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The evaluation of microporosity and mechanical properties in high strength aluminum alloys with the use of numerical analysis and computed tomography

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Abstract

One of the aspects of sustainable development is the reduction of the concentration of CO_2 in the atmosphere. This could be achieved for example by the reduction of fuel consumption. That is why the research for the new construction and material solutions regarding the reduction of the weight of vehicles is so important. Alongside weight reduction of different kinds of vehicles, there is also the possibility of the application of alternative propulsion systems. The lower total vehicle weight allows to extend the lifetime of the batteries with the reduction of recharge cycles. The use of the aluminum base AlZnMgCu as cast alloy which is known as 7xxx series plastic forming alloy, allows to significantly reduce the weight of the components manufactured as cast structures, ensuring high strength properties. The wide range of the solidification temperature, which is more than 150°C, characterizes this alloy with a high tendency to create micro and macro porosity. The study presents the relationship between the cooling rate and the area of occurrence and percentage of microporosity. Obtained results were linked to the local tensile strength predicted in the simulation analysis. The evaluation of the microporosity was performed on the basis of the CT (computed tomography) and the analysis of the alloy microstructure. The microstructure analysis was carried out on a test specimen obtained from the varying wall thickness of the experimental casting. The evaluation of the mechanical properties was conducted on the basis of the static tensile test.

Keywords: AlZnMgCu alloy, microporosity, mechanical properties, computed tomography

1. Introduction

The use of high-strength AlZnMgCu aluminum alloy in critical structures and producing heavy-duty castings remains in the trials and testing stage [1–4]. These alloys are not typical for casting. However, their chemical composition is similar to the 7xxx wrought aluminium series. This material possesses high strength > 500 MPa, while maintaining a good ductility with elongation of up to 20%. These properties are achieved by appropriate plastic processing [5,6].

Using casting technology as a manufacturing process of such a material eliminates the strain hardening mechanism but the expected mechanical properties can be achieved by directional solidification and optimal heat treatment. Good strength in casting AlZnMgCu alloy is the result of the precipitation of nano-sized particles of intermetallic phases, such as: η($AlZn_2$), T(Al_6CuMg_4), S(Al_2CuMg), from supersaturated α-Al solution [7]. The effectiveness of strength precipitation strongly depends on the chemical composition and the solidification rate. For example, the preference for higher strength zinc content, greatly reduces the ductility of the alloy. The elimination of impurities, selection of the heat treatment process and the optimum balance of key alloying elements (Zn, Mg, Cu) will provide the desired structure and strength properties of the alloy.

Castings typically have a non-uniform wall thickness, which effect the solidification rate. For the analyzed AlZnMgCu alloy which has a solidification range of over 150°C, generates a significant problem with the formation of shrinkage porosity and shrinkage gas microporosity. The estimation of the influence of shrinkage porosity and microporosity on the strength properties obtained in the cast structure, allows for more efficient design and topology design optimization technology of castings produced of high-alloy AlZnMgCu.

The aim of this study was to evaluate the influence of microporosity on the mechanical properties of high-strength AlZnMgCu alloy, based on experimental studies of material from a real cast.

2. Research methodology

The methodology for evaluating the effect of porosity on strength properties takes into account the use of numerical analysis of the casting process in order to identify the actual areas of the casting with representative strength values. Additionally, numerical strength analysis of the rocker arm loading process was carried out to determine the most sensitive areas with the highest material stress.

AlZnMgCu alloy strength tests were performed on samples cut from an actual casting made from AlZnMgCu alloy with the chemical composition shown in Table 1.

Table 1. The chemical composition of AlZnMgCu alloy, wt. %

Zn	Mg	Cu	Mn	Zr	Be	Ti	Fe	Si	Al
5.80	1.98	1.53	0.17	0.13	0.14	0.10	0.08	0.06	rest

The rocker arm was manufactured in the gravity sand casting process. The casting has dimensions of 540 × 520 × 140 mm. The shape has I-beam cross-sectional areas of the arms and the non-uniform wall thickness varying from 10 mm to about 40 mm. In the proposed casting technology, the location of gating and feeding systems favors varied solidification time. The cast rocker is poured over with molten metal at a temperature of 710°C. The preparation of the mould and the finished cast are shown in Figure 1.

