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Computer Simulation of Heating Cycle of Aluminum Alloys Using Friction Stir Welding Technology

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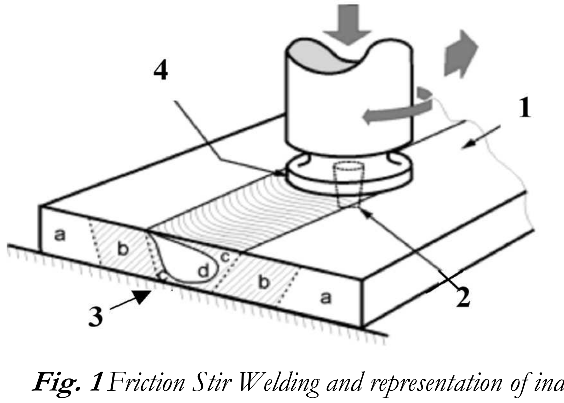
The paper deals with welding of aluminum alloys using Friction Stir Welding technology. This represents one of the solid-state welding technologies in which the base materials are not melted. This welding method provides new possibilities for the use of special and hybrid manufacturing technologies. The article first presents an overview and the current progress in the Friction Stir Welding technology. Further, the key attributes of the technology are stated, focusing on the individual weld microstructure zones and their characteristics. Subsequently, a computer simulation of the FSW thermal cycle of an aluminum alloy specimen was designed in the program Ansys; the simulation provides the distribution of the temperature fields within the welded material. The simulated temperature fields are compared with a real weld joint, and possible defects are pointed out. Finally, the results of the computer simulation and of the visual analysis of the real weld joint are summarized and discussed.

Keywords: Friction Stir Welding, FSW, Aluminum, Aluminum alloys, Simulation

1 Introduction

Friction Stir Welding (FSW) is a relatively new welding method that was patented in 1991 by the TWI Institute in Cambridge and it is one of the solid-state welding technologies. This method was initially predestined especially for metals with sufficient plasticity, such as e.g. aluminum and some of its alloys. Friction stir welding can easily connect homogeneous or heterogeneous materials, including metals, some metal matrix composites, ceramics and plastics. The norm STN EN ISO 25239-5 specifies the capability of a manufacturer to use this welding technology. The welding process is schematically show in Fig. 1; the key part of the welding device is the rotating head with a mandrel, which provides both the rotary movement and the necessary pressure. The length of the rotating mandrel must be slightly shorter than the thickness of the welded material [1], [2], [14]. The weld made by the FSW technology is created by pressing and rotating the tool with the fitted mandrel at the weld joint, until there is a tight contact between the tool arm and the workpiece surface [3], [4]. By friction between the workpiece and the rotating mandrel, the metal is heated and a tubular column of plastic metal is formed around the mandrel. As the mandrel moves in the welding direction, the front side of the mandrel presses the plastic material against the back side of the mandrel, thus forming a weld metal that creates a weld joint [5], [7], [10]. The key parameters affecting the weld joint quality are the rotation speed, the feed rate, the head pressure and the shape of the working tool [6].



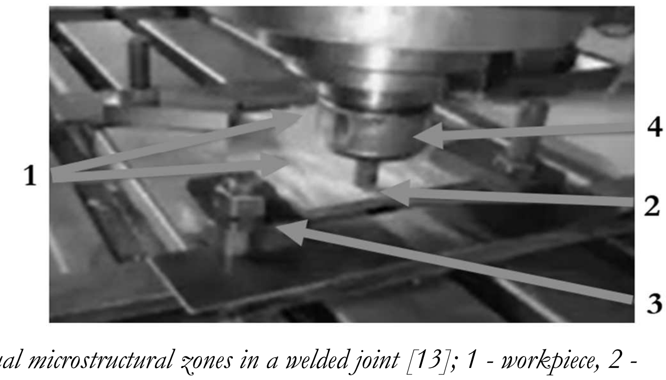


Fig. 1 *Friction Stir Welding and representation of individual microstructural zones in a welded joint [13]; 1 - workpiece, 2 - welding mandrel, 3 - fixed pad, 4 - tool arm*

When welding with the FSW technology, four characteristic microstructural zones are created:

- Zone a - is the base material that is not affected by heat or by mechanical deformation.
- Zone b - remains undeformed, however, the heat from the weld affects the properties of this zone (heat affected zone).
- Zone c – is subjected to plastic deformation and as well as to the thermal influence of the welding process (thermomechanically affected zone).
- Zone d - zone with dynamic material mixing (weld).

