deformation propagation until its destruction at various temperatures with a crosshead rate of 6 mm/min was monitored for the first test series (Figure 2a) and with a rate of 0,6 mm/min for the second series (Figure 2b). The measurements were performed at temperature range of 15°C to 400°C.

Table 1.
Chemical composition of Mg-Si alloys (in weight %)

Alloy	Mg	Al	Zn	Mn	Si	Fe	Be	Zr	Sn
AS31-1	95.32	3.43	0.13	0.31	0.82	0.002	0.001	0.002	0.002

Table 2.
Results of tensile test of Mg-Si alloys (at crosshead rate of 6 mm/min)

Sample	Temperature (C)	Force (N)	R_m (MPa)	Z (%)	Elong. (mm)	IDE (J)
1	18	1353	107.8	4	1.90	1.70
3	101	1012	80.6	3	1.57	1.04
4	203	1187	94.5	19	3.22	2.89
9	300	773	61.5	19	4.20	2.61
10	350	381	30.3	8	1.95	0.44
6	400	443	35.3	25	7.31	2.72

Table 3.
Results of tensile test of Mg-Si alloys (at crosshead rate of 0.6 mm/min)

Sample	Temperature (C)	Force (N)	R_m (MPa)	Z (%)	Elong. (mm)	IDE (J)
11	25	1603	127.7	8	2.57	2.72
15	153	694	55.2	10	1.80	0.86
12	203	751	59.8	0	1.42	0.81
13	251	459	36.5	1	2.11	0.55
14	301	495	36.5	1	2.11	0.68