The cast suspension component, after removal from the sand mould was subjected to heat treatment to achieve a homogenized structure, a desired strength and plasticity values. The T6 heat treatment assumes a two-stage process, such as solution treatment and artificial aging, as shown in Figure 2, in the form of the diagram of temperature changes over time.

Numerical analysis of the exploitation conditions of the rocker arm was conducted in order to determine the maximum stress values occurring in the casting [2,8]. For the load schematic the maximum stress values are located in the front of the arm. The stress distribution scheme for the selected load step is shown in Figure 3.

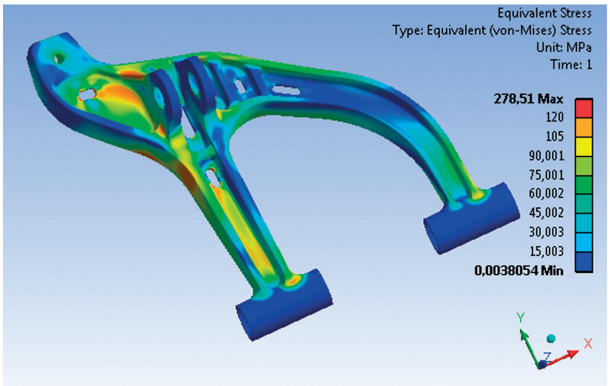

Fig. 3. Stress distribution in the rocker arm casting, MPa

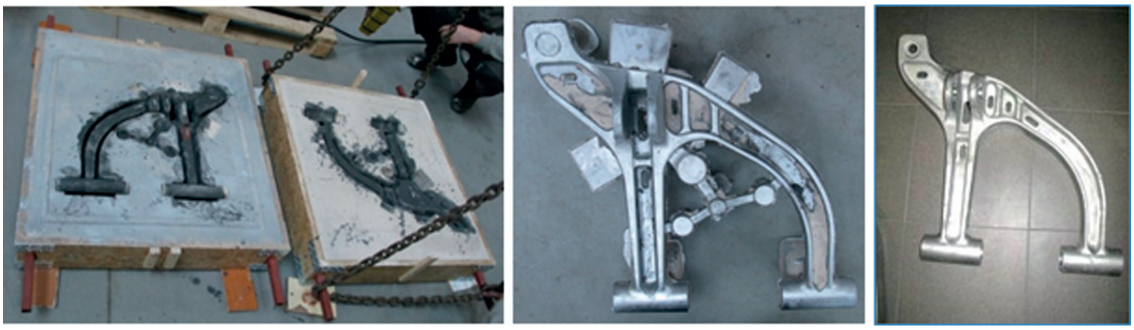

Fig. 1. The manufacturing steps of the sand casting technology: preparation of the sand mould, casting after shaking out of the mould, casting after machining and heat treatment

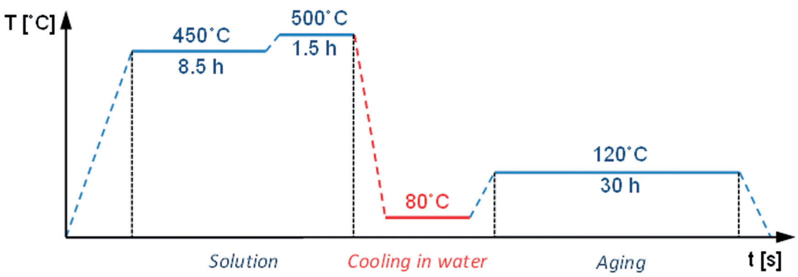

Fig. 2. Scheme of the heat treatment process of the rocker arm castings

Based on the numerical analysis of the exploitation conditions and manufacturing process of the rocker arm the test specimen was obtained for the evaluation of microstructure and mechanical properties (Fig. 4).

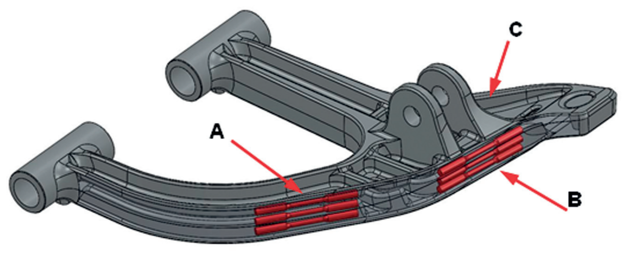

Fig. 4. Sampling areas for structural testing (B i C) and strength test (A i B)

Computer tomography was used to determine the percentage of porosity and microporosity in the strength samples. Experimentally determined percentage of microporosity was compared, with the results of numerical simulation of solidification of the casting.

