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Influence of Process Temperature on Hardness of Friction Stir Welded High Strength Aluminum Alloys for Aerospace Applications

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Abstract

The increasing application of innovative materials, such as high strength aluminum alloys, is challenging the manufacturing processes of the Aerospace and Aeronautics Industries. Despite this challenge the processes need to comply with high requirements regarding the reproducibility and the quality of the products. For this reason the adaption of conventional welding technologies to the new materials is considered to be difficult. Therefore, innovative welding technologies such as Friction Stir Welding (FSW) have been developed [1].
This paper deals with the implementation of FSW into a new production process for lightweight dome structures of fuel tanks: Starting at temper condition O two AA 2219 plates are joined using FSW technology to form a larger blank. After that, the blanks are formed to shape using spinforming technology. The manufacturing process is accompanied by several steps of heat treatment to accomplish a finished tank-dome in temper condition T8.
The studies presented in this paper aimed on finding a correlation between the process parameters and the properties of the welding seam, which are essential for the following spinforming process. For this purpose the experiments were conducted using design of experiments (DoE). The resulting hardness increase of the welding seam was chosen as target variable. Based on the acquired data a regression model was established and used to estimate optimal parameters for dome production.

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Keywords: Friction Stir Welding; high strength aliminum alloy; hardness; temperature; design of experiments

1. Introduction

Friction Stir Welding (FSW) is an adequate process for the production of lightweight structures for aeronautic applications [1, 2]. Compared to fusion welding technologies high quality and highly formable welding seams can be produced in aluminum alloys due to the lower heat input during FSW [3].
Although the process temperature during FSW usually does not exceed the solidus temperature of the workpiece [4], the material being welded is strongly affected by frictional heating. Additionally, the friction between the tool and the workpiece also causes massive plastic deformation in the thermally weakened stirring zone. A friction stir welded seam is known to be asymmetric, since the tool rotation is oriented along with the welding direction at the advancing side (AS) and opposite at the retreating side (RS) [5].
As shown in Fig. 1, usually three distinct microstructural zones – the stirred and dynamically recrystallized nugget zone, the thermo-mechanically affected zone (TMAZ) and the

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heat affected zone (HAZ) – can be identified as a product of the welding process besides the unaffected base material (UABM).

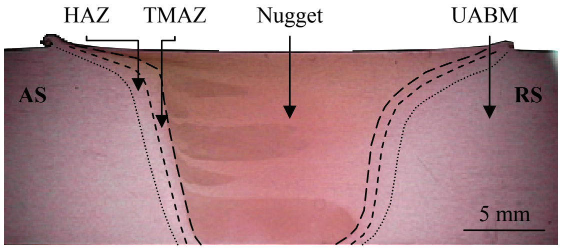

Fig. 1. Microstructural zones of a FSW seam

All of the named zones significantly differ with respect to their mechanical properties. Besides that, even inside each zone a gradient of the mechanical properties, from the top to the bottom and from the AS to the RS, is described in several publications and reviews [6, 7, 8]. The main reasons for this are the inhomogeneous thermal evolution and the complex material flow during the FSW process [9, 10]. It is well known that the thermal conditions [11, 12] and the material flow [12, 13] during the process as well as the resulting welding seam properties [14] can be manipulated by the choice of the parameter setting.
For an appropriate formability of the joint it is necessary that the welding seam shows mechanical properties equal to those of the base material with a smooth transition from hardener to softener areas [3]. It is known that an unequal hardness distribution leads to an inappropriate forming since harder areas offer more resistance to forming than softer areas [15].
Therefore, this paper aims on finding a correlation between the process parameters and the hardness of the welding seam.

