UNIVERSITY OF MISKOLC
FACULTY OF MECHANICAL ENGINEERING AND INFORMATICS

OPTIMIZATION OF TECHNOLOGICAL PARAMETERS OF FRICTION STIR WELDING

Booklet of PhD Theses

ÁKOS MEILINGER
MECHANICAL ENGINEER, EWE/IWE

ISTVÁN SÁLYI DOCTORAL SCHOOL
TOPIC FIELD OF ENGINEERING MATERIAL SCIENCE, PRODUCTION SYSTEMS AND PROCESSES
TOPIC GROUP OF MATERIALS ENGINEERING AND MECHANICAL TECHNOLOGY

HEAD OF THE DOCTORAL SCHOOL
DR. MIKLÓS TISZA
DOCTOR OF ENGINEERING SCIENCES, PROFESSOR

LEADER OF TOPIC GROUP
DR. MIKLÓS TISZA
DOCTOR OF ENGINEERING SCIENCES, PROFESSOR

SUPERVISOR
DR. IMRE TÖRÖK
PHD, HONORARY PROFESSOR

Miskolc
2016

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1. INTRODUCTION

1.1 PRELUDES

In case of metallic base materials the aluminium alloys are used more and more in the industry. This trend is especially typical in the vehicle applications for example structure and body parts of vehicles and wagons [1], [2]. The modern high strength aluminium alloys reach the mechanical properties of conventional structural steel, but its weight only about one third of steels. This significant weight reduction is justified the spread of aluminium alloys [3], because the decrease of fuel consumption of light weight vehicle, thus it means lower operational price and it is advantageous in case of environment protection. In addition to weight reduction there appears the increase safety as a requirement [4], which is achievable with well thought-out design and the precisely used mechanical technologies. The welding is particularly important between these technologies.

In case of welding of aluminium alloys there is a narrow range of parameters to provide the expected quality, which in most cases does not reach the quality of base material. This is primarily true to the strength and strain properties, which were caused by the welding heat cycle. In addition the increasing productivity is a growing demand next to the quality by manufacturers, which is limited by the welding process. Because this recognition there is increasing development of welding processes for aluminium alloys. The basic goal is to improve the quality and the productivity of welded joints. As mentioned the welding heat cycle has significant effect, so the pressure welding processes with low heat input can be used. These processes provide good joint quality, but typically have severe geometrical constrains, so they are less common. A new pressure welding process could be a solution: friction stir welding.

1.2 THE PURPOSE OF DISSERTATION

The friction stir welding is a relatively new welding process so it is possible to develop several areas. Naturally the area of welded joint strength development is very important, because in case of pressure welding there are special methods to increase this strength. If we understand the occurring processes during friction stir welding, so we can perform the necessary optimization of technological parameters to achieve increased strength. In terms of welding processes the friction stir welding is one of the most intensively researched process internationally with serious literature background, nevertheless there are less developed and cleared fields. The friction stir welding is used by several field of industry, independently of the occurring processes are not perfectly understand during welding. Typically used to make long, straight welded seams on an aluminium alloy structure, for example wagons, ships, airplanes and bridges [5], [6].

During the operation of these structures different loads can occur, the cyclic loading is one of the most important load. Because this the investigation of friction stir welded joint properties under cyclic loading conditions is very important. During friction stir welding different processes can occur as fusion welding, so the properties of welded joint can be different under cyclic loading. In this field there are less result and publication, moreover there are many influencing factors due to the process feature, so it requires extended research. In case of aluminium alloy structures the low cycle fatigue [7], the high cycle fatigue [8] and the fatigue crack growth can be occur.

In case of fusion welded joints there are not significant effect of the technological parameters to the cyclic loading properties, because there are not significant opportunity to change these properties and reach the optimum. Contrarily there are technological opportunities during friction stir welding to influence the cyclic loading resistance of welded joints.