The main advantage of the FSW technology compared to conventional welding technologies is that the joining of the materials is achieved below the melting temperature, which avoids the negatives associated with the solidification process in the weld metal, such as introduction of inclusions and inherent defects during solidification, e.g. shrinkage, porosity, gassing, segregation of elements, diffusion processes leading to the degradation of microstructures, etc. [3, 11]. Thanks to intensive plastic deformation and elevated temperatures, it is possible to ensure that the resulting microstructure of the welded material in the weld area is characterized by fine equiaxed recrystallized grains; such a fine microstructure ensures good mechanical properties. However, the microstructure is dependent on the temperature and deformation field at the welding site and on the surrounding material. It is necessary to expect that the microstructure will not be homogeneous throughout the entire weld, that may consist of different microstructural areas (see Fig. 2) [8].

The disadvantage of this welding method is the low welding speed compared to some other mechanized arc welding methods. Welded parts must be rigidly clamped on the pad to prevent welding defects. At the end of each weld, it is necessary to use run-in and run-out attachments.

The aerospace industry (Boeing) and the automotive industry (for the production of radiators) have already shown interest in welding with this method. Table 1 lists some industry branches and product applications of possible use of this method.

Tab. 1 *Industry branches with potential use of FSW [9], [12]*

Industry branch	**Use in production**
Aerospace	aircraft frame structures, fuel tanks and connections of special alloy housings
Aluminum products	large pressings, seam tubes
Automotive	chassis frames, wheels, bulk cargo transport tanks
Building industry	bridges, accommodation on drilling rigs
Food industry	beer barrels
Railroad vehicles	coachworks
Freezing industry	cooling system pipes, heat exchangers
Shipping industry	hulls, decks and internal structures light, fast ships
Pressure vessels	liquid gas tanks

In addition, friction stir welding as a method of solid-phase welding does not have a negative impact on the environment. Before the welding itself, it is not necessary to comply with strict requirements for the cleanliness of the surface of the material. Only surface impurities are removed, any oxide film from the surface of the material is removed by mixing of the weld itself. The FSW process is a dust-free process, without spraying material and with low noise. Since it involves mixing the material only by rotating the welding head, there is a significant saving of energy compared to other technologies of conventional fusion welding.

2 Materials and methods

Measurements on aluminum alloy EN AW 6082 (EN 573-3) were carried out at the Technical University of Munich, Institute of Machine Tools and Business Sciences. For the Friction Stir Welding was used a universal Siemens 840 D CNC machine with a Ø 6 mm welding mandrel, with a corresponding feed rate setting of 200 $mm.min^{-1}$ and with a welding mandrel rotation speed of 560 rpm. The welded material was Al 6082 alloy (AlMgSi1 – DIN 1725); its chemical composition is shown in Tab. 2. For welding aluminum or aluminum alloys, the welding mandrel is usually made of either tool steel or cemented carbides WC-Co. Within our experiment, the welding mandrel was made of tool steel, which was pushed into the welded material with a force of 4,9 kN.

Tab. 2 *Chemical composition of aluminum alloy Al 6082*

Al 6082	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
wt. [%]	0,88	0,35	0,04	0,45	0,76	0,04	0,04	0,03	rest

The macrostructure of the weld joint with highlighted individual heat affected zones of the welded material is depicted in Fig. 2; the microstructure of the zones is A and D is depicted in Fig. 3.

