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RESEARCH OF WELD JOINT FATIGUE LIFE OF THE AlMgSi07.F25 ALUMINIUM ALLOY UNDER BENDING-TORSION CYCLIC LOADING

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The contribution deals with a research into the fatigue life of weld joints of AlMgSi07.F25 aluminium alloy. The paper will present unique biaxial testing equipment, process of preparation of specimen rods for fatigue tests, and the results of fatigue life assessment for the aluminium alloy during cyclic bending-torsion loading. Fatigue tests under constant amplitude loading were performed on a special electromechanical machine with a suitable clamping system. The obtained fatigue curves were compared with the most widely-known fatigue criteria such as LIU, F-S and B-M.

Key words: aluminium alloy, weld joint, fatigue life, bending-torsion test, numerical modelling

INTRODUCTION

The use of materials in technical practice is limited by their properties. All materials are subject to aging, fatigue or wear. It is necessary to reduce the effect of these adverse impacts and increase the material resistance. Requirement is to manufacture machines and devices with a higher performance at a lowered weight, and in synergy with an increased velocity of movement of individual members of mechanisms. During the operation, changes may occur to the operating temperatures, load, as well as other operating parameters. These are all components made of new materials that are capable of withstanding the above criteria thanks to new technologies of manufacture, heat treatment, etc. Usually in technical practice, we encounter joining of components into larger functional units; therefore we have to use new technologies of connecting the materials (e.g. new welding technologies). A weld usually results in the same, or even greater, strength than that of the base material, which depends on the base material type.

No component, even the one made of the "best" material, can perform its function forever. With time, degradation occurs of all its properties. One of the most common manifestations of the component operation is its material fatigue. At the same time, fatigue is also one of the most dangerous processes of damaging the material. This is caused by a gradual disruption of the material integrity by a time-varying stress state as a result of the accumulation of damage by alternating elastic-plastic deformation. This paper deals with examining the uniaxial and multiaxial fatigue life of material and its weld joints at theoretical and practical levels [1, 2].

TEST SPECIMEN

As an experimental material to perform multiaxial fatigue tests we chose the EN AW 6063.T66 (AlMgSi07.F25) aluminium alloy with a normalised chemical composition. This material was used because of the increased use of aluminium alloys especially in the advanced automotive industry, where there is a tendency to replace ferrous materials with non-ferrous.

Prior to the experimental measurement of the specimens it is necessary to create a structural notch that will act as a stress concentrator. This will create a place where we can expect crack initiation and its growth to the breaking point of the specimen. Figure 1 shows the preliminary design of the specimen shape, including the method of its loading.

The specimen will be placed in the device jaws. The device will stress the specimen in an appropriate manner in a combined fashion until the specimen breaks. Figure 2 shows the specimen clamping.

The left jaw causes loading the specimen with bending, whereas the right jaw causes torsion loading. The drives of

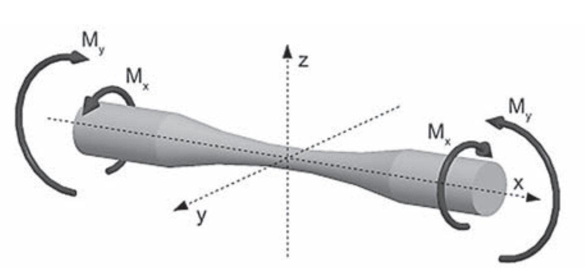

Figure 1 Geometry of the test specimen

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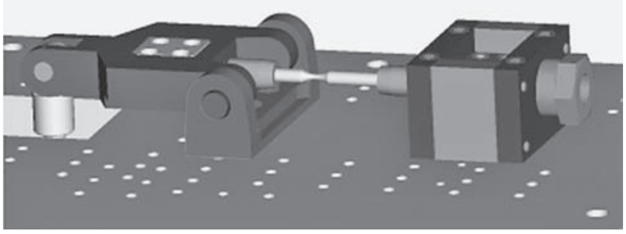

Figure 2 Load system for the bending-torsion load cycle

the two loadings of the test equipment are independent of each other. Therefore, the specimen can be loaded in a combined fashion or even separately with one or the other way. Since it is dealing with a specimen on which will evaluate weld joint fatigue, it is necessary to place the weld joint into the stress concentrator position [3].

