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Friction Stir Welding of Copper Plates

Abstract: The objective of the work was to develop a technology for the friction stir welding (FSW) of copper elements of thicknesses exceeding 15 mm and possible to use in the production of current conductor rails. The length of the conductor rail element joining line amounts to approximately 100 mm. The first stage involved FSP tests, i.e. tests of copper plasticisation, using the FSW method and creating the compact weld structure on plates having thicknesses between 8 and 20 mm. The next stage consisted in friction stir welding of copper elements. The investigation involved testing copper plasticisation conditions while using the FSW process, the development of a welding tool as well as the development of conditions for proper welding of sheets/plates having thicknesses of up to 20 mm. It was observed that properly formed welds require the use of a relatively low tool rotation rate and good cooling of element-fixing tooling.

Keywords: Friction Stir Welding, Friction Stir Processing, copper elements, copper plasticisation

Test Rigs and Tools

The tests of the FSW and FSP processes were performed on test rigs built at Instytut Spawalnictwa on the basis of FYF32JU2 and FY40 conventional vertical milling machines. The test rigs were equipped with special clamps for fixing plates to be welded, a Lowstir device for testing forces and force moments and a welding area temperature measurement system featuring a set of thermocouples and a thermographic camera.

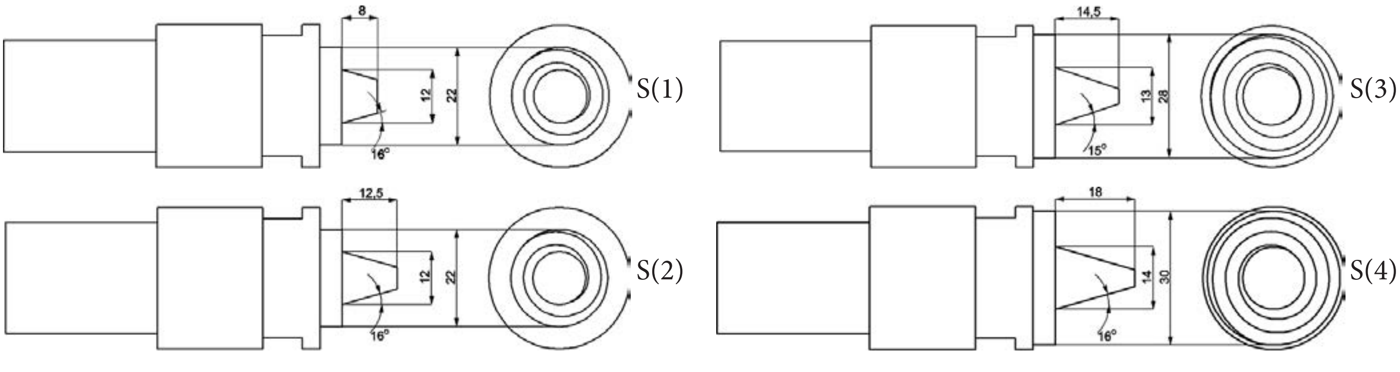

Fig. 1. Tools and dimensions of working parts of the tools used in the tests

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The welding process was conducted using tools made of HS 6-5-2 high-speed steel; the probe was made of a tungsten alloy. Figure 1 presents the shape of tools used in the work, related to testing copper plasticisation while making a linear FSW weld. On the conical probe surface a thread was incised, whereas a spiral was incised on the work surface of the shoulder. Figure 2 presents the working part of the tool used in the tests.

The FSW-based copper plasticisation tests involved the use of 8 mm, 13 mm, 15 mm and 20 mm M1 copper test plates. The plates were prepared in the form of flat bars (100 mm x 250 mm). The flat bars were fixed by means of standard clamps.

