DOI: http://dx.doi.org/10.15407/tpwj2018.06.06

HIGH SPEED FRICTION WELDING OF TITANIUM ALLOYS — STRUCTURE AND PROPERTIES OF JOINTS

D. MIARA[1], **J. MATUSIAK**[1], **A. PIETRAS**[1], **M. KRYSTIAN**[2] and **M. DYNER**[3]
[1]Institute of welding
44-100, Gliwice, Str. Bl. Czeslava 16-18, Poland. E-mail: adam.pietras@is.gliwice.pl
[2]Austrian Institute of Technology
Str. Giefinggasse 4, 1210, Vienna, Austria. E-mail: marciej.krystian@univil.ac.at
[3]Plant of Medical Instruments CHIRMED
Str. Mstowska 8A, 42-240 Rudniki, Czestochowy, Poland. E-mail: m.dyner@chirmed.pl

The article presents test results concerning the high speed friction welding (HSFW) of titanium alloys Ti64 ELI and CP-Ti. In addition, the article presents tests results related to the welding process and the formation of flash. The quality of welds was assessed on the basis of non-destructive tests (visual tests) and destructive tests (static tensile tests and bend tests). The tests resulted in the identification of the correlation between HSFW conditions when joining titanium alloys, i.e. Ti64 ELI, CP-Ti, and the quality of welds. Consequently, the tests led to the determination of the optimum range of welding parameters as regards the strength of joints. 8 Ref., 2 Tables, 6 Figures.

K e y w o r d s : *friction welding, titanium alloys, structure and properties*

Introduction. Conventional friction welding (FW) and high speed friction welding (HSFW) are solid-state joining processes and belong to few processes utilising friction heat emitted during the technological process [1–3].

Most metals (including titanium alloys) are joined using friction welding, where the kinetic energy of the relative motion of elements subjected to welding is transformed into friction heat. There are many various manners in which surfaces to be joined move in relation to each other, where the simplest and most commonly used in industrial practice is rotational motion.

During welding, elements heated by friction heat are pressed against each other by friction downward force, which leads to the movement of metal in the welding area outside the friction-plasticised contact to the so-called metal flash [3, 4]. After the appropriate heating and plasticisation of the material in the welding area the relative motion of elements stops. The joint is obtained after the complete stoppage of motion and the exertion of additional upsetting force so that the contact surfaces of elements could reach the distance of atomic force action. The welding process leads to the formation of a compact structure across the entire cross-section of elements being joined. During friction and upsetting the elements being welded become shorter [3, 4]. Conventional friction welding is usually performed at rotation rates restricted within the range of 500 rpm to 5 000 rpm [5].

High speed friction welding (HSFW) is a variety of conventional friction welding (FW), where the process of welding is preformed using rotation rates reaching approximately 25 000 rpm [6]. The use of the above-named high rotation rates significantly changes joining conditions in comparison with the conventional method of friction welding. The foregoing can be observed when analysing the correlation between the element shortening rate and the rate of friction as well as the change in the thickness of a layer subjected to plastic strain and the change in the friction rate. Because of significantly varying weld formation mechanisms during the HSFW process it is possible to considerably reduce the time of welding (to sever-

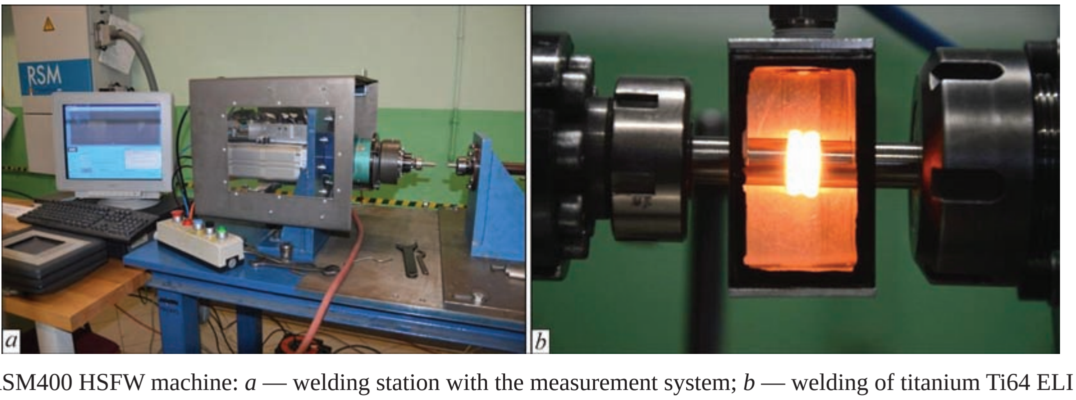

Figure 1. RSM400 HSFW machine: *a* — welding station with the measurement system; *b* — welding of titanium Ti64 ELI [1]