SPECIMEN MODELLING

The main objective of using numerical welding simulations in industries is to determine the deformation of the components and the possibility of fault occurrence. Numerical simulations allow detailed under-standing of the entire technological process because they enable an insight into the results during the process (deformation, stress), which is either not possible at all in the bulk of experimental measurements. The first step was the creation of a Finite Element Method (FEM) model of the specimen welding process [4]. To address the above issue was used software SysWeld.

This model was used to perform welding simulations in order to obtain the weld joint geometry with an accurate localisation of the heat-affected area, the base material, and the weldment welding metal. The simulations result also in a FEM model of the weldment with the desired weld material properties (change in the structure, strength, etc.) to find characteristics needed for fatigue tests [5, 6]. The simulation found the values of deformation and stress arising from bending and torsion in the specimen during fatigue testing. Deformation values were obtained via FEM analysis at all loading degrees at the load concentration site; material input characteristics were determined experimentally from the tensile diagram, and also from the previous simulations using the SysWeld. Analysis of the stress state confirmed the assumption that the greatest stress state in bending as well as in torsion is at the specimen narrowing point (Figure 3). The analysis was carried out in the ADINA computing program.

At the notch site, we measured the stress value and deformation, according to the eccentric pair rotation, expressed by the number of teeth. Bending is most characterised by the dominating stress component $\boldsymbol{\sigma}_{xx}$. Deformation in this case will have the size ε_{xx}, which can be considered plastic deformation amplitude for every single eccentric pair rotation. Torsion is mostly characterised by the dominant stress (deformation) component, which in the case of cyclic torsion is the bevelling $\boldsymbol{\gamma}_{xy}$ that can be considered the value of stress (plastic deformation) amplitude for every single eccentric pair rotation [7].

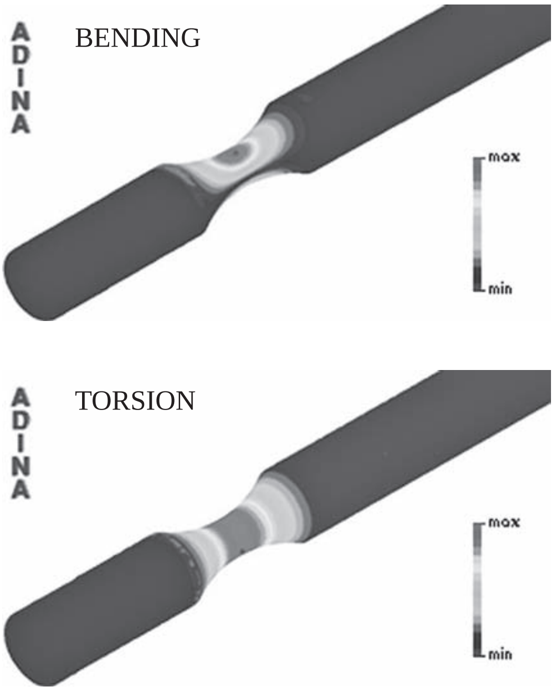

Figure 3 Distribution of equivalent von Mises stress

EXPERIMENTAL DETERMINATION OF UNIAXIAL FATIGUE OF WELD JOINTS

Experimental determination of fatigue characteristics of AlMgSi07 aluminium alloy was carried out using the purpose-built multiaxial fatigue testing device (Figure 4).