Fig. 2. Tool working part used in the FSW and FSP tests

Copper Plasticisation Tests (FSP – Friction Stir Processing)

The programme included a number of tests performed using tools of various probe shapes and lengths, with a tool inclination angle of 1.5° and without tool inclination. According to the research experience of Instytut Spawalnictwa,

Table 1. Welding process test conditions. Welding rate V_{zg} = 71 mm/min

Test no.	Tools shape and dimensions	Rotation rate V_n [rev/min]	Tool inclination angle	Results (remarks)
1	2	3	4	5
1	Conical S(1)	355	1.5°	Proper process. Proper weld face formation
2			-	Proper process. Proper weld face formation
3		450	1.5°	Proper process. Proper weld face formation
4			-	Proper process. Proper weld face formation
5		560	1.5°	Proper process. Proper weld face formation
6			-	Proper process. Proper weld face formation
7	Conical S(2)	355	1.5°	Proper process. Proper weld face formation
8				Proper process. Proper weld face formation
9		450	1.5°	Proper process. Proper weld face formation
10				Proper process. Proper weld face formation
11		560	1.5°	Proper process. Proper weld face formation
12				Proper process. A slight imperfection visible under the weld face, at the end
13	Conical S(3)	355	1.5°	Proper process. Proper weld face formation
14				Slight surface imperfection and an imperfection at the end of the weld
15		450	1.5°	Proper process. Proper weld face formation
16				Proper process. Proper weld face formation
17		560	1.5°	Imperfection at the end of the weld
18				Worm-hole discontinuity
19	Conical S(3)	560	1.5°	At the end of the process the lack of proper face formation and a worm-hole discontinuity
20			-	Imperfection on the face surface
21	Conical S(4)	355	-	Imperfections on the weld face surface, worm-hole discontinuities under the face surface

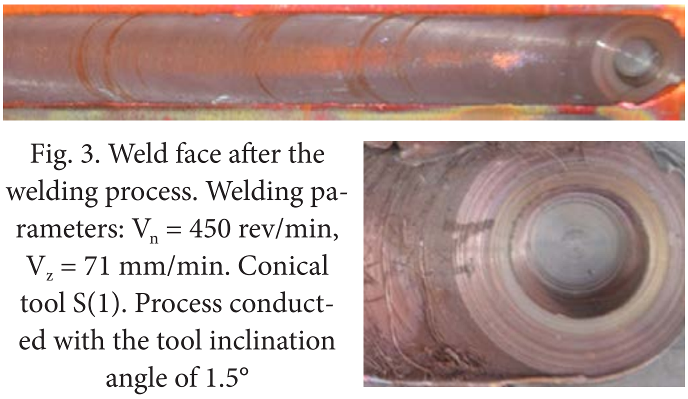

Fig. 3. Weld face after the welding process. Welding parameters: V_n = 450 rev/min, V_z = 71 mm/min. Conical tool S(1). Process conducted with the tool inclination angle of 1.5°

welding processes conducted with a tool inclination enable process performance within a wider welding parameter range than that without tool inclination. However, some milling machines potentially usable in the welding device design do not offer the possibility of spindle inclination. Table 1 presents the range of tests. Figures 3, 4 and 5 present the exemplary results of FSW copper plasticisation process.

Fig. 5. Weld face view at the weld end area after the welding process. Welding parameters: V_n = 355 rev/min, V_z = 71 mm/min. Conical tool S(3). Process conducted without the tool inclination angle

The tests revealed that the friction weld formation process is greatly affected by the welding process temperature. During the process, the tool and the whole welding area heated up to such a high temperature (above 900°C) that after approximately 80 mm - 100 mm the formation of an imperfection-free weld was impossible. On the weld face or at a certain depth from the advancing side, it was possible to observe the formation of worm-hole type discontinuities, the dimensions of which increased along with the growing system temperature. This process was particularly visible while welding elements of thicknesses exceeding 10 mm.

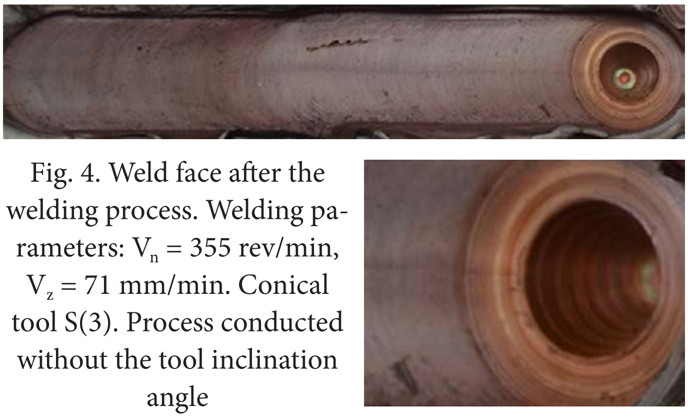

Fig. 4. Weld face after the welding process. Welding parameters: V_n = 355 rev/min, V_z = 71 mm/min. Conical tool S(3). Process conducted without the tool inclination angle

Further FSW weld formation process tests required the development of a special device fixing the elements to be welded. The cooling ducts led in the shoulder material as well as the resistance of the front and the side enabled cooling the whole system, i.e. the tool and the material being welded, which was particularly important at the end of the welding process. The device is presented in Figure 6.

