Influence of the welding tool's geometry on productivity of friction stir welding process

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Abstract

Friction Stir Welding is a nonconventional, frictional welding process dominantly applied on plate-shaped parts. Activation energy-heat, necessary for the weld creation, is generated on the frictional contact between the specialized welding tool and base material. The amount of the generated heat depends from numerous parameters (technological, tribological etc.) where dominant technological parameters are angular rotation of the welding tool, welding speed and geometry of the welding tool. Beside special geometry of the welding tool, Friction Stir Welding has numerous advantages over other welding procedures: energetically is very efficient, it is eco-friendly process, welds are of great quality etc. Intensive researches and industrial application in aero, space naval and railway systems made Friction Stir Welding competitive with other welding techniques. This paper is giving theoretical analysis of parameters that influence productivity of the Friction Stir Welding and direct influence of the welding tool's geometry on productivity. Experimental confirmation of the analysis has been presented on welding of aluminium alloy 2024-T351.

Introduction

Friction Stir Welding (FSW) is a solid state joining process that uses (combined) influence of the heat and the mechanical work for the weld creation [1].

From its invention in December 1991 until present days, FSW is successfully developing and finding application in various technological branches [2]-[4]. This is predominantly influenced by numerous advantages of the FSW over other welding procedures: absence of the melting phase during FSW leads to no hot-cracks and no porosity and, furthermore, minimal distortion of the weld (geometrical stability) is achieved.

In FSW, key parameters for the successful welding and quality gaining are the heat and stirring/mixing the by heat softened material of base metal.

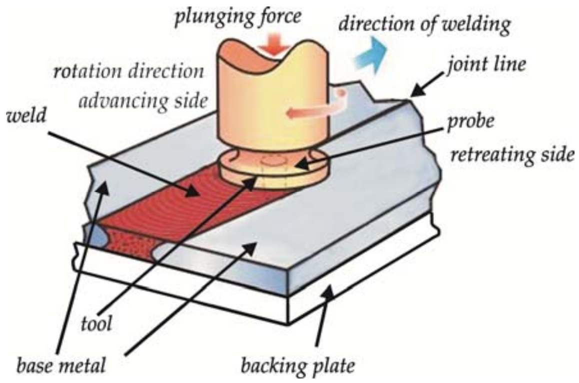


Figure 1 Scheme of the FSW

Heat is generated at the intimate tribological contact between the welding tool and base metal [1] used for the preheating of the base metal and lost over air and contact between base metal and backing plate. The contact between welding tool and base metal is highly frictional and the most of the generated heat is frictional however the amount of the heat generated by the deformation should not be neglected [1]. The input (generated) heat depends on technological parameters (welding rate, rotation of the welding tool – rotation rate, geometry of the welding tool, duration of the welding process etc.), tribological parameters (friction coefficient, contact pressure etc.) and thermo-mechanical properties of the welding tool and the base metal (thermal conductivity, hardness, yield strength etc.). Parameters of FSW that can be directly affected by user with the goal of efficiency increase are just technological parameters; proper selection of these parameters results in productivity, quality and the efficiency increase of the FSW.

To conclude: welding tool must adequately stir/mix softened material of base metal and generate sufficient heat during contact with base metal [1]. However, this is not a task simple to realize: for example, increase of the rotation velocity of the welding tool and plunging force results in higher temperatures of welding plates (as a result of intensive heat generation and/or small heat losses) while increase of the welding rate results in temperature drop (Figure 2).