Loading was done under controlled amplitude of deformation with a zero mean deformation component, where the loading modes were adjusted by turning the eccentric pair by a selected number of teeth. The loading process was characterised by a sinusoidal cycle with the load frequency of 30 Hz. Making the deformation dependence of the welded speci-men was followed by measurement of the weld joint fatigue life on the test specimens cyclically loaded by bending. The size of loading was changed. Table 1 shows the average number of cycles prior to fracture at individual loading levels of

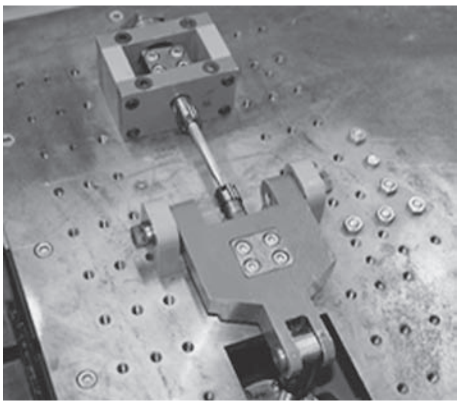

Figure 4 Multiaxial testing device

Table 1 **Number of cycles (bending)**

$\varepsilon_{ac} \cdot 10^{-3}$	Time /s	Number of cycles	Frequency /Hz
4,3	63	$1{,}9 \cdot 10^3$	30
3,8	137	$4{,}2 \cdot 10^3$	
3,1	680	$2 \cdot 10^4$	
2,2	3 033	$9{,}1 \cdot 10^4$	
1,1	8 184	$4{,}1 \cdot 10^5$	50

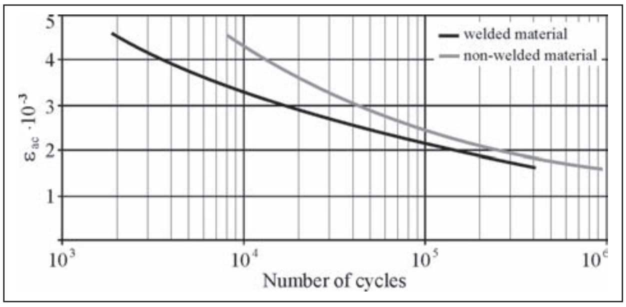

Figure 5 Manson-Coffin curves (bending)

the welded specimen; measured numbers of cycles were processed into a Manson-Coffin curve (Figure 5).

When comparing the measured results we observed a difference in the number of cycles prior to fracture of the base material compared to a welded specimen. The difference in the number of cycles between a non-welded and a welded specimen was approximately twofold at all tested levels. The largest difference was observed at large deformation amplitudes where, however, we cannot consider material fatigue due to the small number of cycles prior to fracture. The adverse effect of welding on fatigue life due to decreasing deformation amplitude is gradually removed [8].

Weld joint fatigue life measurement using the test specimen under torsion cyclic loading was made. Table 2 shows the average number of cycles prior to fracture at individual loading levels of the welded specimen; measured numbers of cycles were processed into a Manson-Coffin curve (Figure 6).

Just like with bending loading, a difference is visible between the welded and non-welded specimens even with torsion loading in the technical life at large deformation amplitudes. This difference is again in favour of the non-welded specimen, where this one withstood approximately twice the number of cycles compared with the welded specimen. This means that the adverse effect of welding on the material fatigue life demonstrated once again.

EXPERIMENTAL DETERMINATION OF WELD JOINTS MULTIAXIAL FATIGUE

Multiaxial fatigue measurement of weld joints was carried out using the same device as the one used for uniaxial testing. Due to the large number of deformation amplitudes combinations of the two loadings, together with the phase displacement combinations it was determined that the phase displacement be measured in two conditions – at 0° and 90° phase displacement. 18 positions for the two deformation amplitudes were divided into 6 levels, from which was created combinations to measure fatigue. In order to verify the measurement accuracy of the test device obtained results was compared with Fatigue Calculator. It is a software program available on the eFatigue website, developed at the Uni-versity of Illinois [9]. It allows easy and quick fatigue life estimation. The values of stress or deformation in the desired units were entered into the program from the calculated tensor for σ_{xx} and τ_{xy}. It was worked with a symmetrical frequency of loading cycles 30 Hz with phase displacements 0° and 90°. After starting the calculation of technical life for low-cycle fatigue, Fatigue Calculator displayed the calculated values of the number of cycles prior to fracture with various patterns of damage, namely N_f (Fatemi-Socie, SWT, Brown-Miller and Liu) [10]. All the measured and calculated figures are plotted in graphs below.