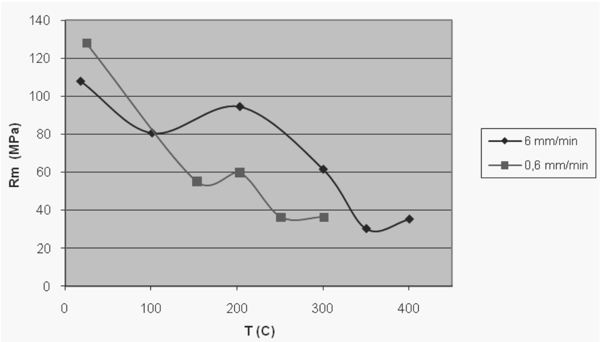


Fig. 2. Influence of temperature and crosshead rate on R_m

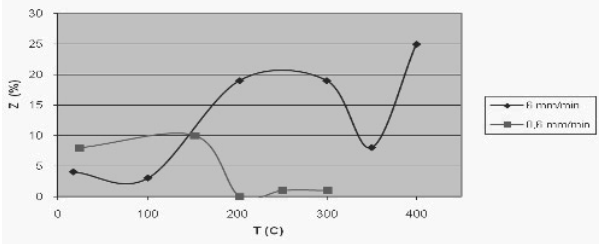


Fig. 3. Influence of temperature and crosshead rate on contraction

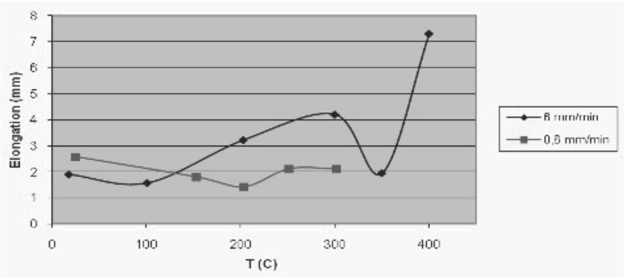


Fig. 4. Influence of temperature and crosshead rate on elongation

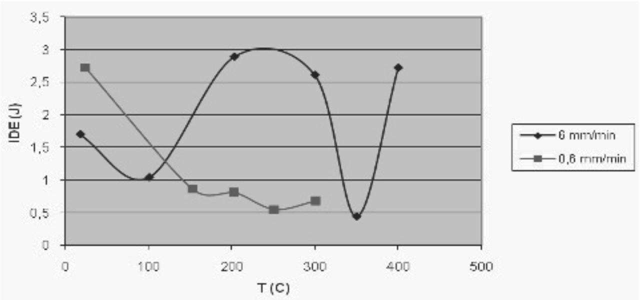


Fig. 5. Influence of temperature and crosshead rate on IDE

The measured tensile strength of the investigated alloy at room temperature at the crosshead rate 0.6 mm/min is slightly higher than in case of 6 mm/min rate. It can be state on the basis of the performed analysis of the temperature dependence on results of mechanical properties tests for two applied crosshead rates that by temperature increase up to 150 ºC the strength of magnesium alloy decreases also with decrease of other measured parameters (contraction, crack deformation and work to crack – integral deformation energy IDE), this decrease is bigger at the crosshead rate of 0.6 mm/min.

Tensile strength value of the investigated alloy, measured in the temperature range of 150 ºC to 200 ºC increases for both the applied crosshead rates. At temperatures above 200 ºC the temperature characteristic of investigated parameters develops differently for both speed rates. At temperature above 200 ºC the measured tensile strength of the alloy drops more steeply at both crosshead rates, and decreases by the crosshead rate of 0.6 mm/min.

Tensile strength of the alloy measured at a crosshead rate of 0.6 mm/min falls below the tensile strength value determined at a crosshead rate of 6 mm/min, and at higher temperatures it is clearly dependent on it, similarly occurs for the crosshead rate 6 mm/min.

In the temperature range between 200 ºC and 300 ºC the contraction and crack work gain considerably higher values at the crosshead rate 6 mm/min than at lower that. Moreover at crosshead rate of 6 mm/min above the temperature of 350 ºC they increase significantly. The plasticity increase can be related either to increase of active dislocations movement or in greater number of slip systems, or connected with quasi-plasticity with quasi-liquid crystal state, while at lower rate the space between grains is smaller - which causes cracks.

3.2. Fracture surfaces

Optical microscope and SEM investigation of fracture areas at selected temperatures are shown in Figs. 6-13.

Macroscopic investigation of fracture surfaces

Macroscopic observation of fracture surfaces was made on stereo microscope Olympus SZX 12. Appearance of fracture surfaces of selected samples are shown in the enclosed Figs. 6a-13a.

SEM images of fracture surfaces performed at crosshead rate of 6 mm/min are shown in the Figs. 6a-9a.

SEM images of fracture surfaces performed at crosshead rate 0,6 mm/min are shown in the Figs. 10a-13a.

It can be seen from the figures that the character of the fractures surface changes substantially with testing temperature. For the samples No. 1 at lower testing temperatures the fracture surface is regularly circular with small contraction. With increasing temperature the shape becomes more irregular and in the sample No. 6 at the temperature of 400 C it is strongly deformed with high contraction.

SEM analyse of fracture surfaces

For detailed investigation of the samples after tensile test SEM JEOL JSM 6490LV was used. Details of fracture areas at selected temperatures are shown in Figs. 6b-13b.

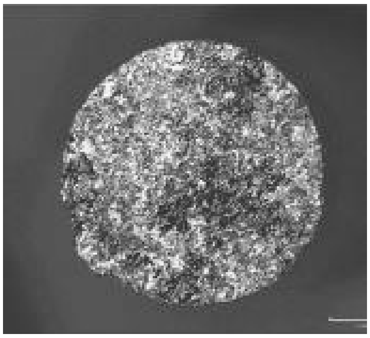


Fig. 6a. Fracture area of sample 1 at 18 ºC (v=6mm/s)

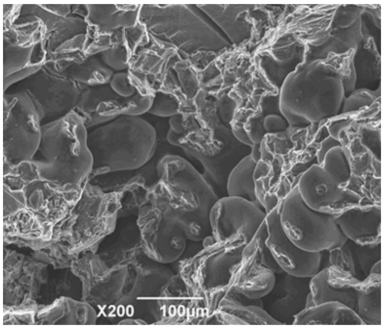


Fig. 6b. Fracture area of sample in Fig. 6a.

