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# FRICTION STIR WELDING (FSW) PROCESS OF COPPER ALLOYS

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The present paper analyzes the structure of the weld joint of technically pure copper, which is realized using friction stir welding (FSW). The mechanism of thermo-mechanical processes of the FSW method has been identified and a correlation between the weld zone and its microstructure established. Parameters of the FSW welding technology influencing the zone of the seam material and the mechanical properties of the resulting joint were analyzed. The physical joining consists of intense mixing the base material along the joint line in the "doughy" phase. Substantial plastic deformations immediately beneath the frontal surface of tool provide fine-grained structure and a good quality joint. The optimum shape of the tool and the optimum welding regime (pressure force, rotation speed and the traverse speed of the tool) in the heat affected zone enable the achievement of the same mechanical properties as those of the basic material, which justifies its use in welding reliable structures.

*Key words:* friction stir welding, copper, microstructure, thermo mechanically process

## INTRODUCTION

The FSW welding technology was first introduced in 1991 by the *The Welding Institute* (TWI) as a result of years of research related to welding light metal alloys, primarily aluminium alloys [1-3].

In conventional welding technologies (MMA), (TIG), (MIG), (MAG), etc. materials were joined based on the process of diffusion in the heat affected zone (HAZ).

This process requires heating the joint zone to the temperature which ensures diffusion, but, on the other hand it requires considerable amounts of energy. This heating results in some negative consequences such as the occurrence of significant deformations, residual stresses, porosity, inhomogeneous and coarse-grained HAZ structure, and so on.

A particular disadvantage of conventional welding technologies is their inability of welding most of the light metals and their alloys (copper alloys, some aluminium alloys, etc.).

In addition to its ability to join both similar and dissimilar materials which conventional methods cannot achieve, the advantage of the FSW technology is also reflected in the segment of improved mechanical properties in the HAZ [4].

The idea behind the FSW welding technique is based on the principles of thermo-mechanical joining the materials by means of a special tool, without the use of filler materials and gas shield. Parallel to the FSW technology, analytical methods and numerical procedures have also been developed for the purpose of identifying parameters that predominantly affect the thermal and mechanical processes occurring in this type of welding [5].

Given that it significantly reduces the residual stresses and distortion of components in the join, the FSW procedure is widely used in welding reliable steel structures [6].

## PRINCIPLE OF OPERATION

The FSW process consists of four phases: 1) plunging phase, 2) dwelling phase, 3) welding phase, and 4) exit or retract phase. The process starts with the first phase when the tool approaches the material, and then penetrates it in order to generate the initial amount of heat.

The second phase is characterized by the process of reaching the operating temperature necessary to start the welding process. This involves a constant pressure force to be present between the tool and the material, which creates the required mechanical (friction) energy. This process continues until the material's elastic modulus, i.e. the pressure force between the tool and the material, drops, which is a sign that the required temperature is reached, and the welding process can start.

The phase of welding (third phase) is realized through a complex thermo-mechanical process that involves the integrated action of thermal heating and plastic deformation. Realization of welding in the FSW processes involves mixing the "doughy" basic material of the work piece along the joint line. Given that the temperature generated this type of heating does not provide a complete diffusion, the basic materials of both pieces in the joint need to be mixed mechanically using the tool pin.

Mechanical work plays a key role in this process: it both affects the generation of thermal energy, ensures the mixing of base materials in their "doughy" phase in

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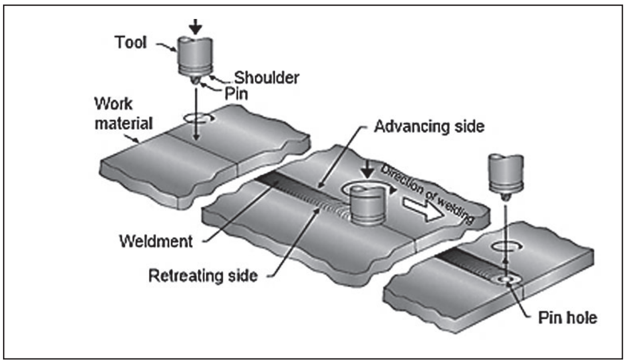



