Strain fields of tensile and shear loaded weldments of AlMgSi0.6 extrusions

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Abstract

The goal of this work is to determine the mechanical properties required for computation of the deformation of welded Al-extrusions. The heat affected zone (HAZ) is characterized by the temperature exposure during welding, by hardness testing, and by microscopy. Tensile specimens are heat treated according to the microstructure of the HAZ. The local strain fields of the specimens are determined during overloading. The distribution of plastic regions depends on the local yield strength. The zones surpassing the local maximum strength indicate the location of crack formation.

Introduction

The mechanical properties of the heat affected zone (HAZ) normally differ from the properties of the base material, especially the ductility. The heat input during welding in combination with the transient cooling conditions changes the microstructure of age hardening Al-alloys. It is known that overloaded weldments suffer damage first in the HAZ [1]. Therefore it is required to know the microstructural changes of the HAZ and its stress-strain behavior to be incorporated into finite element analyses (FEA) where the weldments are segmented into parallel regions of weld zone, HAZ and base material. Thus a simplified multiphase material is considered for the simulation of the plastic deformation of the assembly.

The aim of this work was to determine the mechanical properties of the HAZ by experimental simulations of its microstructure. The tensile test results may be used as input for FEA. The computational simulation can be verified by the determination of the local strain fields during overloading.

Description of Methodology

The material investigated is an AA6008 age hardening alloy with 0.57 % Si, 0.55 % Mg, 0.19 % Fe, 0.07 % Cu, 0.26 % Mn, and 0.11 % V. The material was manufactured by extrusion (t = 3.9 mm) and the as delivered heat treatment condition was T4. The weldments are performed by robotic metal inert gas welding (MIG) with Al-Si filler at standard process parameters. Extrusion profiles were welded together in longitudinal direction [2].

After preparing the samples from the weldments, hardness tests (HB 1) identified the local softening in the HAZ. The local hardness was correlated with time-temperature curves across the profile measured during the welding by means of thermocouples. To assure these results, base material samples were heat treated in the dilatometer using the identified critical time-temperature curves. The dilatometer uses thermocouple controlled inductive heating which offers fast heating and cooling comparable to the heat flow during welding. Tensile samples were made from the unaffected profile to examine the expected difference of base material and the HAZ. The later was simulated by the heat exposure representing by the HAZ. This heat treatment was carried out in a Gleeble 1500, which uses thermocouple controlled direct ohmic heating [3].

To examine the tensile properties of the HAZ in relation to the base material, different shapes of samples (e.g. dog-bone, notched samples) were tested with the help of a Zwick 50 universal test equipment. The resulting stress-strain curves were used as input data for FEA [4]. In order to obtain the influence of the extrusion and weldment direction in this experiment, three different angles (α = 30°, 45° and 60°) with respect to the tensile load were tested. The excessive weld beads were machined off to test samples with flat surfaces as shown in Figure 1. The samples of the base material were always tested in extrusion direction. During tensile testing local strain measurements were made by recording the deformation until crack initiation of the samples. This was carried out by the Aramis [5] strain measurement equipment, where a random pattern is applied onto the surface of the sample and digitized pictures were taken during tensile testing. By the use of photogrammetric calculations it is possible to calculate the strain distribution along the samples from the beginning until crack initiation.
Results

Hardness tests (HB 1) along the cross section of the weldments were made to measure the softened regions in the HAZ as a result of the heat impact during welding. Figure 2 shows the resulting hardness measured at the series of visible dots using 5-point smoothing. On both sides of the weld seam softened regions can be observed. The result of hardness testing represents the precipitation condition of the weldments compared with the average T4 hardness of the extrusion 52±1 HB 1.

According to the ca. 11 mm distance of these softened regions from the center of the weld seam, the local temperature-time cycle can be identified by the measurements made with the thermocouples during welding, thus leading to a correlation with the hardness. Figure 3 shows the temperature-time cycle of thermocouple TC104 and TC105 which had a distance of 9 mm and 11.5 mm from the weld seam, respectively.