The global aim of this research is to create a conceptually compilation of technological parameters and technological development, which result good mechanical properties through optimum microstructure in case of quasi-static and cyclic loads.

Taking all these into account during research must be examined the technological parameter determination and its effect to the joint properties:

- occurring processes during welding and theirs effect to the formation of microstructure,
- aspects about selection of technological parameters, taking into account the improvement of joint quality,
- the effect of different tool geometries to the welding and joint quality,
- the effect of welding heat cycle to the material microstructure and joint quality too,
- the cyclic loading resistance of friction stir welded joints next to the static loading.

2. METHODOLOGY

During theoretical research I especially study with the effect of technological parameters of friction stir welding, and with the tool geometry. This is a solid-phase pressure welding process, so it has different joint formation and structure as fusion welded joints. Consequently, I study the joint structure and its basic mechanical properties. The friction stir welded joints have different grain sizes in different parts of the joints, which basically influences the strength properties. This is due to the fact different metallurgical processes can occur in different parts of joint during welding, so I especially research these processes in the literature. In the heat affected zone the static recovery and static recrystallization can occur. In the weld nugget and in the thermo-mechanically affected zone the dynamic recovery and dynamic recrystallization is the decisive [10], [11], [12]. In the weld nugget fine-grained structure is occurring due to the dynamic recrystallization according to the literature [11], [12]. Due to this fine-grained structure the friction stir welded joints have good strength properties. Consequently I especially research the dynamic recrystallization. The experts have been discovered that the dynamic recrystallization can occur in case of aluminium alloys too [13], [14], [15], [16]. I collected the typical temperatures, strain rates and strains during friction stir welding, and it was a good base to plan and perform my investigations. The friction stir welding can economically apply to weld aluminium structures, so I did theoretical reviewing on aluminium alloys, and I choose two usually used alloys: 5754-H22 and 6082-T6.

As it mentioned in several literature the friction stir welded joints have better mechanical properties as fusion welded joints in case of aluminium alloys [17], [18], but it is also typically published by the results of conventional destructive and non-destructive tests. The frictions stir welding is used more and more product where the cyclic loading can occurs. We can meet low cycle fatigue [19], [20], [21], [22] and high cycle fatigue [23], [24] loads too, so very important to analyze the resistance of friction stir welded joints against cyclic loading. There are quite few literature in this field, so I felt important to investigate these friction stir welded joint under cyclic loadings, and to find contexts between the this and the technological parameters which can help the technological planning.

During experimental research I designed a friction stir welding tool, which result more balanced temperature distribution across the wall thickness. I measured the grain-sizes on the joints which welded by this tool, and I made grain-size maps in case of both materials. I was found that there are significant differences between the advancing and retreating side, and between the face and root side. There are significantly greater grain-sizes on the root side than the face side in case of 5754-H22 and 6082-T6 joints. Figure 1. shows an example to these differences:

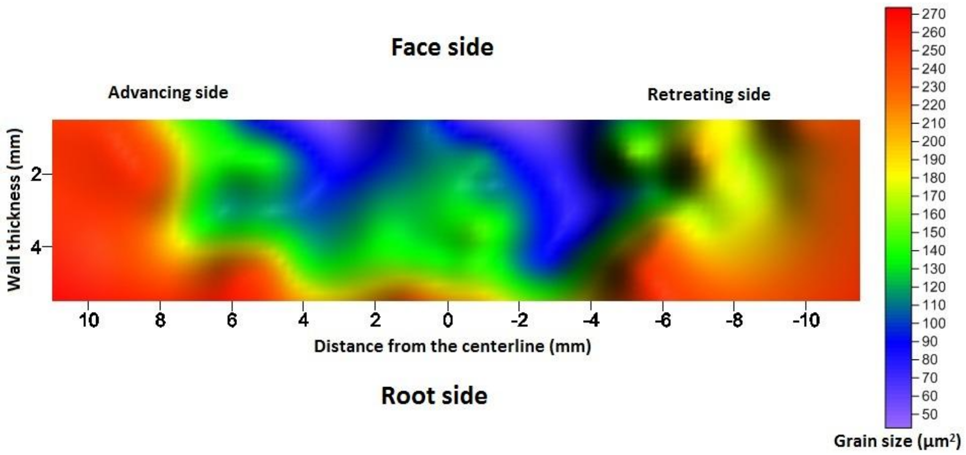

Figure 1. Grain-size map in case of 6082-T6 welded joint

During welding necessary use a backing plate (because pressure force), so the coarser grains can be resulted by the slower heat cycle on the root, because the material of the backing plate is steel so it has lower heat conduction than aluminium. Consequently I investigated the application of the faster heat cycle and its effect to the grain size on the root side. I determined that smaller grain sizes can be reached by additional root cooling and it has good effect to the strength properties on both alloys. In case of 5754-H22 the range of technological parameters can be extended with root cooling as well. The other reason of coarser grains on the root side can be the lack of dynamic recrystallization. I made preliminary experiments to determinate the dynamic recrystallization on both material. Based on these experiments (hot compression tests) it became clear the dynamic recrystallization can take place both base material but the conditions were significantly different. After this I made experiments with the previously measured root heat cycles and the values of strains and strain rates were determined according to literature [25], [26], [27], [28], [29], [30], [31]. Based on these experiments I determined that in case of 5754-H22 alloy the dynamic recrystallization cannot be took place with root side conditions, but in case of 6082-T6 it had took place.

The friction stir welded joints typically have cyclic loading, so I investigated low- and high cycle fatigue too. Based on the low cycle fatigue test results I determined that the number of cycles with strain amplitudes are basically same both base material and friction stir welded joints in case of 5754-H22. In case of friction stir welded joints the measured values of stress amplitudes were higher than base materials' which referring that the strain hardening overcompensates the metallurgical processes caused softening processes.

The values of total strain amplitudes of 6082-T6 base material are same as 6082-T6 welded joint in case of lower strain amplitudes. The elastic strain amplitudes of joints are lower than base materials', the plastic strain amplitudes of joints are higher than base materials'. There are significant difference between the connections of plastic strain amplitudes-stress amplitudes. The values of measured stress amplitudes of friction stir welded joints shows significantly lower values than base materials'. Probably in case of heat treatable aluminium alloy the softening processes are more dominant than strain hardening.

There are significant differences between the parts of the friction stir welded joints, so it is advisable to examine the location of crack formation too. The low cycle fatigue tests were not made to fracture of test specimen, just to the 10% decreasing of peak stress, so the cracks were visible. After visual examination of crack location and propagation, I recognized that most of cracks propagate as "S" shape on middle of the joint. Figure 2. shows an example.

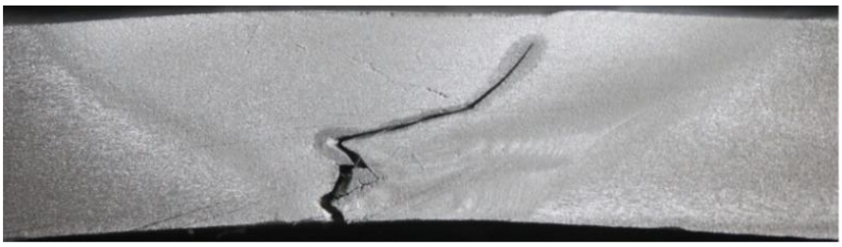

Figure 2. Example for crack propagation in 6082-T6 joint (1,25x zoom)

After detailed examination it became clear that the crack propagation follows the broken oxide layer which stirred from the base material. Consequently the stirred oxide can influence the low cycle fatigue resistance of friction stir welded joint. I designed a new welding tool which cause more efficient break of the oxide layer. I welded joints with this tool and I tested against low cycle fatigue with two different strain amplitudes. I prove with statistical method that new joints (made by new tool) have better low cycle fatigue resistance.