**Figure 1** The principle of joining in the FSW welding process [5]

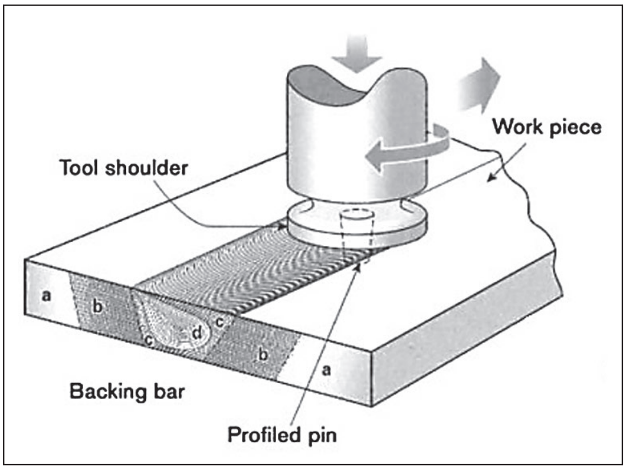



**Figure 2** The welded joint in the FSW procedure [7]

order to achieve a quality structure in the weld joint. In the last (fourth) phase, the tool exits the material (by vertical movement), completing thereby the welding cycle (Figure 1).

The FSW procedure found its widest application in butt and lap welding, while creating corner joints is also possible. Heat is generated using a special tool that consists of a body, a larger diameter (shoulder) and a smaller diameter (pin), see Figure 2.

## THERMO-MECHANICAL PROCESS IN THE FSW PROCEDURE

The FSW welding process is based on a thermo-mechanical process unfolding directly in the joint zone. The thermo-mechanical process is characterized by conduction heat transfer due to friction between the tool and the material, and material flow in the zone of the heated material. The tribological effect at the outset of the weld process has a role of generating the minimum amount of welding heat. This heat leads to the reduction in mechanical properties of the material (hardness and strength), making it suitable for plastic deformation without wrecking the material.

## MICROSTRUCTURE OF THE WELDED JOINT

Microstructure of the welded joint achieved using the FSW procedure consists of: d) weld nugget, c) thermo mechanically affected zone (TMAZ), b) heat-affected zone (HAZ), and a) the parent metal. Depending on the microstructure of welded joint, there are three different mechanical properties of the weld. The present research is focused on welding copper and its alloys. Grains of the base material (copper) are elongated in shape and their size is about 30 microns [8].

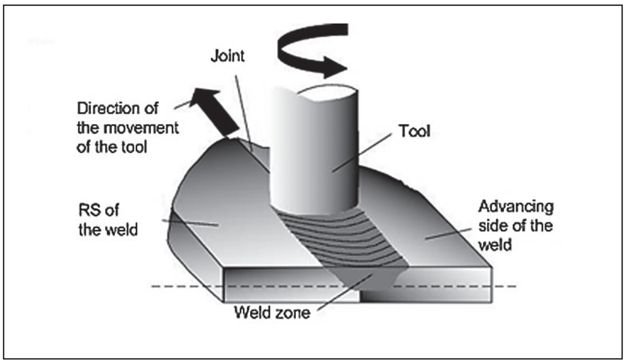



**Figure 3** Advancing and retreating side of the weld

Microstructure of the weld nugget is very fine, with a grain size of about 11 microns. This seam zone is characterized by dynamic recrystallization due to the influence of tribological processes (mechanical friction and plastic deformation), which results in higher hardness compared to the base material.

The TMAZ zone is characterized by small-grain structure that is simultaneously exposed to plastic deformation and the influence of temperature. In this zone, the elongated grains are rotated by 90 $^{o}$ compared to the parent material viewed from both sides of the joint (advancing and retreating side), see Figure 3.

The transition between the TMAZ and the HAZ is characterized by a gradual increase in grain size as a result of the insufficient plastic deformation, as here the tool acts with its peripheral portion. On the other hand, grains in the HAZ zone are larger, but the grain size depends on which side of the welded joint they are.

The structure of grains located on the advancing side is finer, while on the retreating side grains grow due to the lower intensity of plastic deformation (Figure 4).

This phenomenon is expressed to a lower extent in the TMAZ zone, while in the HAZ it is visible. Structure of the weld in the HAZ zone is almost identical to that of the base material, which indicates a good quality weld.

It should be noted that grain size is the largest in the HAZ of retreating side (RS) part, and this is the most critical seam zone.

Experiments have shown that welding speeds does not affect the size of the grains in the HAZ zone.