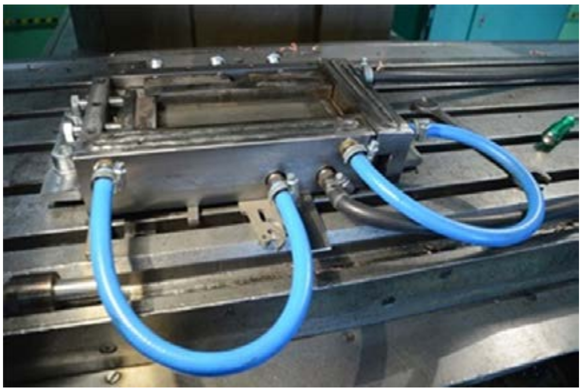

Fig. 6. Welding device provided with the welding area cooling system installed on the FY 40 milling machine

During the tests performed using this device the welding process was accompanied by intensive cooling with water of ambient temperature and water cooled to a temperature of 7°C. The device enabled conducting welding tests with specimens having thicknesses of up to 20 mm.

The rig provided with the cooled tooling was used to conduct FSP tests on plates having thicknesses of 10 mm, 15 mm and 20 mm. In the case of the thicker elements it was possible to observe the problem of heat accumulation in the welding area; the presence of excessive temperature resulted in the tendency of longitudinal worm-hole discontinuity formation. The weld structure underwent macroscopic tests leading to the conclusion that properly conducted FSW enables the obtainment of a weld characterised by a compact structure and the lack of imperfections and discontinuities (Fig. 7). The hardness measurements revealed the lack of significant hardness fluctuations in the tool affected area. A significant decrease in the HAZ area hardness, common in copper welding processes, was neither observed. The hardness measurement results along with marked measurement points are presented in Figure 8. In order to examine the welding area temperature field it was necessary to conduct temperature measurements using the thermographic camera following and preceding the tool moving. The welds made were up to 200 mm in length. During the process the continuous growth of the welding area temperature was recorded.

Fig. 7. Structure of FSW plasticised material (copper). Tool S(5). Welding parameters: V_n = 450 rev/min, V_z = 71 mm/min

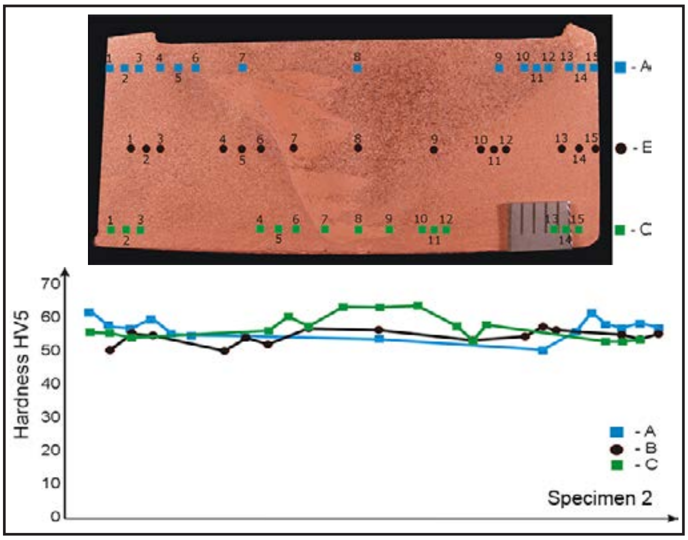

Fig. 8. Measurement line marked on the weld cross-section and hardness measurements. Tool S(5). Welding parameters: V_n = 355 rev/min, V_{zg} = 71 mm/min

In order to properly determine the temperature in the welding area using thermovision, the first test stage included temperature measurements carried out using thermocouples welded at 8 points on the plate and the thermographic camera. Afterwards, by comparing the measurement results it was possible to determine the most advantageous emissivity coefficient for copper heated during the FSW process. Figure 9 presents the exemplary courses of recorded