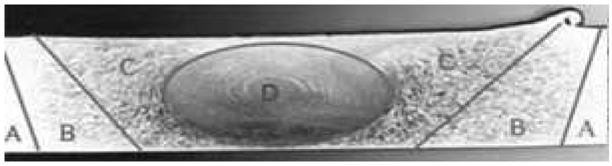
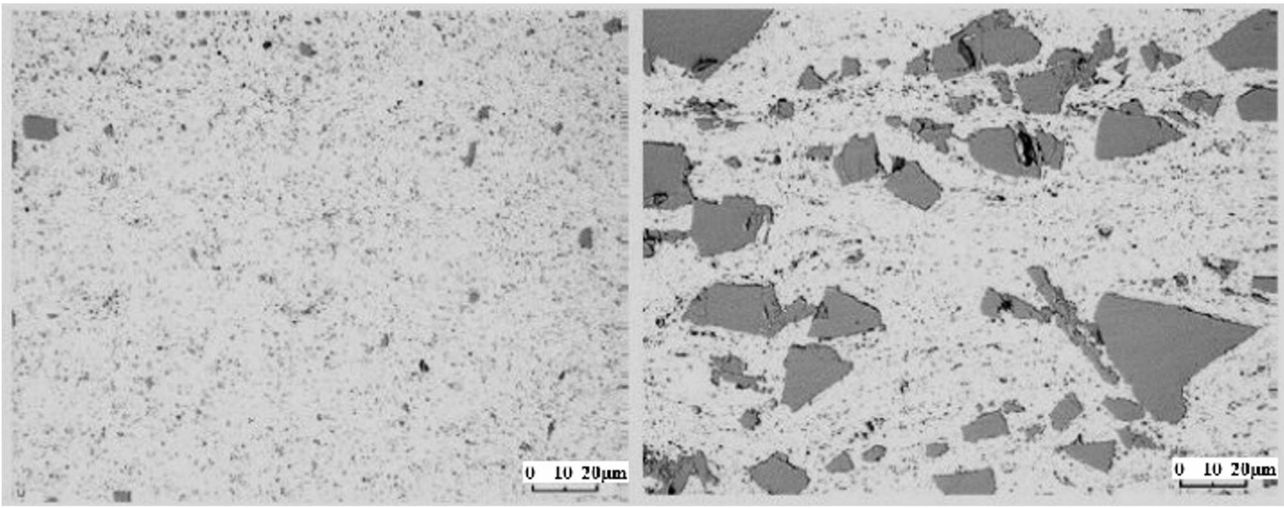


Fig. 2 *The macrostructure of the Aluminum alloy Al 6082 weld joint using the FSW method*



a) Zone D (nugget) **b)** Zone A (unaffected material)

Fig. 3 *The microstructures of selected zones of the weld joint*

- Zone A - unaffected material or parent metal; material remote from the weld that has not deformed and which, although it may have undergone a thermal cycle from the weld, is not affected by heat in terms of detectable changes in microstructure or properties.
- Zone B - heat affected zone (HAZ); a zone close enough to the weld for the thermal cycle to change the microstructure and properties, however, no obvious plastic deformation has been detected by light microscopy.
- Zone C - thermomechanically affected zone (TMAZ); in this zone, the material was plastically deformed by applied pressure of the mandrel tool and by the heat from the processing; in the case of aluminum, it is possible to generate considerable plastic stress in this zone without recrystallization, and in general there is a clear boundary, at least at the macroscopic level, between recrystallized and deformed zones.
- Zone D - dynamically recrystallized zone ("nugget"); it is an area of highly deformed material that roughly corresponds to the location of the welding tool. The grains in this zone are equiaxed, oriented in one direction and often several times smaller than the grains of the base material.

3 Results and discussion

To visualize the whole process, a computer simulation of the FSW thermal cycle of the aluminum alloy was designed. The aim of the numerical simulation is to describe the technological process and to approach the real conditions of the process through current mathematical models. The geometrical model of the welded material is generated in the environment of the program Ansys using finite element network method.

In the program environment, it is possible to create simulation of trees and links between the individual steps. The axis-symmetric model of the welded material is depicted in Fig. 4.

The model allowed to combine thermal analysis with the analysis of velocity fields, thus providing a basis for a dynamic model that simulates the effect of the moving mandrel on the surface of the material. Graphical outputs from the simulation, namely temperature fields in selected sections, are documented in Fig 5.; temperatures are given on the thermodynamic scale in Kelvin [K].