Table 2 **Number of cycles (torsion)**

$\gamma_{ac} \cdot 10^{-3}$	Time /s	Number of cycles	Frequency /Hz
10,7	11	$3{,}3 \cdot 10^2$	30
10	11	$4{,}1 \cdot 10^2$	
8,8	28	$8{,}3 \cdot 10^2$	
7,92	47	$1{,}41 \cdot 10^3$	
6,9	109	$5{,}2 \cdot 10^3$	
5	204	$2{,}2 \cdot 10^5$	
3,8	8 034	$4{,}41 \cdot 10^5$	
3,5	11 611	$6{,}35 \cdot 10^5$	
2,5	21 433	$1{,}1 \cdot 10^6$	

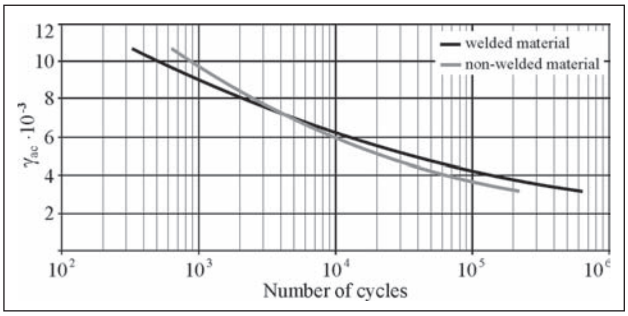

Figure 6 Manson-Coffin curves (torsion)

Comparison of the ε–N_f curves for assessing low-cycle multiaxial fatigue and from the experimentally obtained values at constant torsion deformation $\gamma = 2{,}5 \cdot 10^{-3}$; the mutual phase between the loadings $\varphi = 0°$ (Figure 7a) and $\varphi = 90°$ (Figure 7b).

The dependence shows a relatively good compliance of the experiment with the Brown-Miller hypothesis in the domain of low-cycle fatigue. As mentioned above, the Brown-Miller features less limiting cycles compared to other hypotheses. This damage pattern uses the normal deformation range that is changed by the tensile-compressive deformation ratio, and this may result in a fatigue life reduction [11].

Comparison of the γ–N_f curves for assessing low-cycle multiaxial fatigue and from the experimentally obtained values at constant bending deformation $\varepsilon = 2{,}2 \cdot 10^{-3}$; the mutual phase between the loadings $\varphi = 0°$ (Figure 8a) and $\varphi = 90°$ (Figure 8b).