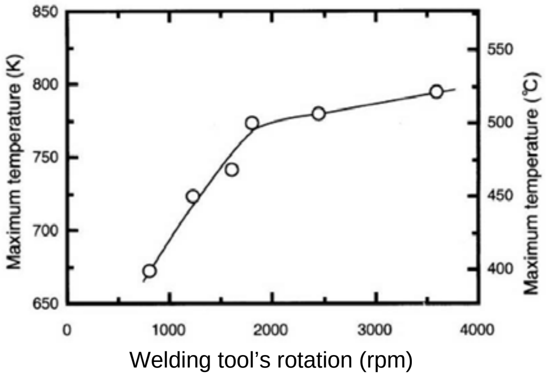


Figure 2. Influence of welding tool's rotation on temperature of the alloy Al 6063 during FSW [5]

Welding rate is transversal velocity of the welding tool and it depends on mechanical properties and height of the base metal. Welding rate is directly affecting the material deposition – stirring/mixing (Figure 3). For example, if height of the base metal increases, welding rate must decrease [6].

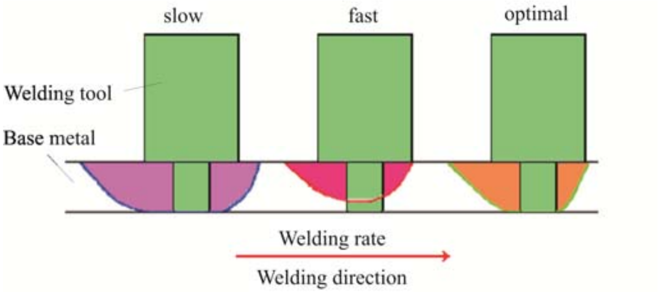


Figure 3. Material deposition vs welding rate [6]

Experimental investigations have shown that imperfections-less FSW products are developed if ratio of the rotation rate *Vrot* and the welding rate *Vwel* (also known as welding step *Vrot* /*Vwel*) has some specific values (Figure 4) [7]-[8].

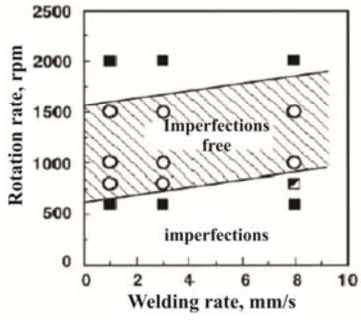


Figure 4. Influence of rotation and welding rate on imperfections existence in by FSW developed products [7]

Experimental research

Alloy Al 2024-T351, used in experimental researches [8], is alloyed with copper (Table 1) and is a member of, by conventional welding procedure, nonweldable (difficult to weld) materials.

TABLE 1. CHEMICAL COMPOSITION OF THE BASE METAL

Alloy	Elements involved, mass %							
	Cu	Mg	Mn	Fe	Si	Zn	Ti	Al
2024-T3	4,70	1,56	0,65	0,17	0,046	0,11	0,032	rest

However, copper in the alloy gives high strength (Table 2) and makes this alloy usable in industry in key structural elements (railways, aero, space, shipbuilding industry, automotive etc.).

TABLE 2. MECHANICAL PROPERTIES OF THE BASE METAL

Alloy	$R_{p0,2}$, MPa	R_m, MPa	A, %	Hardness, HV
2024-T3**	370	481	17.9	-

** Average experimental values according to the ASTM E-8M, after surface machining.

Welding samples (base metal plates) were cut from the forged sample, with machined edges, with dimensions of plates 325mm × 65 mm × ≠6 mm. Prepared welding plates were put on the backing plate, fixed on the work plate of the machine and prepared for the butt "I" weld (Figure 5).

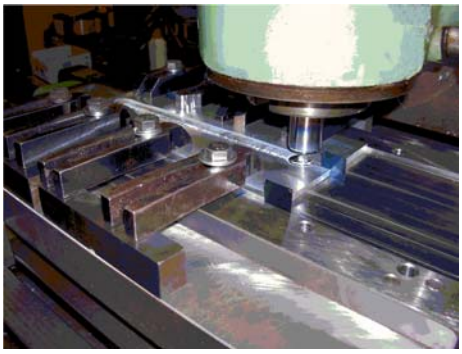


Figure 5. Experimental setup for the FSW

For the presentation, this paper gives results from experimental researches conduced with 2 different welding tools, marked as A10 and A11 (Figure 6, *a* and *b*).

a) *b*)

Figure 6. Welding tool a) exp. mark: A10, b) exp. mark: A11

Tools are with different geometrical properties and they were used for various technological parameters and all joints made with them were without imperfections. Welding tool

A11 has a shoulder of ∅25mm, cone probe of 5,5 mm height and concave probe tip. Probe is left threaded and the normal thread has small edge radiuses. Shoulder tip has a “material reservoir” with radiuses. Welding tool A11 has a shoulder of diameter ∅25mm, cone probe of 5.5 mm height and concave probe tip. Probe is left threaded with the oval thread. Shoulder tip has a “material reservoir” with radiuses [8].