3. Results of the numerical simulations, tomography and test of microstructure

Based on the numerical analyses of the casting process, the predicted values of tensile strength R_m were estimated and assigned to the selected casting areas, taking into account the heat treatment cycle and the microporosity. Distributions of these values are shown in Figure 5.

By using the MAGMASoft simulation software, it is possible to estimate the total microporosity as a sum of the shrinkage and gas porosity. The first is defined as the cavity created during grain growth and mutual interconnection of dendrites and the isolation of the inappropriately supplied area, mainly blocked from the liquid metal supply during solidification. The gas porosity is defined as the presence of gas in the liquid metal, mainly – hydrogen. The B area of the casting, is where the feeder is located, which has a longer solidification time and because of that there is a lower level of microporosity. The estimated distribution of maximum strength values R_m in the swing arm, clearly shows that in area A, which has a much shorter solidification time compared to area B (localization of the feeder), it has a much higher strength of the casting material with a difference of up to 60 MPa.

Experimentally determined in the static tensile test, the maximum strength of the specimen material cut from the selected casting areas confirms the conclusions of the numerical analysis. Table 2 shows the results of the strength tests (tensile strength R_m and elongation A) of the samples cut from the castings shown in Figures 4, A and B.

Table 2. The results of the strength tests of specimen from the A and B area of the casting

	area A		area B	
Specimen	R_m, **MPa**	A, **%**	R_m, **MPa**	A, **%**
1	397	0.77	397	0.69
2	444	0.74	361	0.60
3	470	1.21	398	0.73
4	467	1.28	399	0.65
5	–	–	362	0.59
Average	444	1.00	383	0.65

In the case of microporosity analysis and its distribution there is a large variety of these values. In area B where the solidification time is longer a significantly lower maximum value of microporosity occurs. At the same time area C where the solidification time is shorter the values of microporosity is more than two times lower. This is confirmed by experimentally determined porosity values on samples cut from these areas, as shown in Figure 6.

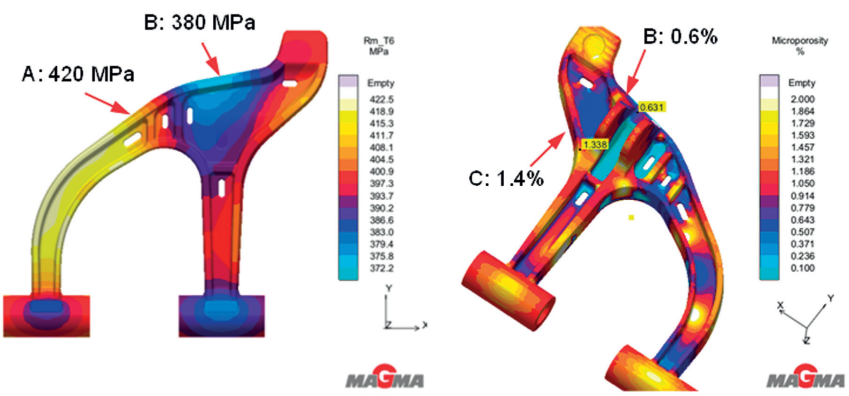

Fig. 5. The results of the numerical calculations of the rocker arm casting process: predicted strength R_m [MPa] in A and B areas, and the percentage of microporosity in areas B and C