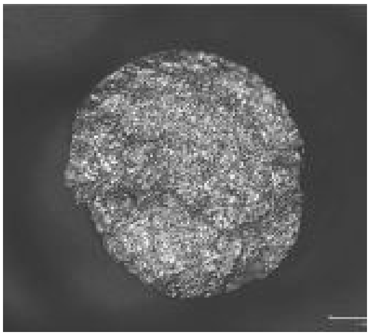


Fig. 7a. Fracture area of sample 4 at 203 ºC (v=6mm/s)

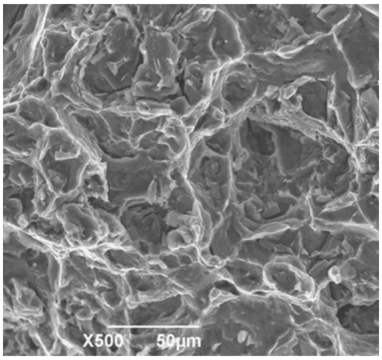


Fig. 7b. Fracture area of sample in Fig. 7a.

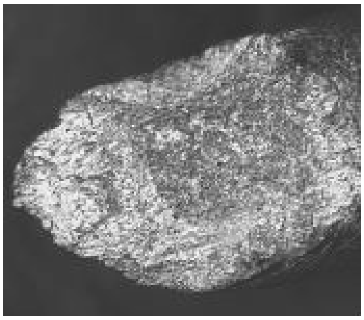


Fig. 8a. Fracture area of sample 9 at 300 ºC (v=6 mm/s)

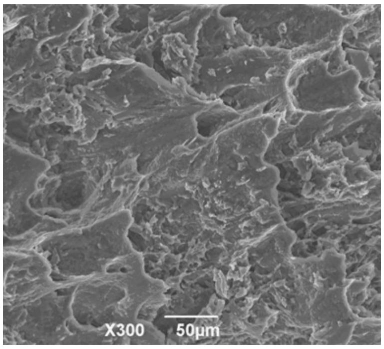


Fig. 8b. Fracture area of sample in Fig. 8a.

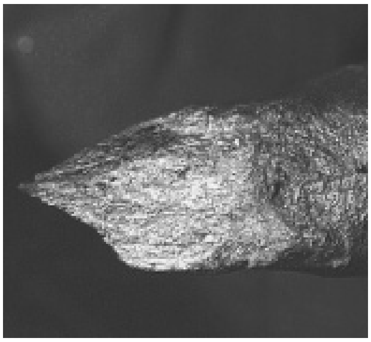


Fig. 9a. Fracture area of sample 6 at 400 ºC (v=6 mm/s)

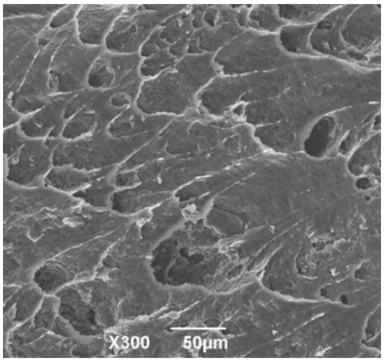


Fig. 9b. Fracture area of sample in Fig. 9a

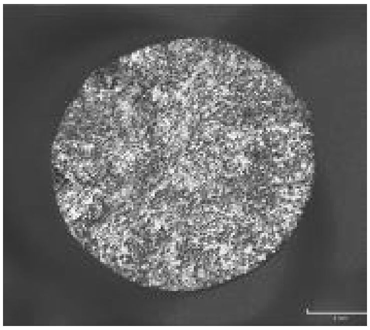


Fig. 10a. Fracture area of sample 11 at 25 ºC (v=0.6 mm/s)

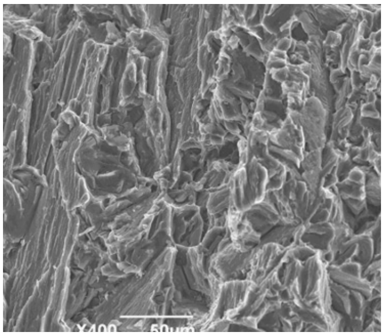


Fig. 10b. Fracture area of sample in Fig. 10a.