2. Approach

As the FSW process offers a multitude of adjustable parameters with a large range of settings, the usage of an efficient methodology like design of experiments (DoE) is advisable for obtaining reliable information.
The experiments in this study were conducted using a D-optimal design, which is known to be efficient at high numbers of factors and levels [16]. Furthermore, a D-optimal design offers high flexibility regarding the choice of the regression model and is expandable by more factors [16].
The process parameters rotational speed (n), feed rate (v) and the axial Force (F_z) are considered as most influential and were chosen as independent variables and varied at five levels. In order to support the subsequent analysis and interpretation of the achieved information all welding experiments were accompanied by temperature measurements.
A cross section specimen of each seam was taken to investigate the microstructural evolution of the welding seams.
Furthermore, Vickers hardness testing was conducted to evaluate the mechanical properties of the joint.
Finally, a linear regression was used to find the relationship between the independent variables (process parameters n, v and F_z) and the scalar response variables (process temperature and maximum Vickers hardness increase).

3. Experimental and Analysis Setup

3.1. Friction Stir Welding

The welding experiments were conducted using a four-axis CNC milling machine Heller MCH250 with integrated force control [17].
The tool features a concave shoulder with a diameter of 27 mm and a conical pin with a diameter of 12 mm at the bottom. The pin length was set to 11.8 mm, which is sufficient for joining 12 mm thick blanks of heat treatable aluminum alloy AA2219 O in butt welding configuration. The chemical composition of AA2219 according to SAE AMS-QQ-A-250/30 is shown in Table 1.
To achieve reliable data, stationary process conditions are requiered. Therefore, the length of each seam was set to an adequate value of 250 mm, at which the investigations, concerning specimen extraction and temperature measurement, were conducted at the middle of the seam as shown in Fig 2.

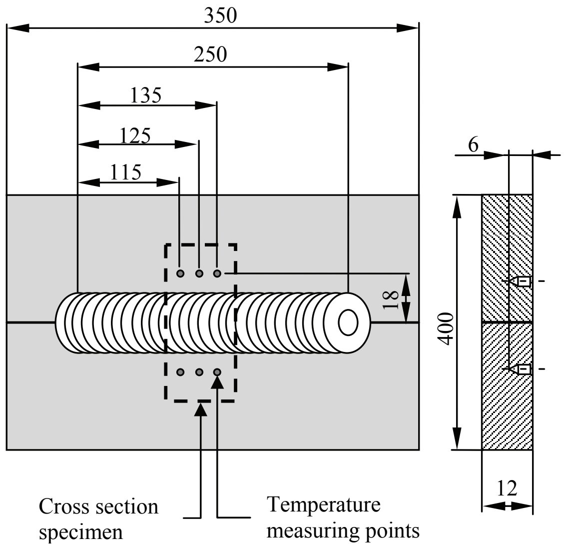

Fig. 2. Dimensions of the welding samples

Table 1. Chemical composition of AA2219 (SAE AMS-QQ-A-250/30)

AA2219	Si	Fe	Cu	Mn	Mg	Zn	Ti	V	Zr	others	Al
Wt. %	0.2	0.3	5.8 – 6.8	0.2 – 0.4	0.02	0.1	0.02 – 0.1	0.05 – 0.15	0.1 – 0.25	0.15	bal.

3.2. Design of Experiments

The process parameters n, v and F_z were spread systematically using a D-optimal design. The design incorporated a variation of the parameters on five levels, which enables the application of polynomials up to degree four during the following regression [18]. Furthermore, the described practice enables the determination of interdependencies. The levels of the normalized parameters are shown in Table 2. All data points were tested once, whereas the center parameter setting was conducted three times.

Table 2. Normalized process parameters and their levels

Experiment Number	n	v	Fz
1	0	0	0
2	1	1	-1
3	-1	-1	-1
4	-0.5	-1	1
5	-0.5	1	0
6	0.5	-1	-0.5
7	-0.5	0	-1
8	0	0.5	0.5
9	-1	1	-1
10	-1	1	1
11	0.5	-0.5	1
12	1	0.5	0
13	1	1	1
14	0.5	1	-1
15	-1	0	0
16	0	-0.5	-0.5
17	1	-0.5	0.5
18	-1	0	1
19	1	-1	1
20	0	0.5	-0.5
21	1	-1	-1
22	-1	-1	0.5
23	0	0	0
24	0	0	0