Table 1. Chemical composition of the titanium alloys used in the tests

No.	Alloy designation	Chemical element content, %							
		Al	V	O	Fe	C	N	H	Ti
1	Ti64 ELI (Ti6Al–4V)	5.930	3.960	0.103	0.180	0.023	0.002	–	Rest
2	CP-Ti	–	–	0.210	0.220	0.010	0.040	0.001	Rest

al seconds) and decrease diameters of elements being welded (to a mere 5 mm).

Both during the conventional and the high speed friction welding process attention is drawn primarily to the identification of the appropriate range of welding parameters, particularly to the correlation between the rotation rate of the spindle and the downward force. The foregoing is particularly important when adjusting optimum welding parameters in relation to individual materials as it affects the joint formation mechanism and joint properties.

Test stand. The welding process was performed using an RSM400 HSFW station (Figure 1, *a*) and bars having a diameter of 10 mm and made of titanium alloys Ti64 ELI and CP-Ti. The chemical composition and selected physical properties of materials in the as-delivered state used in the tests are presented in Tables 1 and 2. The materials were welded in the similar material joining configuration. The welding station was provided with an additional housing preventing the access of oxygen to the argon-shielded process. The welding process and the housing with the shielding gas are presented in Figure 1, *b*.

The tests of the HSFW of titanium alloys Ti64 ELI and CP-Ti were performed using the following welding parameters:

• during the welding of titanium alloy Ti64 ELI: rotation rate v_n=20000 rpm, friction time t_t = 0.5 s, friction downward force f_t = 3 bar, upsetting time t_s = = 3 s and upsetting force f_s = 6 bar;

• during the welding of titanium alloy CP-Ti: rotation rate v_n = 20000 rpm, friction time t_t = 0.5 s, friction downward force f_t = 1 bar, upsetting time t_s = = 3 s and upsetting force f_s = 3 bar.

Visual tests. Selected welds of titanium alloys Ti64 ELI and CP-Ti made using the HSFW process are presented in Figure 2. The obtained friction welds were characterised by the specific shape of flash, the size of which varied in relation to the material subjected to welding. The flash formed during the welding of titanium alloy CP-Ti was significantly larger than that formed during the welding of titanium alloy Ti64 ELI.

Macroscopic metallographic tests. All of the test welds were subjected to macroscopic metallographic tests. The test specimens were cut out mechanically and subjected to grinding and polishing until the obtainment of appropriate smoothness. The metallographic tests were performed in accordance with the requirements of the PN-EN ISO 17639:2013-12 standard [7]. The structure of related metallographic specimens was revealed using the Keller's reagent. Macrostructures of

Table 2. Selected properties of the titanium alloys used in the tests

No.	Alloy designation	Minimum properties		
		$R_{p0.2}$, MPa	R_m, MPa	$A_{50\ mm}$, %
1	Ti64 ELI (Ti6Al–4V)	795	860	10
2	CP-Ti	610	520	22

selected welds made of titanium alloys Ti64 ELI and CP-Ti using the HSFW process are presented in Figure 9, *a*, *b* respectively. The macroscopic metallographic test results revealed that the structure of the welds was proper and characteristic of the friction welding method. The size and shape of flashes depended on a material subjected to welding and applied welding process parameters. The materials subjected to welding revealed various HAZ areas and the distribution of individual zones in the welding area.