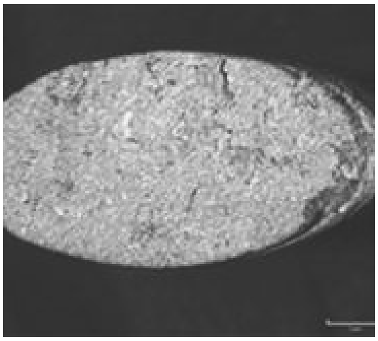


Fig. 11a. Fracture area of sample 12 at 203 ºC (v=0.6 mm/s)

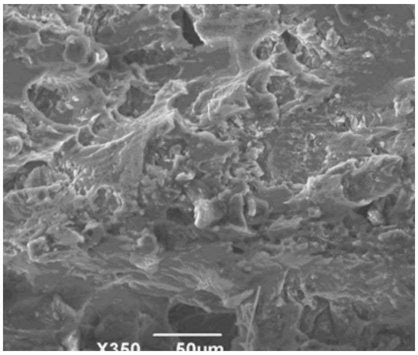


Fig. 11b. Fracture area of sample in Fig. 11a

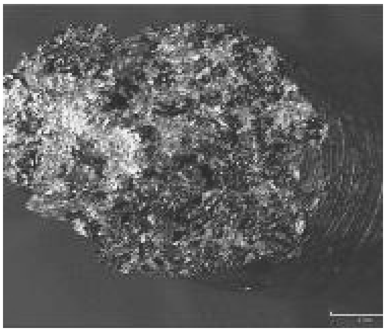


Fig. 12a. Fracture area of sample 13 at 251 ºC (v=0.6 mm/s)

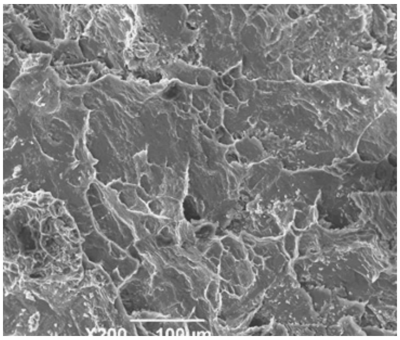


Fig. 12b. Fracture area of sample in Fig. 12a

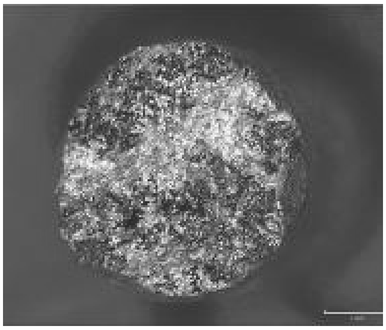


Fig. 13a. Fracture area of sample 14 at 301 ºC (v=0.6 mm/s)

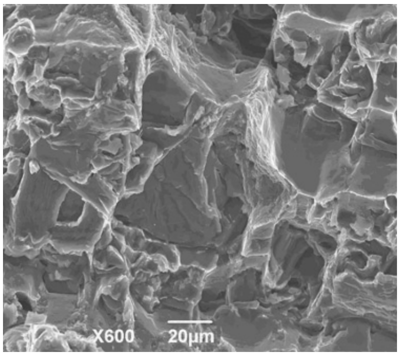


Fig. 13b. Fracture area of sample in Fig. 13a

Fractures at low temperatures at both crosshead rates has prevailing a brittle character along the boundaries of inter-dendritic grains with small share of plastic fracture areas. At medium temperatures the fractures achieves also the areas with higher share of plastic fracture. At higher temperatures there is a higher occurrence of fracture on the grain boundaries with significant share of cavities formation. At the crosshead rate of 6 mm/min and temperature of 400 ºC the plastic character of fracture surface prevails the formation of cavities.