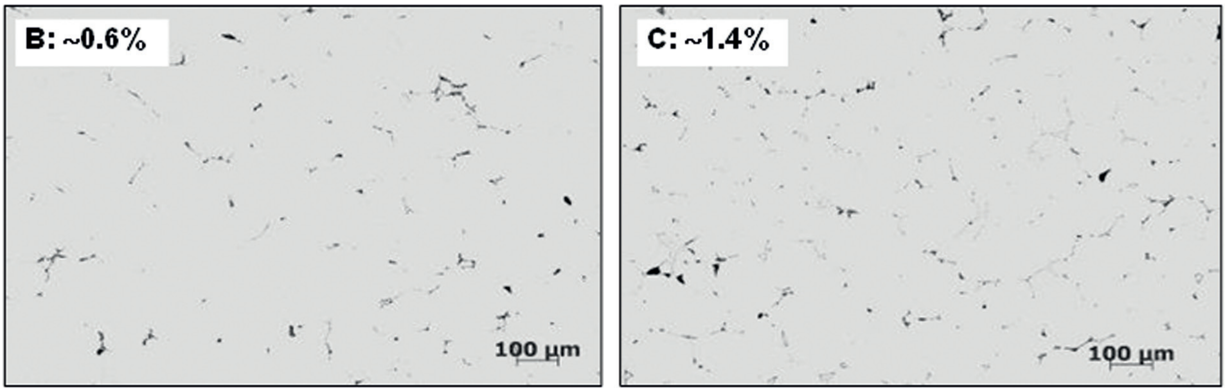

Fig. 6. Percentage of the microporosity in the areas: B = 0.6% and C = 1.4%

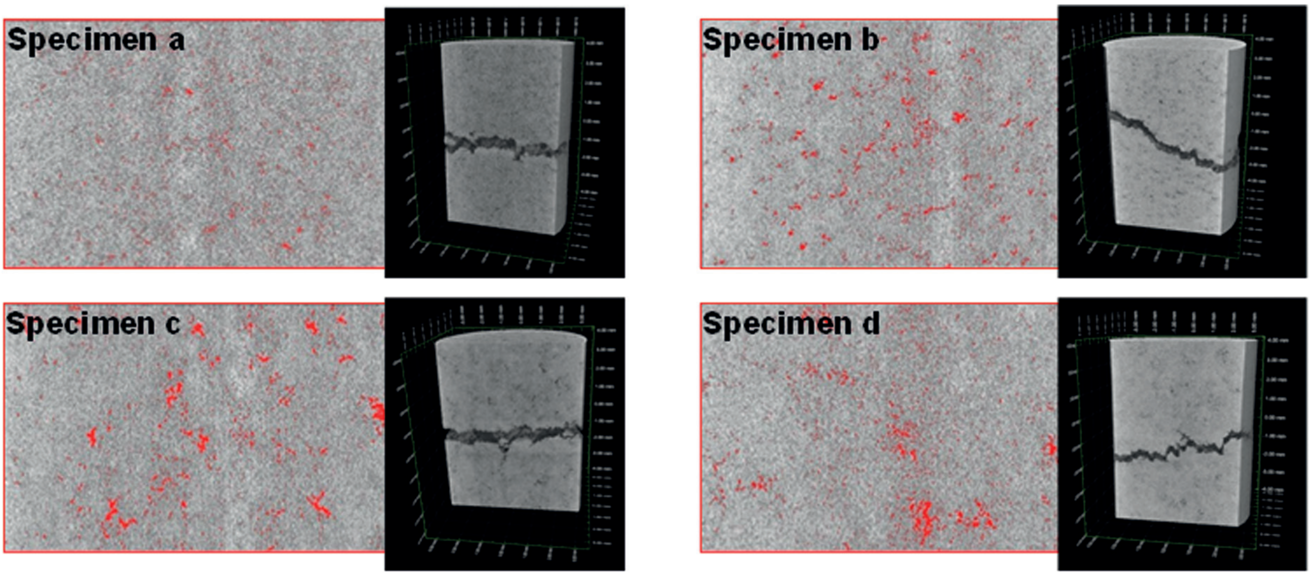

Fig. 7. Microporosity in selected cross sections of samples, determined on the basis of tomographic imaging analysis

In order to determine the values of microporosity, the selected samples were scanned by computer tomography (CT). For analysis a representative area located in the middle of the axial samples with a width of a normalized area of 6 mm was selected. The resulting areas of microporosity in representative samples are shown in Figure 7.

Based on the analysis of C images and the strength properties of selected samples, attempts were made to establish a correlation between the volume fraction of microporosity and the elongation and the maximum deformation in the case of variable loads over time. Comparative data are represented in Table 3.

Table 3. Experimentally determined strength and microporosity in the areas of the rocker arm (A – percentage elongation, ε_p – permanent elongation, E_{180} – modulus of elasticity for R_m = 180 MPa)

Specimen	R_m, MPa	A_5, %	ε_p, %	E_{180}, MPa	Micro-porosity, %
a	467	1.28	0.125	54554	0.836
b	433	0.73	0.077	66649	1.735
c	325	0.58	0.045	62567	2.114
d	325	0.54	0.028	64991	2.229

Based on analysis of the fracture surfaces and images obtained in Scanning Electron Microscope of selected samples the fracture characteristic was determined. The SEM images for selected samples are shown in Figure 8.