## EFFECTS OF TOOL SHAPE AND WELD PARAMETERS ON SEAM QUALITY

The tool shape and the welding regime are the main parameters affecting the quality of welded joints. Due to the complex mechanism of the FSW welding procedure, optimum values of these parameters are determined solely by experiments. Recently, some studies

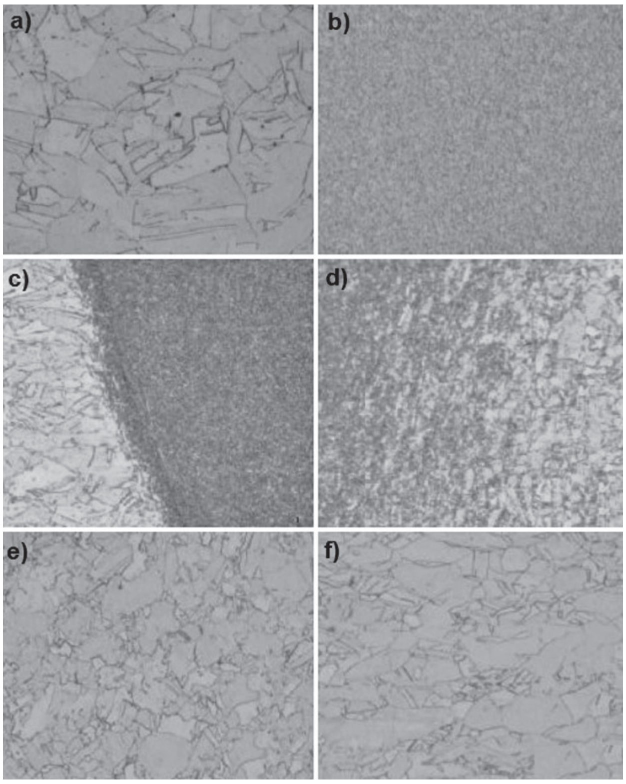
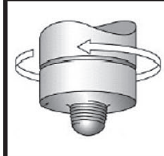
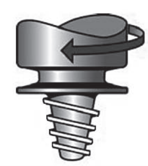
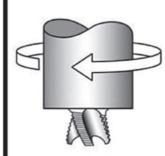
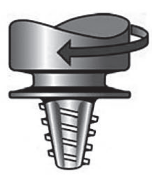



**Figure 4** Microstructure of the welded copper joint [8]: a) base metal, b) nugget zone, c) TMAZ of TMAZ, d) TMAZ of RS, e) HAZ of AS of , f) HAZ of RS

have been presented using numerical approach (software simulation) in the analysis of the effects of tool shape and welding regime on the amount of generated heat and the welded joint [5].

The aim of this approach is to reduce the costs and duration of experimental tests. The welding regime in the FSW procedure is defined by the axial force, speed of rotation and the translational speed of tool, all of which depend on the thermo-physical properties of the material and the thickness of plates. The rotation speed of the tool is a direct indicator of the amount of heat generated and can range from 200 to 1 500 r/min. The translational tool velocity is the welding speed, which is a function of mechanical properties of the material and the thickness of pieces to be welded. The highest share in the generation of heat is that of the peripheral area of the tool and accounts for 86 % of the energy, while the tip of the tool only for 3 %, while the rest of the energy generated by the pin. The appearances of characteristic tools and their purpose are presented in Table 1.

Table 1 **Types of tools designed for the FSW [9]**

| Schematics | Tool pin shape | Ratio of pin volume to cylindrical pin | Swept volume to pin volume ratio | Application |
|---|---|---|---|---|
|  | Cylindrical with threads | 1 | 1,1 | Butt welding fails in lap welding |
|  | Tapered with threads | 0,4 | 1,8 | Butt welding with lower welding torque |
|  | Threaded, tapered with three flutes | 0,3 | 2,6 | Butt welding with further lower welding torque |
|  | Inclined Cylindrical with threads | 1 | depends of angle | Lap welding with lower thinning of upper plate |
|  | Tapered with threads | 0,4 | 1,8 | When minimum asymmetry in weld property is desired |

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## CONCLUSION

The present study has analyzed the welding parameters influencing and the microstructure of the welded copper joint using the FSW process. Heat inducing mechanisms of this welding process, zones of influence and the structure of the welded copper-alloy joint were analyzed. Advantages over conventional welding processes were identified, with special emphasis on the minor influence of residual stresses. It has been concluded that the shoulder face of the tool mostly generates thermal energy that preheats the material and creates conditions for quality welding. The tool pin has the role of mixing and plastic deformation of the base material, which results in fine-grained seam structure. Mechanical properties of the welded joint are the same as the base material.

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**Note:** The responsible translator for English language is prof. Jelisaveta Šafranj, Novi Sad, Serbia