The findings described above correspond with the results of increased plasticity obtained at tensile tests at these temperatures.

3.3. Microstructure investigations

Microstructure of the AS31 alloy in as cast state is shown in Figure 14 [14]. The microstructures of the sample centre and of the crack area performed in the cutting plane parallel with its axis at selected temperatures are shown in the Figs. 15-22.

Central part of the sample was investigated for the reason of possible structure anomalies occurrence due to the fact, that on the basis of previous works with similar magnesium alloys the occurrence of inhomogeneity was observed, also shrinkage porosities formed during casting process can be expected [12].

It can be stated on the basis of comparison of microstructures from central parts of investigated samples after tensile test (Figs .15a – 22a), that no substantial differences in structure were observed. Some structure deviations can be explained by changes caused temperature increase.

Structure near the fracture area is differences for samples tested under different temperatures and at various crosshead rates. These differences are caused by different crack development at various temperatures and different crosshead rates, they will also compared on the basis of characteristics made by SEM investigations. From metallographic point of view it is possible to observe on the boundary of fracture surface depends on presence of structural components, crucial for placement of the crack.

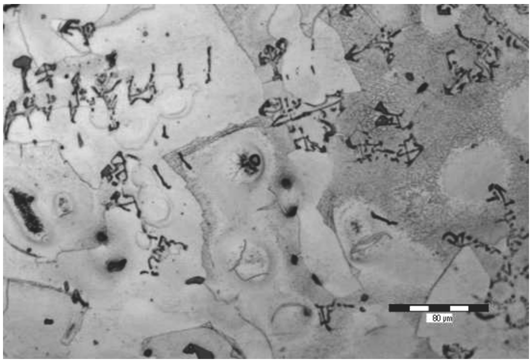
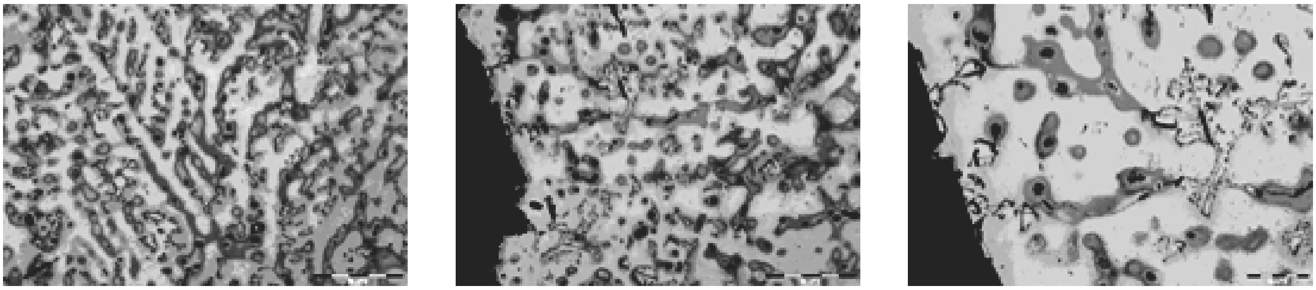


Fig. 14. Microstructure of alloy AS31 as cast

In case of metallographic observations of the samples tested at the crosshead rates 6 mm/min the following interdependences