Analysis of the above results indicates that the breakthrough in the analyzed samples obtained from the AlZnMgCu alloy casting, can be found along the grain boundary (Fig. 8b), in the areas of microporosity (Fig. 8c), as well as inside the precipitations e.g. silicon (Fig. 8a). Based on the results from scanning electron microscopy and EDS microanalysis, the chemical composition of the precipitations was identified. The selected area was determined along with the analysis of the silicon precipitations and intermetallic phases such as T(Al_6CuMg_4) and S(Al_2CuMg) which has great

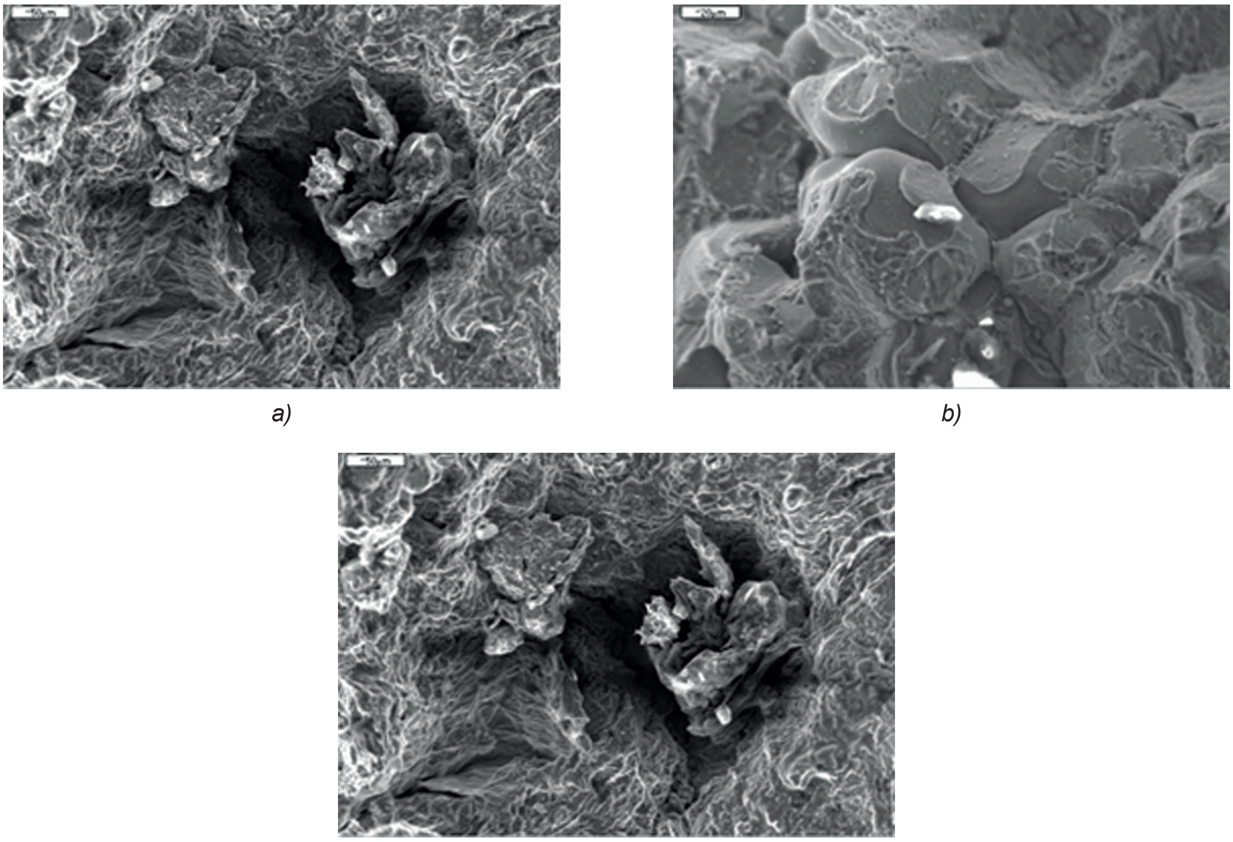

Fig. 8. SEM image: a) split Si distribution in the structure, b) separated grain surface covered with intermetallic phase, c) porosity in the sample structure