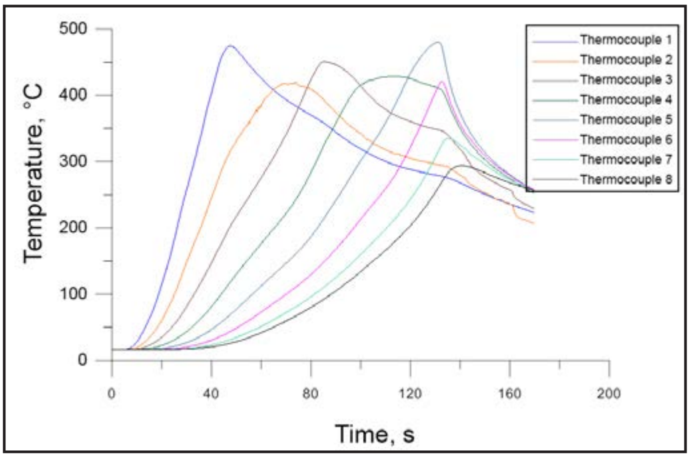

Fig. 9. Temperature course recorded using thermocouples welded along the friction heating line

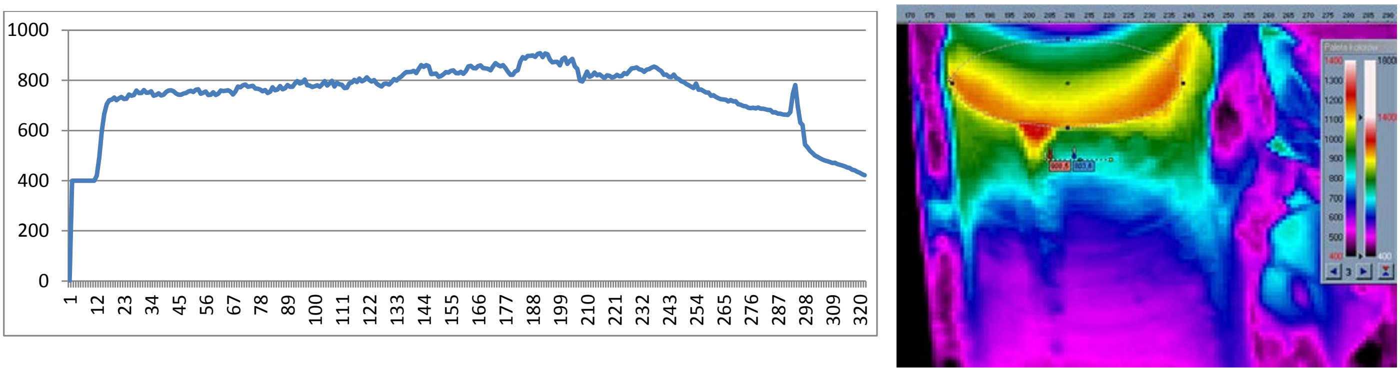

Fig. 10. Temperature in the welding area determined using the thermographic camera computer programme (left) and the image obtained from the camera with the shoulder shape marked (right). Welding parameters: V_n = 560 rev/min, V_{zg} = 71 mm/min

temperature measured by means of the thermocouples. Figure 10 presents the image obtained using the thermographic camera.

The test and calculation-based emissivity coefficient for FSW-based heating of copper amounted to 0.35. The coefficient of such a value, entered into the VIGOcam v50 camera computer programme, enabled the maximum determination of the whole welding area temperature. Figure 11 presents selected correlations between the welding area temperature and the FSP conditions.

The Lowstir device was used for measuring forces and force moments during FSP. Figure 12 presents selected correlations between the force in the direction of welding Fx and the force moment Mt on the tool rotation rate.

FSW Process Tests

The FSP-related tests enabled the selection of the tool shape and dimensions, the preparation of test tooling ensuring proper fixing and pressing of elements being welded as well as cooling of the welding area. In accordance with the assumptions, the tooling design should allow the temperature stabilisation at a sufficiently low level making it possible to perform the FSW process along the whole interface length.

Figure 13a presents the tooling intended for fixing the conductor rail elements. Figure 13b presents the tooling with elements to be welded fixed. In accordance with the previous test result the tooling was water-cooled. The tooling contained an exchangeable pressure plate for fixing elements of various shapes.