3.3. Temperature Measurement

In order to achieve information about the thermal evolution during the welding process, type K thermocouples (TCs) with 1.5 mm in diameter were inserted into the welding samples. To avoid damage due to the acting of the welding tool, the TCs were inserted into the HAZ – three at the RS and three at the AS (Fig. 2). However, the measurement of the process temperature during FSW is complicated as the thermal distribution is transient and inhomogeneous with a strong gradient. The reproducibility of the measurement requires an exact positioning of the measurement device. Therefore, the FSW process was conducted after drilling the holes for the TCs without rechucking the workpieces.
The peak temperatures of all six measuring points were averaged to form the required scalar response (Ø T).

3.4. Hardness Measurement

The measurement of the hardness distribution is a suitable method for estimating the mechanical properties of the joint. For the investigation of friction stir welded seams, the measurement of Vickers hardness is appropriate since the hardness values may vary significantly and unsteadily over the small distinct zones [19, 20]. As shown in Fig. 3, ten measuring points were set to determine the hardness distribution in the nugget - five at the AS and five at the RS. Another ten measuring points were set to determine the hardness distribution in the TMAZ, the HAZ and the UABM.
All measuring points were located on the middle line of the workpieces and had a distance of 1 mm to each other. All measurements were conducted with a test load of 0.981 N and dwell time of 13 s.

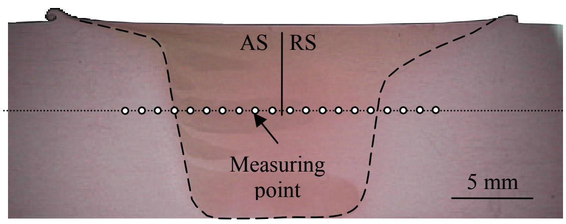

Fig. 3. Hardness measurement – location of the testing points

3.5. Metallography

The specimens were polished and etched using NaOH to evaluate the microsturctural evolution of the weld. For a more detailed view on the microstructure selected specimens were investigated using scanning electron microscopy (SEM).

4. Results and Discussion

The FSW process causes significant microstructural changes in the welded material, due to mechanical stirring and local heating. These changes are also reflected in the hardness distribution of the welding seam. The hardness increases from the UABM to the Nugget, where the maximum is reached at the AS of each specimen. As mentioned in the introduction of this paper the mechanical properties of the welding seam should ideally not differ from the properties of the base material. This includes that the increasing of the hardness should be low for an appropriate formability of the joint. Therefore, the averaged hardness value of the nugget zone at the AS (Ø HV_{AS}) was evaluated as a scalar response.

As a result of the regression a functional relation between the process parameters (n, v and F_z) and the Ø HV_{AS} was determined. This relation is described by the following equation:

$$\emptyset\, HV_{As} = 74.87 + 3.28 \times n - 2.99 \times v - 0.34 \times F_z - 3.75 \times F_z^2 \qquad \text{eq. (1)}$$

The equation was computed in a stepwise regression: From an initial polynomial the term with the highest p-value was removed. The procedure was repeated until the polynomial contained no terms with a p-value greater than 10 % anymore. Since the adjusted coefficient of determination R_{adj}^2 has a value of 0.715, the final model for Ø HV_{AS} is considered as a good representation of the experimental results.

The coefficients indicate that increasing n leads to an increase and increasing v to a decrease of Ø HV_{AS}. Both parameters exhibit a linear effect on the hardness, while the effect of n is slightly higher than v, due to the higher gradient. It is remarkable that the resulting effect of F_z is quadratic with an unexpected decrease of Ø HV_{AS} at high levels. The reason for this is thought to be in the excessive plunge of the tool at high F_z and the resulting contact between the tip of the tool-pin and the backing plate. At this condition, a part of the applied F_z is bypassed around the workpiece and is not able to affect the material in the welding zone. Significant interdependencies between the process parameters were not identified.