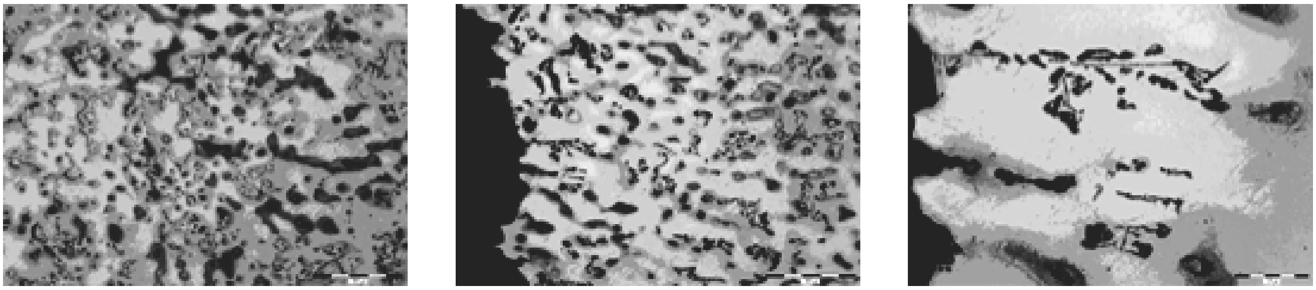


a) Centre of the sample

b) Areas near the fracture

c) Detail of b)

Fig. 15. Sample 1, 18 ºC (v=6 mm/s)

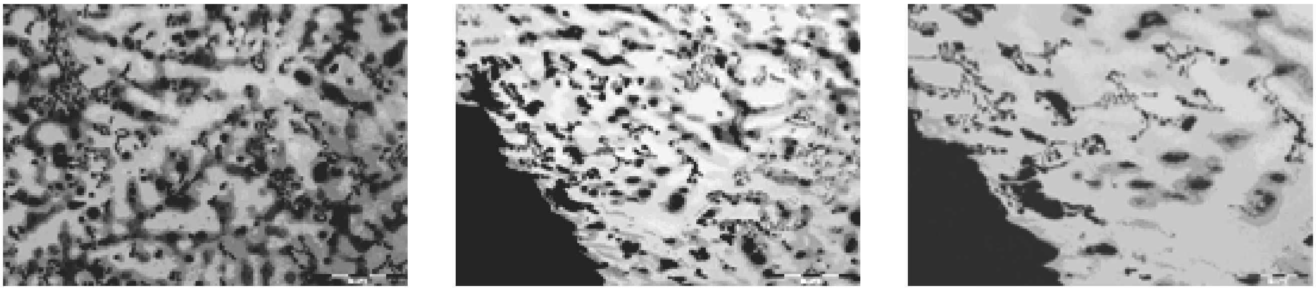


a) Centre of the sample

b) Area near the fracture

c) Detail of b)

Fig. 16. Sample 4, 203ºC (v=6 mm/s)

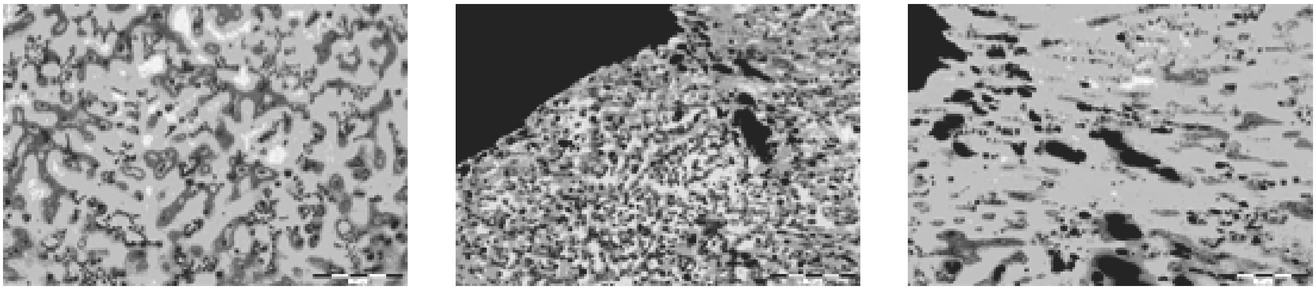


a) Centre of the sample

b) Area near the fracture

c) Detail of b)