The tooling presented above was used in the welding tests. Figures 14, 15 and 16 present selected test results. Properly friction stir welded copper butt joints and T-joints were characterised by appropriate mechanical properties, whereas the welds were characterised by a compact structure. Figure 14 presents a properly

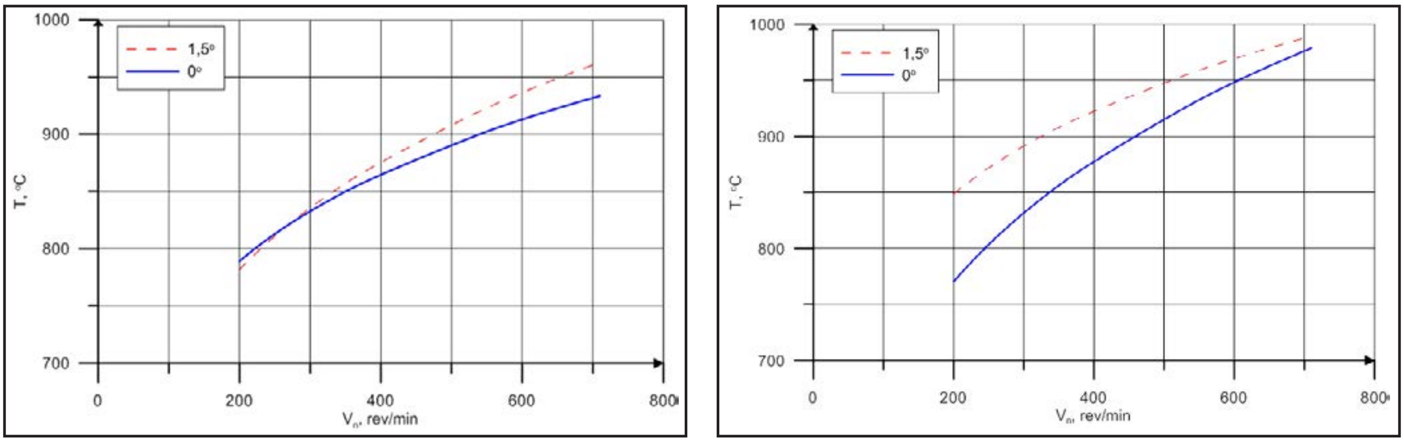

Fig. 11. Effect of the tool rotation rate in the welding area temperature for tools: a) S(4) b) S(3)

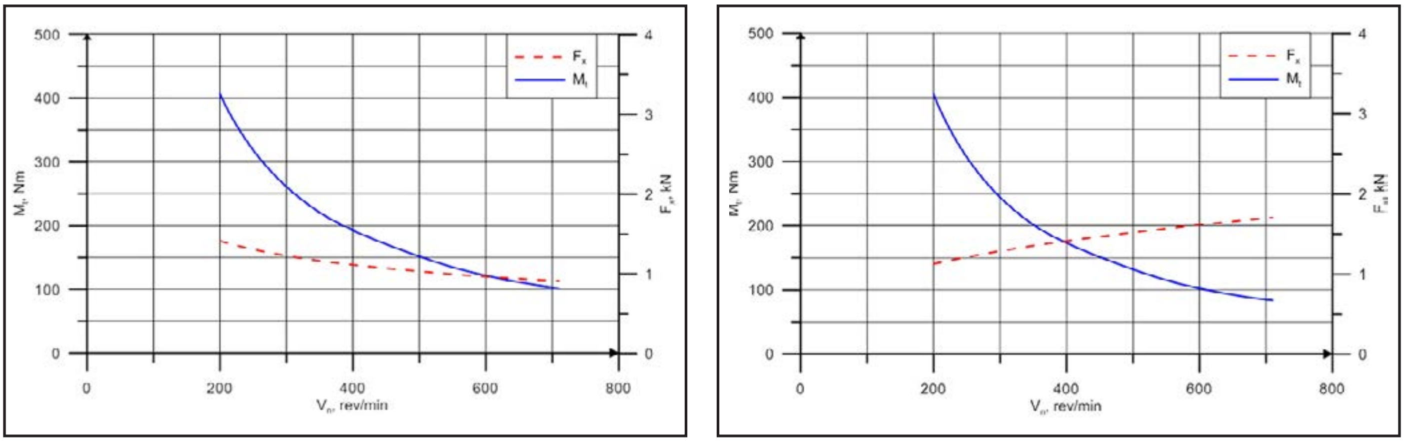

Fig. 12. Effect of the tool rotation rate on the friction moment Mt and force in the direction of welding Fx during the process performed with the tool inclination of 1.5° (a) and without tool inclination (b)

made T-shaped conductor rail with a FSW joint. Figures 16 and 17 present the macrostructure of the properly made joint. The joint quality was proper along the whole length of the joint.