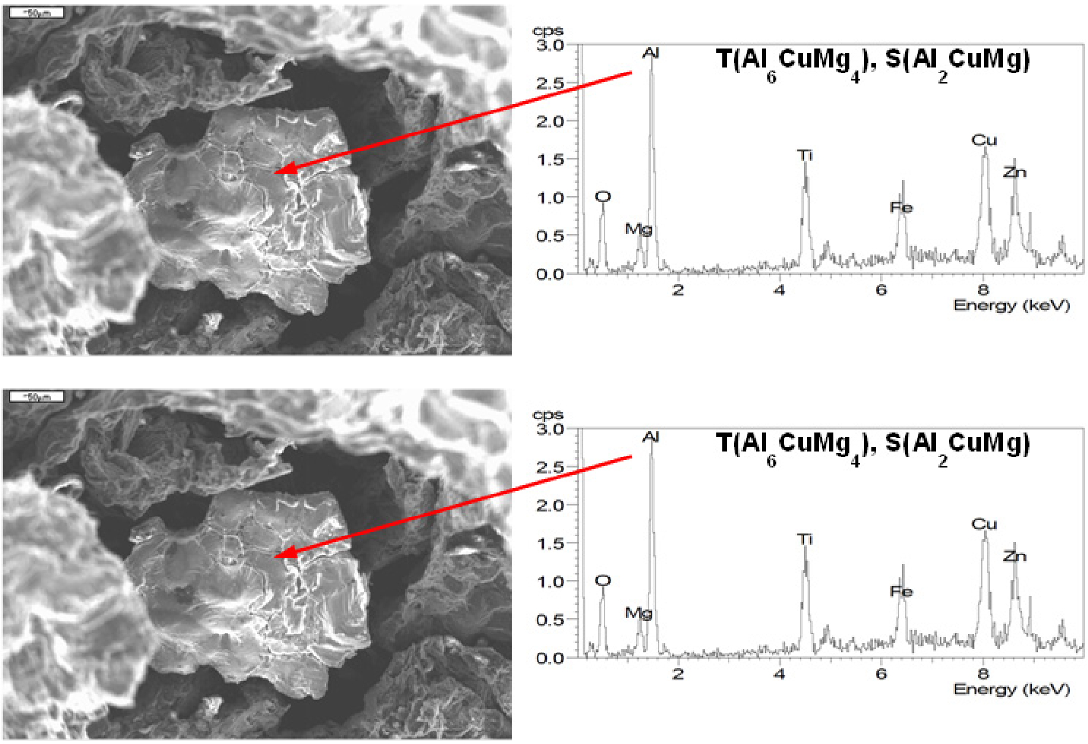

Fig. 9. SEM and EDS spectrum presents an image of phase precipitates in the analysed alloy. Phase T, S and Si are reducing the elongation of the alloy

impact on the lowering of the plasticity of the AlZnMgCu alloy. The results of analyses performed using the EDS microanalysis are shown in Figure 9.

4. Analysis of research results

The analysis of the structure of the fracture surface, shows that the initiation of the crack started passing through the grain on its surface, in the area of microporosity and on the surfaces of intermetallic precipitates. No preferential slip surface was observed in the analysed samples. Most of the samples showed brittle fracture. There are, however, breakthroughs of samples with a higher tilt angle of the rupture plane, e.g., sample 4 (Table 2), which may indicate a more plastic character of the damage. It is also the sample with the highest strength value R_m = 467 MPa and the greatest elongation A = 1.28%. At the same time, the sample exhibits the lowest microporosity values of 0.836%. Analogously for the "d" sample with the lowest tensile strength (Table 3), which is R_m = 325 MPa, and the elongation reaches A = 0.54%, the determined microporosity value is above 2.2%.

The obtained experimental results of the strength and microporosity distribution in the rocker arm and the estimated values obtained during the numerical analyzes show a high correlation between the microporosity and the strength of the analyzed AlZnMgCu alloy.

5. Conclusions

Based on the results, it is clear that an increase in the percentage of microporosity results in a decrease of plastic properties of the alloy as well as a decrease in fatigue strength and maximum acceptable deformation in the case of variable time-dependent loads. The initiation of fatigue cracks is observed in the area by the presence of microporosity or on the matrix boundary separation, usually in the zone close to the outer surface of the specimen. The research has shown good comparability between the numerical simulation of the solidification process and the porosity with CT analysis.

Acknowledgements

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