Tensile tests. The mechanical properties of the welds made using the HSFW process were identified in a static tensile test performed in accordance with the requirements of PN-EN ISO 4136:2013-05E [8]. The joints were subjected to uniaxial tension performed using an INSTORN 4210 testing machine. The tests were performed at ambient temperature and a strain rate of 5 mm/min. The test results concerning the strength of the friction welds made of titanium alloys Ti64 ELI and CP-Ti using the HSFW process are presented in Figure 4. The test results are presented in relation to the base material of alloy Ti64 ELI and that of CP-Ti. As regards titanium alloy Ti64 ELI, the mean strength of the base material amounted to 906.7 MPa, whereas the mean strength of the friction welds amounted to 916.8 MPa, i.e. was on average by 1.1 % higher than that of the base material. The materials in the welding area were hardened during the welding process. As regards titanium alloy CP-Ti, the mean hardness of the base material amounted to 662.2 MPa, whereas the mean value of friction welds (HSFW) amounted to 660.6 MPa, i.e. was by a mere 0.3 % lower than that of the base material. The

Figure 2. Welds in titanium alloys Ti64 ELI (*a*) and CP-Ti (*b*) made using the HSFW process [1]

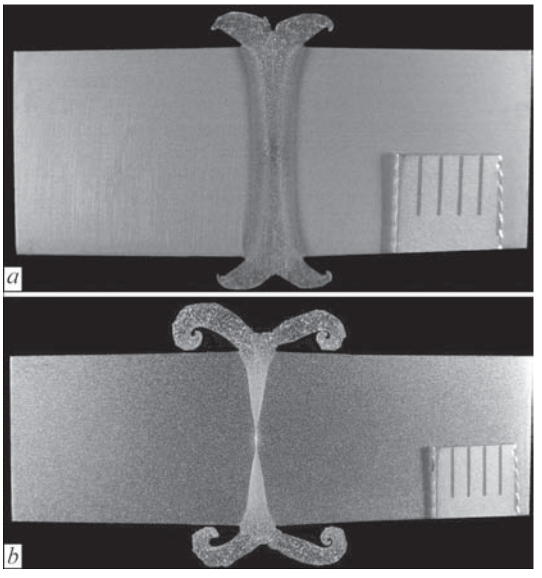

Figure 3. Macrostructures of the welds in titanium alloys Ti64 ELI (*a*) and CP-Ti (*b*) made using the HSFW process [1]

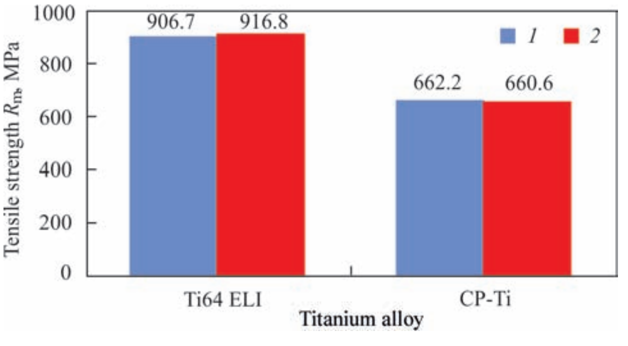

Figure 4. Tensile strength of titanium alloy Ti64 ELI and CP-Ti [1]: *1* — parent material; *2* — welded material

above-presented high mean tensile strength values revealed that the welds made using the HSFW process were characterised by high and repeatable quality. The weld after being subjected to the tensile test is presented in Figure 5.

Bend tests. Selected friction welds were also subjected to bend tests. The bend tests of all three test specimens made of titanium alloy Ti64 ELI proved successful, i.e. the specimens reached an assumed bend angle of 180°. In terms of the specimens made of titanium alloy CP-Ti, the assumed angle amounting to 180° was reached by two out of three specimens. One specimen made of CP-Ti reached a bend angle of 50° and developed a brittle crack in the base material, indicating the high quality of the welded joint. An example of the weld after the bend test is presented in Figure 6.

Conclusions

• The above-presented tests and analyses of test results justified the formulation of the following conclusions:

Figure 5. Test specimen made of titanium alloy Ti64 after the tensile test [1]

Figure 6. Test specimen made of titanium alloy Ti64 after the bend test [1]

• Titanium alloys Ti64 ELI and CP-Ti can be welded using the high speed friction welding (HSFW) method. Appropriately adjusted welding conditions enable the obtainment of high-quality joints characterised by required mechanical properties.

• Appropriately adjusted welding process parameters ensure process stability and joint repeatability.

• The internal structure of both materials subjected to welding (titanium alloy Ti64 ELI and CP-Ti) was continuous and did not reveal the presence of «no-joint» traces or the lack of joint integrity (tightness).

• The friction welding process performed using a special welding programme makes it possible to properly heat fragments of internal surfaces of titanium bars and, after exerting appropriate force, to obtain a joint characterised by required tensile and bend strength.

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Received 11.04.2018