3. NEW SCIENTIFIC RESULTS

T1. I pointed out that the heat cycle on the root side influences significantly the grain size on the root side on examined aluminium alloys (6) (25):

a.) In case of 5754-H22 friction stir welded joint I proved that the faster root cooling and the lower root peak temperature result significant reduction of grain size and improve the strength of joint.

b.) In case of 5754-H22 friction stir welded joint I reached the fine grained microstructure on the root side with the additional root cooling and suitable technological parameters. I determined an ideal root peak temperature range (250-300 °C), where the strength properties of joint can improve.

T2. I proved that the occurring of dynamic recrystallization depends on material properties, temperature, strain rate, and strain (11) (12):

a.) I proved that the dynamic recrystallization can occur in 5754-H22 base material.

b.) In case of 6082-T6 friction stir welding the dynamic recrystallization significantly occurs – with lower strain rate and strain – independently of the degree of root cooling. I proved that higher strain rates require higher strains to reach the dynamic recrystallization.

T3. The friction stir welded joints of 5754-H22 and the friction stir welded joints of 6082-T6 show different behavior in case of low cycle fatigue (25) (26) (27):

a.) In case of low cycle fatigue tests of 5754-H22 friction stir welded joints the measured values of stress amplitudes were higher than base materials' which referring that the strain hardening compensates the metallurgical processes which caused softening processes. It is in accordance with the results of dynamic recrystallization.

b.) In case of low cycle fatigue tests of 6082-T6 friction stir welded joints the measured values of stress amplitudes of friction stir welded joints shows significantly lower values than base materials'. It is accordance with the results of dynamic recrystallization, in case of 6082-T6 friction stir welded joint the softening processes are more dominant than strain hardening.

T4. I proved that the geometry of friction stir welding tool influences the distribution and dimensions of stirred oxide layer (26) (27):

a.) In case of friction stir welded joint of 5754-H22 aluminium alloy I proved that the distribution and dimensions of stirred oxide layer and the higher material flow ensuring tool does not influence significantly the resistance of low cycle fatigue not even with additional root cooling.

b.) In case of friction stir welded joint of 6082-T6 aluminium alloy I showed that the distribution and dimensions of stirred oxide layer has significant influence to the resistance of low cycle fatigue. I proved that the resistance of low cycle fatigue of friction stir welded joint increase with the higher material flow ensuring tool.

4. UTILIZATION AND DEVELOPMENT OPPORTUNITIES

There are several industrial utilization of my research, I would like to highlight the opportunities of strength increasing. The additional root cooling is easily feasible and it results significant improvement in this field. The results of dynamic recrystallization are similarly well suited for tool- and technology design. These results also showed that the quality- and processing of base materials greatly influence the success of welding. I think the results of fatigue tests are very important because these showed that important to know the operating stresses of welded structural part for technology design. In terms of welding equipment the applicability of robotic friction stir welding system is one of the most intensively researched area. These robotic systems have significant limitations in respect of loading, hence the tool- and technology design is crucial, so the principles of tool design can be very useful. In my opinion this research work will help the spread of friction stir welding and it can be useful for welding experts.

According to research work it became clear for me that there are several fields to investigate in this topic, so more development opportunities can be formulated. Based on this dissertation different aluminium alloys behave differently in case of friction stir welding, so I think very important to broaden the investigations to other base materials. It can be worth to investigate the opportunity of additional root cooling in case of materials with bad weldability (for example Al-Cu aluminium alloy). In case of these materials the occurring of dynamic recrystallization can be interesting too. I investigated just one wall thickness, but it has significant effect to the strength properties of friction stir welded joints, and it can influence the effect of additional root cooling too.

In terms of fatigue tests additional aim that to continue the high cycle fatigue tests on force cooled friction stir welded joints. Besides the fatigue crack growth tests can provide very important results to supplement the available fatigue tests results.

5. LIST OF THE PUBLICATIONS RELATED TO THE PHD DISSERTATION

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