The test results revealed that the weld thermomechanical plasticisation zone was characterised by lower hardness than that of the materials welded. Irrespective of the joint configuration (butt joint or T-joint) the stir zone hardness amounted to approximately 50 HV5. The stir zone revealed slight hardness fluctuations which could be ascribed to the presence of various degree upset bands (detected during microstructural examination). Both on the advancing and retreating sides, the hardness in the thermoplastic zone and in the HAZ increased to that characterising the parent metal.

The hardness decrease in the thermomechanical strain zone was connected with copper material heating and softening process during the friction and deformation of the welding area with the cutting tool. This hardness decrease was unavoidable in the welding process, yet it did not significantly affect the hardness of the whole joint.

The selected joints underwent weld microstructure examination. The area of transition between the parent metal and the thermomechanical deformation zone during the welding process is presented in Figures 18 and 19. In spite of the structural threshold it is possible to notice metallic continuity. In the root area, depending on the probe length, the probe may not affect the whole plate thickness. If the probe is overly short the root may contain an area without a metallic joint. For this reason, for each plate thickness it is necessary to select a probe of appropriate length.

Fig. 13. Tooling for fixing the conductor rails: a) view without welding elements, b) view with welding rails. On the left: the exchangeable pressure plate

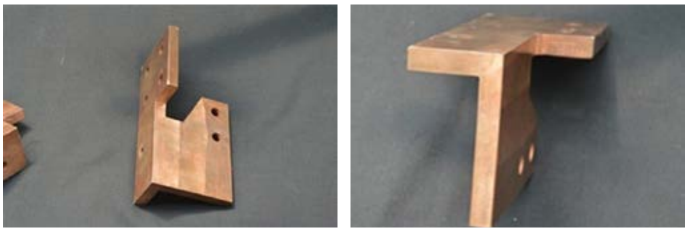

Fig. 14. Exemplary technology-based conductor rail made using the FSW method

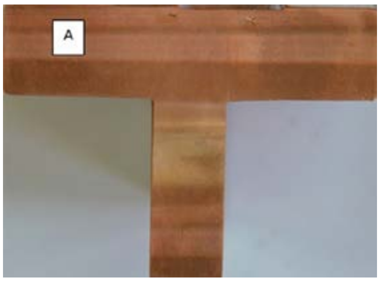

Fig. 15. Cross-section of the exemplary conductor rail

Fig. 16. Macrostructure of the joint made of copper plates using the technology developed. V_n = 560 rev/min; V_z = 71 mm/min

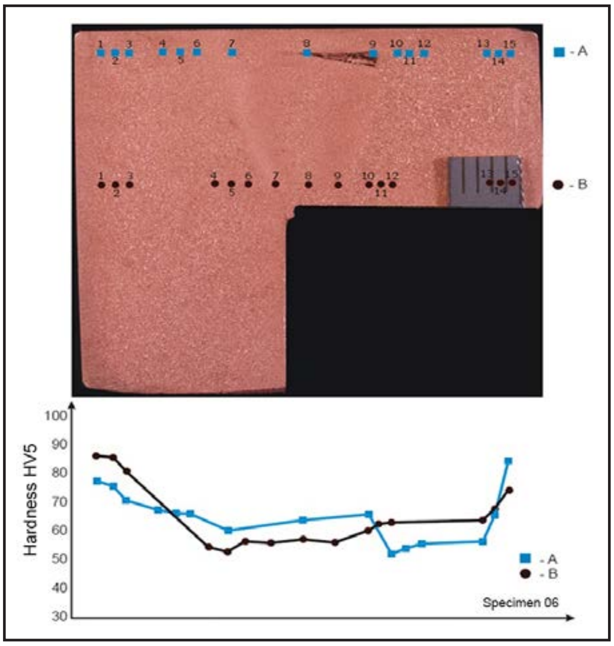

Fig. 17. Weld structure and hardness measurements on the FSW joint cross-sections. Welding parameters: V_n = 560 rev/min; V_z = 71 mm/min; welding without cooling