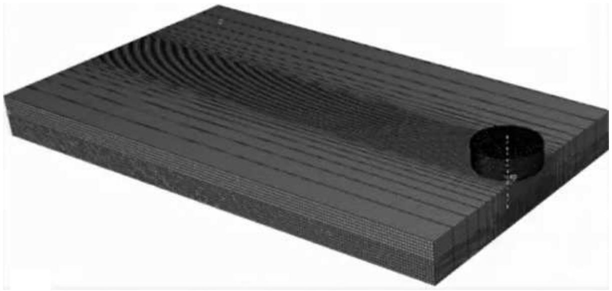


Fig. 4 *The generated network of the model*

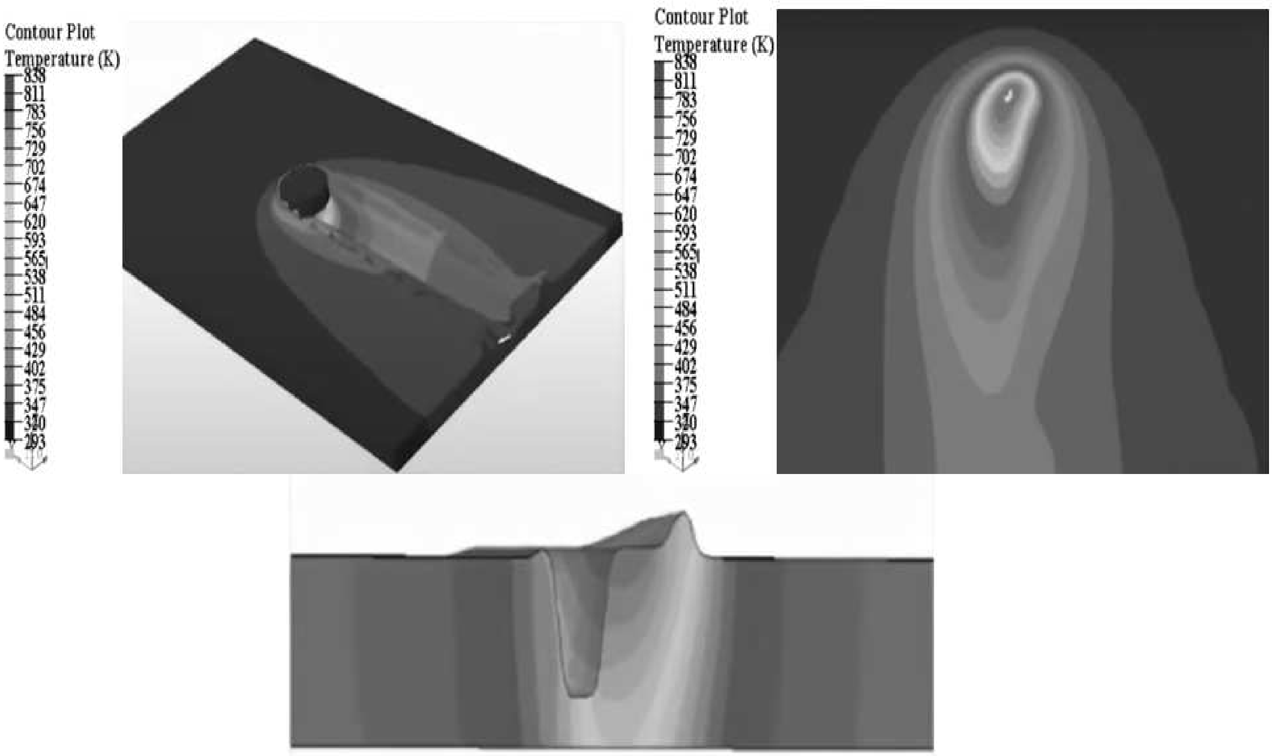
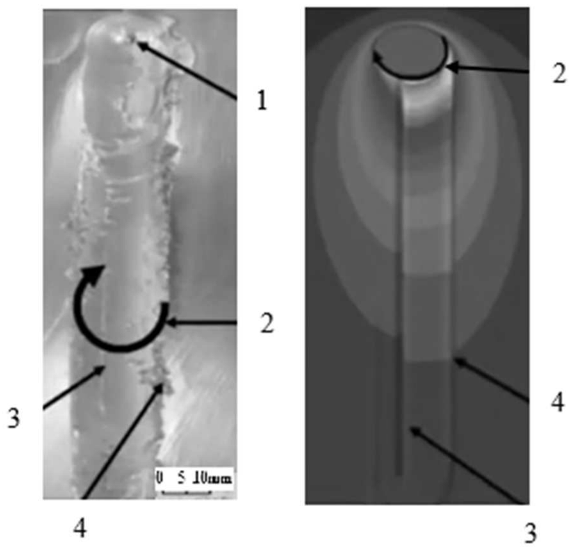


