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MODELLING OF FSW PROCESS AS AN ASPECT OF APPLICATION IN MANUFACTURING

Univ. Assist. Mr Petar Tasić, dipl. ing.
Faculty of Mechanical Eng. Sarajevo
Vilsonovo šetalište 9, Sarajevo
Bosnia and Herzegovina

Prof. Dr. Damir Hodžić, dipl. ing.
Faculty of Mechanical Eng. Sarajevo
Vilsonovo šetalište 9, Sarajevo
Bosnia and Herzegovina

Prof. Dr. Ismar Hajro, dipl. ing.
Faculty of Mechanical Eng. Sarajevo
Vilsonovo šetalište 9, Sarajevo
Bosnia and Herzegovina

ABSTRACT
Although friction stir welding is joining process with still relatively poor explained phenomenology, it is widely used in industry. It has been proven for welding of light metals and such structures, and in particular for aluminium alloys. This is also process which gives excellent metallurgical properties of weld, and enables avoidance of pre-weld and post-weld heat treatment. This leads to significant reduction in costs and time, thus increases manufacturing efficiency. However, this is process which requires more time for implementation in production line due to relatively long process of setting right parameters. This can be done either by using experiments or other methods (e.g. FEM simulations), and both are time consuming. This paper summarizes aspects, advantages and disadvantages, of modelling process and its influence on implementation of FSW in production line.
Keywords: FSW,

1. INTRODUCTION
Welding processes relaying on heat created by friction have several significant advantages in comparison with conventional (fusion) processes. Most importantly, there are no detrimental changes of microstructure that are usually connected with fusion. Heat input is generally lower, enabling narrower heat affected zone, less deformation and absence of residual stresses. This is specially case with friction stir welding. [1]
Process itself is very simple (Figure 1).

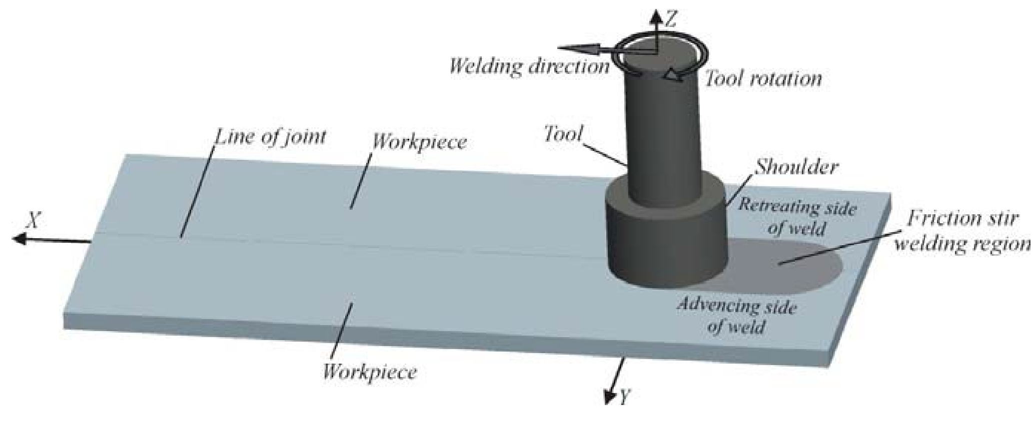

Figure 1. Schematic drawing of friction stir welding [2]

Tool penetrates material while rotating, and then moves along weld line. Heat produced on contact surfaces (pin and shoulder) and plastic deformation generate heat, what softens material, which is stirred while in such condition [2]. Joint can take many configurations, depending on needs, but the welding principle is the same.

So far, FSW has been widely used for welding of aluminium and its alloys, and, slightly less common, other light metals and their alloys (magnesium and titanium). However, for steels and high strength Ni alloys, cost effective welding and long tool life remain in research and development, as well as subject of processing technology optimisation [3].

2. MODELLING OF WELDING PROCESS

This is welding process with relatively few key process parameters. Tool geometry can be considered as one of the most important ones, if not the most important one [4]. Beside tool, there are rotational and traverse speed of tool. Other, usually less influencing, parameters are, for instance, inclination angle of tool and forces. Forces must be sufficient to enable welding, therefore directly depending on principal parameters, i.e. tool geometry. In general, there is no shielding gas, powder or protective atmosphere used during welding, hence simplifying process and process modelling.