Table 3 gives values of used welding steps (*Vrot /Vwel*) during experiments. Wide range of welding steps used in experiments gave opportunity to monitor influence of the welding tool’s geometry and technological parameters of the FSW on quality and properties of the weld, from the aspect of productivity increase.

TABLE 3. WELDING STEP VALUES (*VROT /VWEL*)

Tool	*Vrot /Vwel*			
A10	1180/116=10.17	1180/46=25.65		
A10	750/150=5.00	750/116=6.64	750/93=8.06	750/73=10.27
A11	750/150=5.00	750/150=5.00	750/150=5.0	750/150=5.00

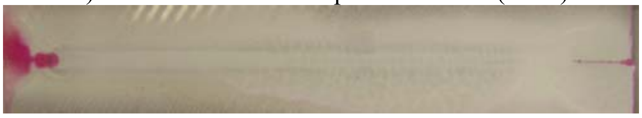
After welding, welded plates were examined by non destructive test (NDT – radiography and penetrate fluids) and after that by destructive – mechanical and structural testing (strength determination, hardness, bending properties, macrostructure etc.).

Results

NDT has been done to show the presence of voluminous imperfections throughout the weld whose non-existence would confirm the good selection of technological parameters. Figure 7 shows characteristic weld without imperfections, after NDT.

a) face of the weld

b) face of the weld with penetrate fluid (NDT)



c) root of the weld with penetrate fluid (NDT)

d) radiograph of the weld

Figure 7 An example weld without imperfections

Tensile properties of the weld and fracture position were determined on probes with parallel sides manufactured according to the ASTM E-8M. Probes were extracted from direction perpendicular to the weld and they were taken from base metal (BM), heat affected zone (HAZ) and thermo-mechanically affected zone (TMAZ) and all of them have a nugget (N) in length greater than 4 heights of the probe. Median values of measured results, obtained from probes as well as the efficiency of the weld are given in the Table 4.

TABLE 4. AVERAGE VALUES OF PROPERTIES OF FSW PROBES

probe	$Rp_{0,2}$, MPa	R_m, Mpa	A_5 ,%	efficiency	tool	*Vrot /Vwel*
1	323	398	6.0	82.7	A10	1180/116=10.17
2	316	319	7.1	81.3		1180/46=25.65
3	324	330	4.8	82.13	A10	750/150=5.00
4	318	395	7.5	82.2		750/73=10.27
5	/	210	2.2	43.8	A11	750/150=5.00
6	313	365	4.2	76.0		750/73=10.27

Metallographic tests consisted of macro-structural analysis of BM, HAZ, TMAZ and N done on the stereo microscope (Figure 8). Hardness distribution throughout the section of weld is obtained in root zone according to the Vickers HV3 method, according the standard SRPS C.T3.051. Figure 9 gives some hardness distributions for various experimental results.