The influence of each parameter on Ø HV_{AS} with the remaining parameters being on their center level is illustrated in Fig. 4 by the solid lines. The dashed lines represent the 95 %-confidence intervals.

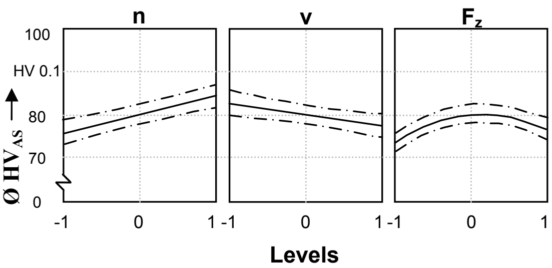

Fig. 4. Main effect plot of each parameter on Ø HV_{AS} (solid line) with 95 % - confidence limits (dashed line), remaining parameters on their center level.

The interpretation of these results requires a detailed view on the process temperature. In fact, the comparison of Ø T with Ø HV_{AS} indicates a correlation between the process temperature and the resulting hardness of the microstructure. As shown in Fig 6, an increasing Ø T causes a higher Ø HV_{AS}.

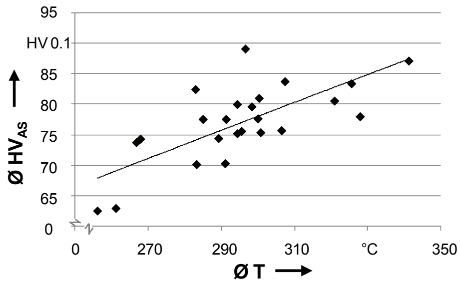

Fig. 6. Correlation of Ø T with Ø HV_{AS}

It is known that the local heating during FSW, which typically reaches the solution temperature of the base material [21, 22], leads to the solution of the overaged precipitates and hence to a solid solution hardening of the nugget [23]. Additionally, the thermal solution process is supported by mechanical stirring of the material, due to the high dislocation density and recrystallization of the material [22]. Taking into account these facts, a higher process temperature leads to a more effective solution of the overaged precipitates and as a consequence to a higher hardness increase, due to a homogeneous allocation of the precipitates.

This conclusion is confirmed by the conducted scanning electron microscopy (SEM), where the precipitations (Al_2Cu particles) occur as bright spots. The SEM micrograph shown in Fig. 7 exhibits a discontinuous change of the precipitation size between the nugget and the TMAZ at the AS of the specimen, which indicates a solution annealing of the nugget zone due to the FSW process.

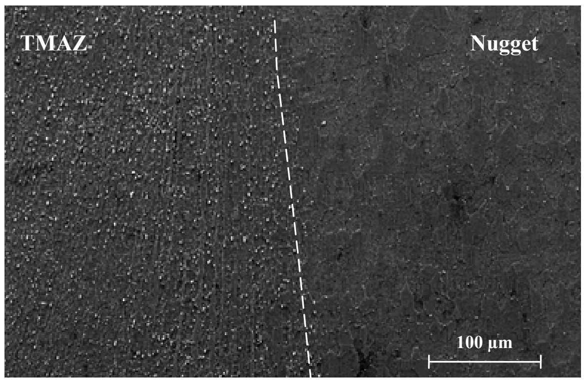

Fig. 7. SEM micrograph (precipitations occur white)

5. Conclusions

Considering AA2219 in temper condition O, a functional relation between the process parameters (n, v and F_z) and the average hardness value of the nugget zone was established in this paper. It is known, that a high formability of the joint requires a low hardness increase of the welding seam. The results of this paper show that this can be achieved by a reduced rotational speed n, an increased welding speed v and a reduced axial Force F_z.

Furthermore, a correlation between the changes of the process temperature and the hardness of the microstructure was found. The results indicate that a thermal solution of the overaged precipitates and a resulting solid solution hardening are responsible for the increasing hardness in the weld zone. Therefore, "cool" welding conditions lead to an enhanced formability of the joint. In addition to the described parameter settings a cooling of the workpiece or the welding tool is appropriate.

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