Fig. 17. Sample 9, 300ºC (v=6 mm/s)



a) Centre of the sample

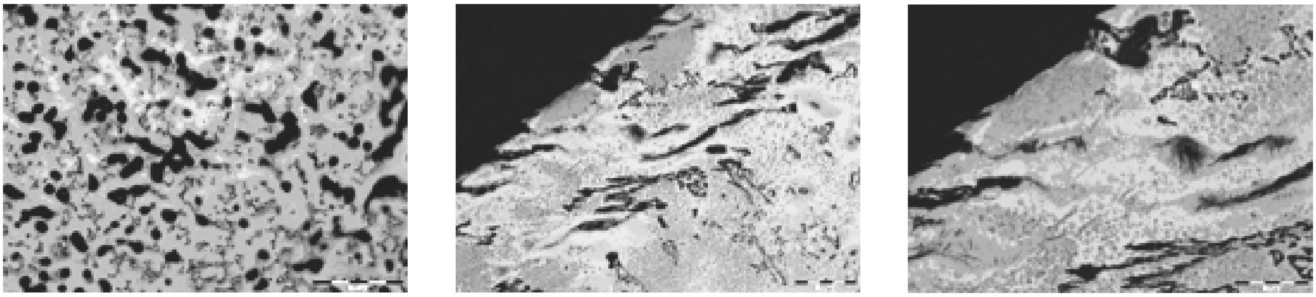
b) Area near the fracture

c) Detail of b)

Fig.18. Sample 6, 400 ºC (v=6 mm/s)

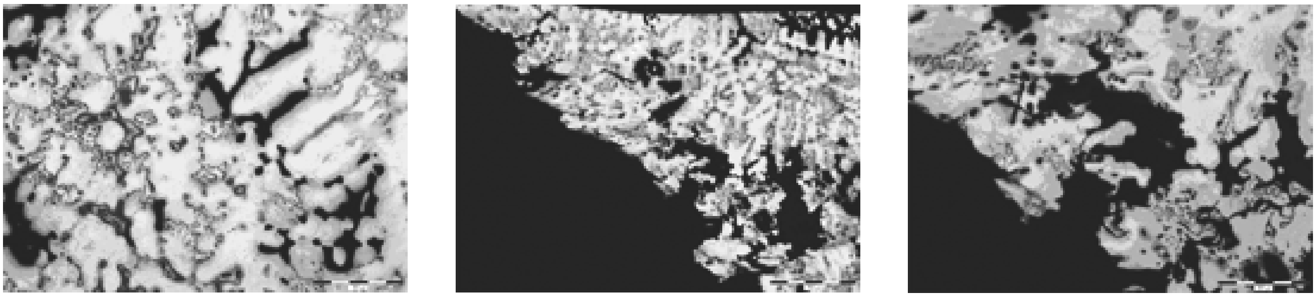
a) Centre of the sample b) Area near the fracture c) Detail of b)

Fig. 19. Sample 11, 25ºC (v=0.6 mm/s)



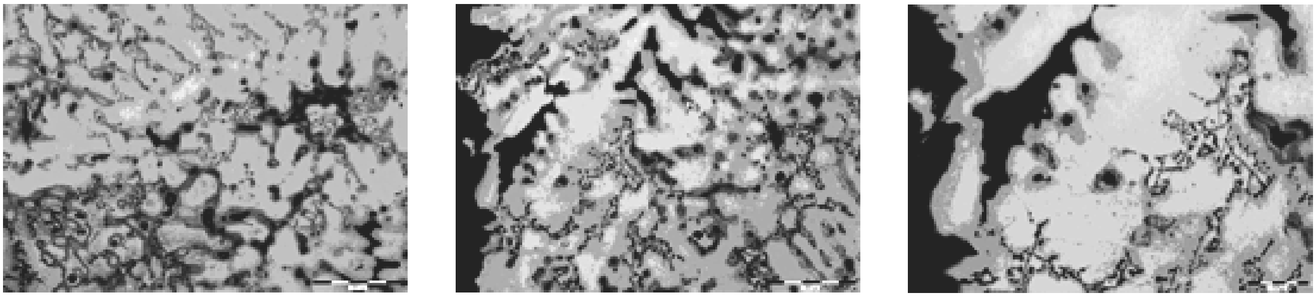
a) Centre of the sample b) Area near the fracture c) Detail of b)