a) experiment 1, tool A10, *Vrot /Vwel*=1180/116=10,17

b) experiment 3, tool A10, *Vrot /Vwel*=750/150=5,00

c) experiment 4, tool A10, *Vrot /Vwel*750/73=10,27

d) experiment 6, tool A11, *Vrot /Vwel*750/73=10,27

Figure 8 Macroscopic view of section view of FSW weld

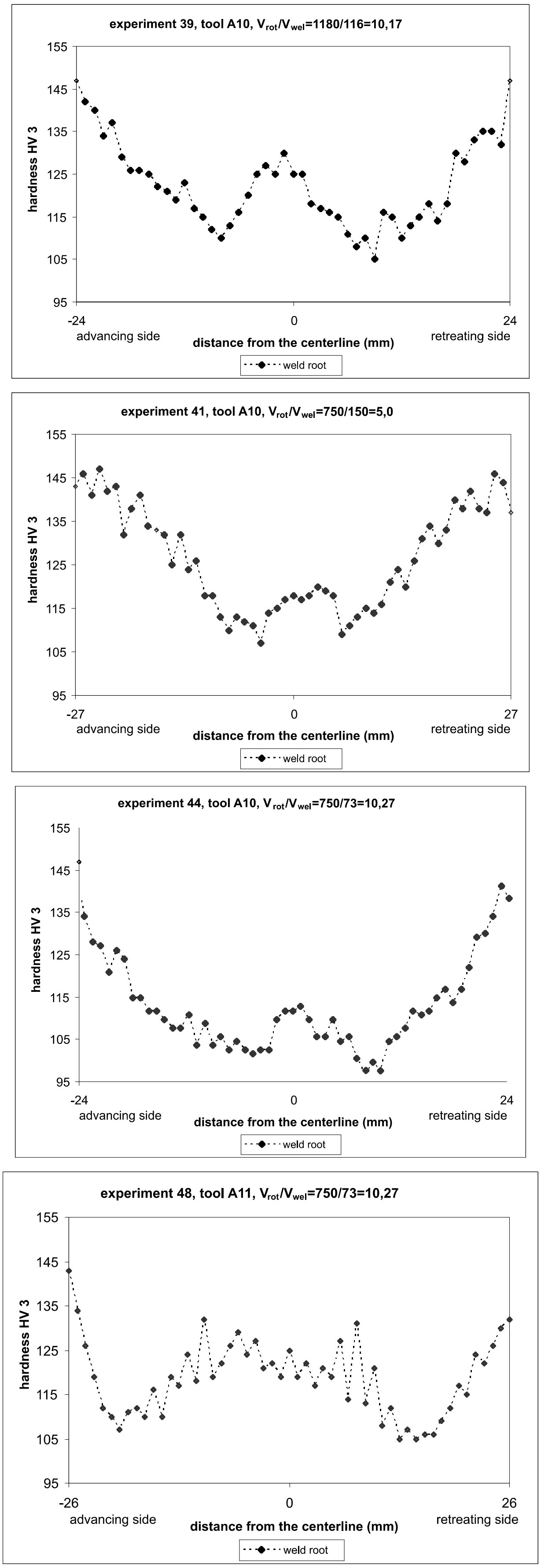


Figure 9 Hardness distributions for various experiments

Discussion

Influence of the welding tool's geometry on FSW productivity has been analyzed on welds achieved with approximately the same welding steps. Welding steps of 10.17, 10.27 and 5.00 applied with welding tool A10 gave efficiency of the welds of 82.7%, 82.2% and 82.1%, respectively. Welding tool A11 gave a bit weaker results: for the same technological parameters of the FSW, for welding steps 10.27 and 5.00) efficiency of the welding was 76.0% and 43.8%. This can be explained by influence of probe's geometry and smaller amount of generated heat, stirring, mixing and material flow during welding. Increase of the welding rate V_{rot} increases mechanical properties of the weld. Values of the yield strength of welds show that change of tools of geometry change the productivity of FSW and it reaches values over 80%. Hardness distribution has a "W" shape – characteristic shape for this Al alloy. The greatest hardness decrease appeared in HAZ while extreme values of hardness have been found in N zone. Increase of the hardness in N zone appeared after significant recrystallization of material being deformed.

Conclusions

Change of the tools geometry can give qualitative welds for large scale of welding steps from 25.65 to 5. It it possible to use greater welding rates if other parameters are adjusted to process. Rounded thread on the probe generates less heat during process and stirring/mixing process is weaker.Smaller rotation rate implies application of smaller welding rate.

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