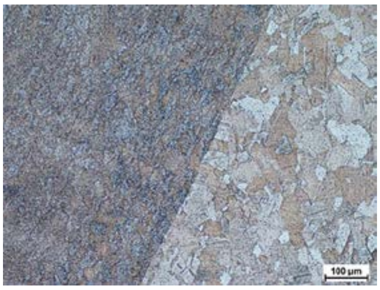

Fig. 18. Advancing zone area: boundary between the thermomechanically deformed layers and the heat affected zone; etching with $FeCl_3$

Fig. 19. Recrystallised structure of the central FSW weld area from the retreat side; etching with $FeCl_3$

Summary

The first stage involved testing the influence of process parameters for welding with five different conical tools on the weld face formation process during FSW and on the metallic continuity in the subsurface areas at the tool probe effect depth. The tests revealed that copper plates of thicknesses up to approximately 10 mm can be successfully plasticised and welded with a conical tool both with tool inclination (tilt angle amounting to 1.50 , as in the case of welding aluminium) and without tool inclination. In order to obtain a longitudinal weld of high and repeatable quality, it is necessary to properly select the probe length and shoulder dimensions in relation to the tool probe diameter as well as tool motion parameters (rotation rate below 560 rev/min, welding rate below 100 mm/min) (see Table 1).

For greater element thicknesses the process becomes more complex with increasingly many factors affecting its quality repeatability. Plates having thicknesses of 12 – 15 mm are poorly weldable during welding without tool probe inclination. The weld face contains surface linear discontinuities disqualifying the joint due to easily visible imperfections or subsurface worm-hole type discontinuities even more dangerous as invisible from the tool effect side (e.g. Fig. 5). Such imperfections are formed at a certain depth on the advancing side. The place of their presence depends on process parameters, tool shape and welding area temperature.

For thicker elements it is possible to observe intensive heating of the whole tool-material system and the accumulation of heat in the welding area increasing the welding process-accompanying temperature to the level preventing proper upset and forming of the weld behind the tool. Excessively heated and, as a result, excessively plasticised copper material makes it impossible to achieve appropriate upset level by the shoulder. It was ascertained during the tests that relatively high welding area temperature and high process-related forces lead to the deformation of the elements and squeezing of some material from the root side, impeding proper material upset behind the tool. The necessary material rigidity for achieving appropriate upset can be obtained by heating a strictly specified amount of material around the tool while maintaining a relatively low temperature of the whole area.

Such conditions can be created by conducting the FSW process at a very low rotation rate with the intensively cooled tooling. It was observed that cooling the element-fixing tooling with water having a temperature of 7°C ensured the proper and repeatable processing of elements having thicknesses up to approximately 20 mm. The use of ambient temperature cooling water proved inefficient.

Welding at a low tool rotation rate is connected with relatively high resistance and torque (Fig. 12). The previously conducted tests demonstrated that the test rigs at Instytut Spawalnictwa allow achieving proper conditions for welding copper elements with a tool having a maximum probe length of 18 mm and a shoulder diameter of 22 mm (tool S(4)). The tool probe penetration depth amounts to approximately 18.5 mm, which means that the process can be used for joining copper elements having a maximum thickness of 19 mm. Greater cross-sections can be welded using the FSW method, yet Instytut Spawalnictwa is not in possession of a sufficiently powerful and rigid welding machine.

Concluding remarks

- With a properly selected tool and its motion parameters, copper plates having thicknesses of up to do 10 mm can be welded both with the tool inclined and without the tool inclination.
- Intensive material heating during welding plates having thicknesses of 12÷20 mm reduces the proper formation of welds behind the tool. Worm-hole discontinuities may be formed on the advancing side; in some places such discontinuities may reach the weld surface. These imperfections can occur particularly if welding is conducted without tool inclination.
- High welding area temperature and significant forces related to the tool movement cause material deformations also on the root side. Such deformations push the metal towards the shoulder and detrimentally affect the proper weld formation.
- The obtainment of properly formed welds along the whole length of copper plates requires the welding area temperature to be maintained on a relatively low level (below 850°C). The tooling cooled with liquid of a temperature below 7°C ensures the stabilisation of conditions along the whole welding length.
- The use of a properly-sized tool, low tool rotation rate and proper tooling conditions make it possible to obtain friction stir welds of good repeatable quality and proper structure along the whole joining line.

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