Fig. 20. Sample 12, 203ºC (v=0.6 mm/s)



a) Centre of the sample b) Area near the fracture c) Detail of b)

Fig. 21. Sample 13, 251ºC (v=0.6 mm/s)



a) Centre of the sample b) Area near the fracture c) Detail of b)

Fig. 22. Sample 14, 301ºC (v=0.6 mm/s)

can be observed: at room temperature (Fig. 15b) as well at temperature of 100 ºC it is obvious that failure occurs in the area were the phase Mg_2Si is present in form of needle, this phase is etched in a dark colour in the optical microscope images. It is possible to observe, that this type of failure is present at the temperature of 200 ºC, this phenomenon is practically not observed at higher temperatures. In the temperatures range of 200 – 300 ºC higher plasticity near the fracture surface is state. At the temperature of 350 ºC there occurs another change of the crack character, the crack passes more distinctly through the inter-dendritic space and also the cavities increase noticeable, similarly as in the study [12] of the AZ91, or AZ61 alloy.

At the temperature of 400ºC there are big deformations in the crack area, which is characterised by elongated grains and cavities occurrence, which are also elongated and placed according to the applied tensile stress direction. The character of so called “Chinese characters” is also changed and disrupted (Fig. 18b). It is possible to conclude that for the samples deformed by a rate of 0.6 mm/min (see the Figs. 19b – 22b), that the crack characteristics are different for both applied crosshead rates 0.6 and 6 mm/min. In case of crack achieved by the rate of 0.6 mm/min at temperatures above 250ºC the contraction and IDE values are nearly zero.At lower temperatures the failures in the area near the main axis of so called “Chinese characters” does not clearly appears (Figures 15b, 19b). Cavities formation occurs in this case at lower temperatures, as it was observed for the samples with bigger deformation rate. Beside this, no increase of plasticity near the fracture surface was observed. These conclusions are conform with results of the tensile test.

4. Conclusions

The following can be conclude on the basis of the achieved results:

- For the investigated AS31 alloy an dendritic aluminium structure with partially segregated phase $Mg_{17}Al_{12}$ and with segregated solid solution so called “Chinese characters” - Mg_2Si phase was observed.
- Optimal mechanical properties of the alloy at crosshead rate 6 mm/min were achieved at the temperature of 200°C; the properties decrease above this temperature.
- Mechanical properties for the crosshead rate of 0.6 mm/min have lower values than it could be state for the crosshead rate of 6 mm/min.
- Above the temperature of 350 °C the R_m achieves its minimum, which can be caused by smelting of inter-dendritically segregated eutectics, as it was confirmed by metallographic structure analysis from the near fracture surface, as well as by fracture analysis.
- Microstructure Changes and crack characteristics of the samples deformed by the 0.6 mm/min rate differ from that’s at the crosshead rates of 6 mm/min observed. The biggest difference between structure near the fracture area and placed in sample centre in the case of the samples tested at crosshead rate of 0,6 mm/min.
- It was established on the basis of metallographic and SEM analysis, that the crack runs preferably inter-crystallically at the places with inter-dendritically segregated eutectics with contents of Mg_{17} Al_{12}, or Mg_2Si, however, in dependence on temperature of testing areas with certain share of plastic trans-crystalline fracture were observed.
- The structure and fracture characteristics described above correspond with the results obtained for tensile tests dependent on the temperature.
- It can be state that an increase of cavities share occurs according to temperature increase during the performed tests, this was confirmed for samples deformed by the 0.6 mm/min rate.

Acknowledgements

The work was financed by aim of project MSM 6198910015 and Grant Agency of the Czech Republic GA-101/08/1110 and developed in the framework of solution of the MSM 6198910013 and Czech-Poland project INTERREG IIIA.

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