Fig. 5 *Temperature fields of the welded material in selected sections*



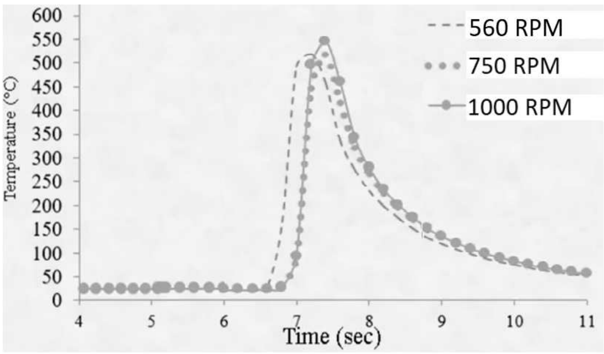
a) *Photograph of the real sample* ***b)*** *Temperature field simulation*

Fig. 6 *Weld joint of the aluminum alloy*

Where:
1…End of the weld joint,
2…Direction of rotation of the pin,
3…Crack of the weld joint,
4…Tunnel.

Defects can also occur when welding materials with the FSW technology. One of the defects may be e.g. improper mixing of the welded materials. As a result, the joint itself may break, as shown in Fig. 6. Also, a so-called "Tunnel" which may form in the material due to material vibration can be seen in the figure. Fig. 6 a) is a photograph of a real aluminum alloy sample with marked welding defects, Fig. 6 b) represents a corresponding simulation of the temperature fields.

The welding temperature is directly proportional to the rotational speed of the pin. Graph 1 shows the course of temperatures at individual settings of the rotation speed of the welding mandrel. At a rotation speed of 560 rpm, maximal temperature of 510 °C is created in the welded material, at 750 rpm, the temperature is 520 °C and at 1000 rpm, the temperature reaches 545 °C.



***Graph 1** Time course of temperature at individual rotation speeds*

4 Conclusion

The aim of our research was to test the parameter settings during the realization of the weld of the specimen, as well as to make a computer simulation basing on the same welding parameters. During the welding itself, as well as during the simulation, we focused on detection of defects, which will serve to prevent these defects in the future by appropriate adjustment of the welding parameters. Following findings basing on the computer simulation of the temperature fields and on the visual analysis of the specimen of the aluminum alloy EW 6082 specimen using Friction Stir Welding technology are pointed out:

- The welding of materials occurs below the melting temperature, which prevents deterioration of the mechanical properties of the joints,
- Using the FSW technology we may obtain high-quality welds, but the exact welding parameters must be observed,
- Minor defects appeared even when the welding parameters were observed such as signs of cracking of the weld joint or the formation of a tunnel,
- It will be necessary to perform a test of the mechanical properties on the mentioned samples, to confirm or refute the effect of the defects on the mechanical properties of the joint,
- By the comparison of the microstructure of the weld joint "nugget" and the microstructure of the base material, it is possible to confirm the refinement of the grains of the weld joint.

Since this is a welding in which the welded joint is formed in a solid state at elevated temperatures of the joined materials without the need to melt them, the chemical composition of the welded materials does not change during the welding. Thus, the weld joint has comparable, if not better mechanical properties compared to the base material. After welding, minimal deformations of the welded materials occur, no vapors, radiation, spatter or pores are generated. However, the only problem that is already being solved by run-in and run-out attachments is the hole that is created at the beginning and at the end of the weld by the welding mandrel.

In terms of the welding process, future possibilities of using the FSW technology depend primarily on the progress in the development of welding tools and of welding equipment. The shape of the tool determines the heating and the plastic deformation of the welded joint. The dimensions of the welding tool set the size of the weld joint and the welding speed. The tool material determinates its strength, the frictional heating rate and the welding temperature, that specifies the materials that can be joined by this method. Each of these aspects contributes to creating flawless welds at the desired operating temperature and other process parameters. Although this technology is currently used mainly for materials that can be welded at low melting points, such as aluminum, copper, magnesium and others, an improved type of welding mandrel is under development that can weld other types of materials with minimal wear and long lifetime of the tool.

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