FSW process seems to be simple, and in application, it is. Even though it seems quite easy to explain welding mechanism, in reality that is tough task. There is still no comprehensive model that can explain process in its entire, what somewhat limits its usability in manufacturing process. In particular, it is hard to predict optimal set of parameters and, consequently, properties of weld. Therefore, it is quite hard and challenging to implement FSW welding process into production line.

Having detailed and well-known relationship(s) between process parameters (as input) and weld properties (as outcome), is essential in this case. Since weld properties are closely connected with microstructure, and microstructure is consequence of thermal cycle, it should be sufficient to have sound and comprehensive thermo-mechanical model of welding process. Coupling with microstructural model is desirable, yet even more challenging.

Universal relations between process parameters, material properties and thermo-mechanical cycles are still not established or verified, and they are to be found for every single case of welding setup. Such relations highly depend on tool geometry. Since its invention, FSW process yielded many tool geometries to fulfil manufacturing needs. Some of them are shown in Figure 2. Most of them have been developed for specific industrial applications and successfully used, even before scientific explanation about their usability was given.

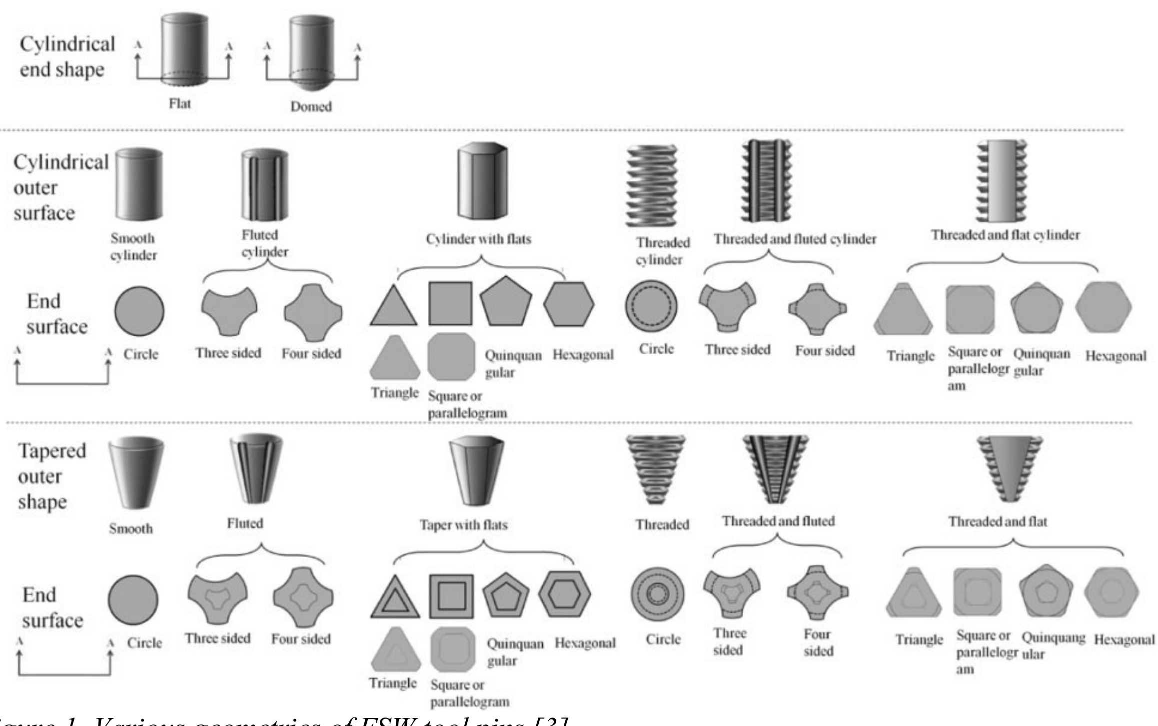

Figure 1. Various geometries of FSW tool pins [3]

Tool shapes shown in Figure 2 are designed to reduce force during plunging or moving, increase tool life by eliminating local stress concentration and improve the quality of the weld root directly at the bottom of the tool [3]. However, due to complex tool geometries, modelling of process is difficult and time consuming task. Over time, two different approaches to modelling of process are developed, describing heat generation and, consequently, microstructure. Both have their own pros and cons.
The first is indirect, when temperatures are measured during welding, and then model created, established and/or verified. [1,4]
The second is direct, when explicit mathematical relations between welding parameters, material properties and thermo-cycles are given [1]. Output is heat generation (heat input) as a function of parameters and material properties. In recent researches, direct approach is much more used.