According to the data of the thermocouples TC104 and TC105, samples of the base were heat treated in a Gleeble 1500 and dog-bone samples were manufactured. Figure 4 shows the characteristic stress-strain curves of the base material and the heat treated samples. As shown, the heat input of TC104 (9 mm) reduced the ductility most with respect to the base material. The two stress-strain curves represent the HAZ.

To calculate the strain flow of real weldments (see Fig. 1) using Aramis, several samples with different angels to the extrusion direction were tested, thus also the shear influence could be detected. Figure 5 shows a weldment in the extrusion direction with $\alpha = 45^\circ$ to the tensile direction. The crack initiation takes place at the lower notch. Figure 6 and 7 show the strain at crack initiation in y-direction close to the notches. As shown, the local strain concentration is not symmetric with respect to the weld seam. The required strain...
for crack initiation is about 33 % in the lower HAZ of the lower notch. Remarkable is the broader straining of the upper HAZ in the upper notch reaching about 25 % in the y-direction. This corresponds roughly to the strain at fracture of the heat treated samples TC104 and TC105. When the maximum strength of the HAZ is surpassed, the tensile test of the base material shows about 5 % strain at this stress level. It is observed experimentally, that the crack propagates by shear along the HAZ.

![Figure 5: Calculated equivalent strain from tensile test with α = 45° between weldments and vertical load direction](image)

Dog-bone specimens of 15 mm gauge length with the weld seam transverse to the tensile direction were strained up 10 %. Figure 8 shows the soft regions on both sides of the weldment with the beginning of the damage in the upper HAZ. The determined local maximum strains of 10 % are less than the strains at maximum strength of the HAZ represented by Figure 4. The crack formed in the upper HAZ at 5 % total elongation of the sample.

![Figure 6: Calculated strain component in y-direction along line 6 in Figure 5 (upper notch)](image)

![Figure 7: Calculated strain component in y-direction along line 7 in Figure 5 (lower notch)](image)

![Figure 8: Local equivalent strains calculated from displacements during vertical tensile deformation of a specimen with transverse weld seam](image)
**Discussion of results**

After identifying the HAZ by hardness testing, the corresponding heat treatment can be simulated experimentally. Maximum temperature $375 \, ^\circ C < T_{max} < 415 \, ^\circ C$, which represents partial solution treatment, where limited reprecipitation occurs after cooling.

Regions closer to the weld seam suffered higher temperatures producing complete solution treatment fully naturally aged afterwards similar to the base material. Regions further away from the weld seam were not solution treated, but suffered some aging progress, which produced little change in hardness with respect to the base material. The changes of the precipitation condition in the HAZ during welding will be investigated and verified by Differential Scanning Calorimetry (DSC) experiments as a next step.

As a result of the tensile testing of specimens made of base material and of simulated HAZ, it is possible to compare the strain to failure of these regions. The stress-strain behavior of the welded region corresponds to the different stress-strain flow in the multiphase material of the real weldments. Figure 4 shows the local maximum strain for the HAZ about 30 %, whereas the base material fractures only at 35 % strain. The maximum strength of the HAZ corresponds to the maximum stress produced in the tensile sample. The elongation of the base material at maximum strength of the HAZ reaches only 5 % strain. The local strain distribution is reflected by the Aramis strain mapping. The local strain behavior in y-direction calculated with Aramis predicts the location of maximum strain, where the crack initiates. In this way, it is shown that stress-strain curves of a simulated HAZ can be used as input data for FEA.

The crack initiation of the biaxially loaded weldments was induced by the tensile component of the strain. All samples in any direction of the weldment ($\alpha = 30^\circ, 45^\circ$ and $60^\circ$) failed by shear damage after the crack initiation within the HAZ where the age hardening was partly reversed.

**Conclusion**

Determining the locally softened regions of weldments by hardness testing and temperature-time measurements during welding is a proper way to study the HAZ of aluminum weldments. By this, the correlation between real weldments and simulated HAZ show a good agreement and therefore the flow curves of heat treated tensile specimens can be used as input for FEA.

**References**

[5] Aramis, GOM mbH, Braunschweig, Germany