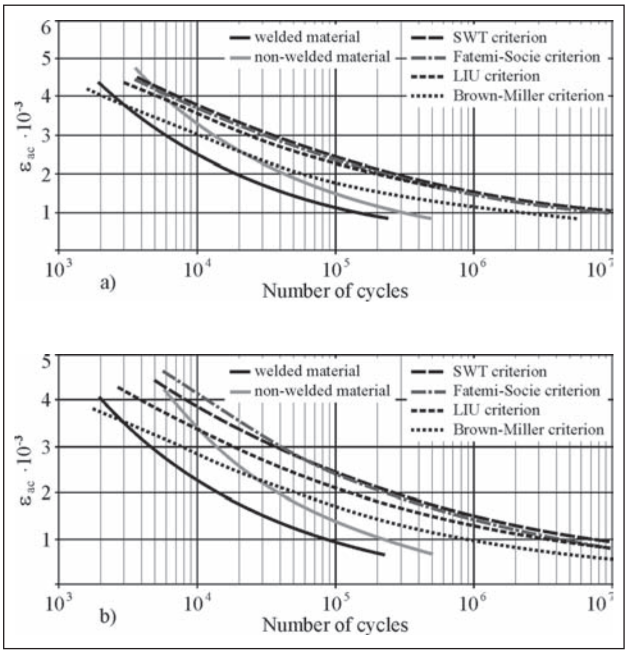

Figure 7 Comparison of the ε–N_f curves

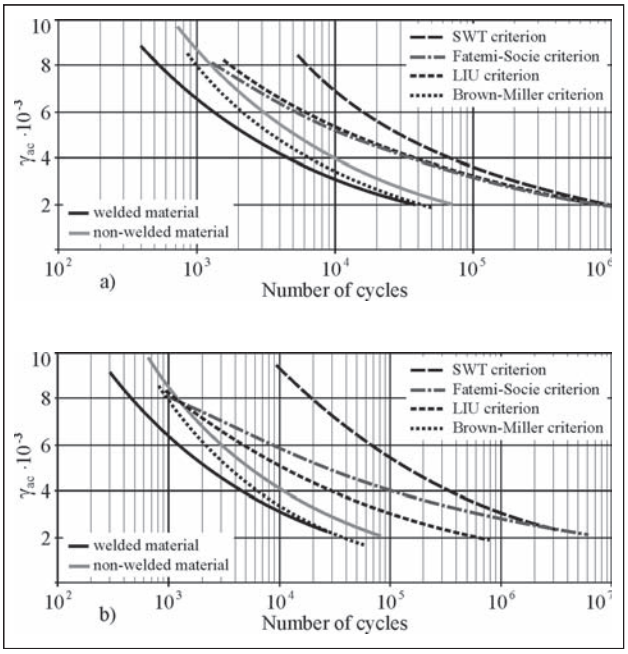

Figure 8 Comparison of the γ–N_f curves

The numerous created dependencies for an experimental welded material result in the fact that phase displacement will not play such a significant role in the case of weld joints than in the case of non-welded specimens. We can conclude that bending loading will respond to a larger extent to an even a small change in the deformation amplitude. Thus, bending will be the more dominant component of the total deformation amplitude in multiaxial testing.

For large deformation amplitudes, when the two uniaxial measurements always showed the fatigue life of the welded specimen shorter than that of the non-welded specimen, the resulting fatigue life when combining the two loadings was in favour of the non-welded specimen, which thus withstood a greater number of cycles compared to the welded specimen. This finding may be a valuable lesson in predicting multiaxial fatigue life with the following recommendations:

1. For “large” deformation amplitudes at the torsion and bending combinations – a more suitable material will be the non-welded specimen, where a dominant role will be played especially by the material strength.
2. For “small” deformation amplitudes at the torsion and bending combinations – a more suitable material will be the welded specimen, where a dominant role will be played by all the factors that affect the differences between the two types of specimens.

Experimental measurements, in which the number of cycles reached values above 10^6 shows that the welded specimen fatigue life will start to exceed that of the non-welded specimen. Fatigue life increases with decreasing total deformation amplitude. This is an important finding, the results of which can be applied in the design of components and machine parts to efficiently utilise the material to ensure the greatest possible number of cycles to failure.

CONCLUSIONS

This paper aimed at investigating the fatigue life of aluminium alloy specimens, into which we implemented weld joints. These weld joints were tested by uniaxial fatigue loading (bending, torsion), as well as multiaxial fatigue testing (bending-torsion combination) to obtain fatigue curves. The investigation was preceded by the determination of the test material, exact specimen geometry through the test specimen shape and dimensions design, technological procedure of manufacturing the specimens and welds, and simulation analysis to determine the material changes due to welding. All these stages resulted in the necessary input parameters for the subsequent specimen testing and assessing, and evaluation of the results obtained by testing on the original purpose-built multiaxial test device.

The process also included calibration of loading degrees of the test device for the investigated weld joint from the AlMgSi07 base material and the AlSi5 additive material. Work included comparison of a weld joint fatigue life with the base material. The paper represents a combined research in the multiaxial fatigue loading of components, especially in terms of linking the modern computer methods of continuum mechanics (numerical analysis using FEM) with experiments.

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