3. MODELLING OF HEAT GENERATION

Main problem of process modelling is description of principal heat generation mechanism. In the beginning of FSW research, friction has been considered as main source of heat, while heat due to plastic deformation has been considered as negligible or insignificant [5]. Nowadays it is considered that significant part of heat is generated by plastic deformation. Furthermore, plastic deformation is considered to be dominant mechanism if tool has complex geometry, or if material is very plastic [6]. Tool and its geometry surely has principal role in heat generation, no matter which mechanism is dominant.
Relationships between all factors influencing heat generation are still not determined and explained in detail, so there is no universal comprehensive model for heat generation, and, consequently, calculation for heat input. There are, for instance, equations describing heat input for tools of polygonal pin shape (see Figure 2), and it was shown that heat input is between 120 and 170 J/mm [6]. Some other models consider sliding of material during welding [7], or consider plastic deformation as main source of heat [8].
All mentioned above regarding process modelling is varying from case to case. Almost every case has to be analysed, modelled and verified separately, including tool geometry and material properties. In most cases, modelling is done by using computers and software.

4. IMPLEMENTATION IN MANUFACTURING

There are few different aspects of FSW application in manufacturing. They cannot be analysed or discussed separately, due to strong connection between them.
Tool is one of the main aspects of efficient FSW application. Properly chosen geometry of tool can help avoiding possible adverse effects of welding. Simple changes of geometry features can lead to increased welding speed, heat input or decreased tool wear. It has important role for weld aesthetic, and under some conditions can be used for pre-heating or post-weld heat treatment. [1] Every change in tool directly influences production costs and time, and nowadays a variety of tool geometries is employed to achieve high production and quality.
However, tool also directly affects process modelling. And modelling is important aspect of FSW, strongly influencing efficiency in manufacturing process, although that is not something clearly visible. There are no comprehensive relations describing connection between process parameters, material properties and welding outcome (either thermo-cycles or microstructure). Even more, there is no universally applicable model that can be used for variety of welding setups.
To develop and verify accurate model of FSW process for particular setup in manufacturing requires a lot of time, and often includes welding of test series. Furthermore, good model relies on well-described material properties, what means detailed characterization at room and elevated temperatures. All this is time consuming, and increases costs, therefore it is not always justified to conduct such detailed tests. Another significant obstacle with modelling is experimental verification of model. Without it, model cannot be considered as accurate and reliable. Verification is usually done by checking temperatures during welding process and, additionally, microstructure [1,5,6].
In most cases, successful implementation of FSW in manufacturing is done in shorter way, by welding series for trial-and-error evaluation or using design of experiments. In certain cases, regression analysis has been used to optimise welding parameters [9]. However, all optimally set parameters are required to be adjusted in case any (significant) changes in input, making model valid only for one particular set of input data.

5. REMARKS

Efficiency is considered to be one of main advantages of friction stir welding over fusion welding processes. Process parameters, in particular tool geometry, have significant influence on all of them. Since tool and its geometry vary from setup to setup, it is justified to assume the same for efficiency. It is hard to calculate it, and sometimes even estimate it, because process modelling is problematic. However, problems with modelling have more significant consequences regarding prediction of thermo-cycles, microstructure and, consequently, weld properties. Additionally, almost each model needs experimental verification, what significantly increases time required to implement FSW into production. In many cases, FSW has been successfully implemented in manufacturing after making test series of welds and their examination, what is faster method that modelling. Other approaches, like design-of-experiment, are used as well. Therefore, it could be concluded that modelling of FSW process is still probably inadequately responsive to dynamic requests and challenges often present in production line. However, knowledge about FSW, including already gained experimental and numerical results, is cumulative, and that can serve for enhancing manufacturing process.

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