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Investigation of the Material Welding Using the High-Speed Liquid Impact

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Feasibility to use the high-speed liquid impact for joining similar and dissimilar metals was investigated experimentally. An experimental setup that entails a launcher for projectiles formation and samples folders was constructed. The experiments involved joining of sandwiches containing two or three layers of metals were impacted by a high-speed projectile. The metals combinations included copper, brass, steel, and nickel alloys. The generated samples were examined visually, the strength of the joint was explored, and the integrity of the weld was estimated using ultrasound. In most of the experiments metallurgical bonding of joined metals was confirmed. The results of the ultrasound test demonstrated high quality of the generated joints. The performed experiments showed feasibility of the liquid impact-based welding. This process is the improvement of the explosion welding. Unlike the explosion welding impact-based process does not require special placing of work pieces while the stresses in the impact zone can be precisely directed and controlled.

Keywords joining, liquid impact, liquid projectile, solid state, welding

1. Introduction

Main objective of this study was to investigate the welding of metals using high-speed water projectiles. Several modifications of the water jets have been adopted by the industry. Continuous water jets found wide applications in cleaning, cutting, transportation, etc. The use of the water projectiles instead of the continuous water jets improves the energy utilization in the course of the jet-target interaction and, thus, enhances productivity of the existing processes and makes possible some new jets applications. For example, these jets are successfully used for rock fragmentation (Ref 1) and mining (Ref 2). Energy utilization can be improved still further if the pulsed jet is replaced by the impulsive one which is also termed as the liquid projectiles. Explosive forming, welding, and cladding since early 1960s became widely available technologies for rapid manufacturing of metals (Ref 3-13). In this study such processes as liquid projectile-based solid-state welding and cladding were explored. Similar technology of explosive welding requires special conditions. Metals plates used in this study included high-ductility steel, brass, copper, and nickel-based alloy. As a result, ten similar and dissimilar combinations of metals were successfully welded by impact of water projectiles. The performed experimental study showed that high-speed liquid projectiles can be used to assemble heterogeneous metal structures. Experimental data acquired in the course of the performed experiments was incorporated into the knowledge base of the metal welding by high-speed water projectiles. As a result of the performed experiments feasibility of the use of high-speed water projectiles for water projectile impact-based welding was demonstrated.

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2. Experimental Procedure

Water projectiles impacting a target at a high velocity act similarly to an explosive charge activated on an impact surface. The impact generates a sequence of compression and rarefaction waves in the target. Propagation of these waves through a target consisting of two or more metal plates cause melting of very thin layers at the interface of plates to be joined. This resulted in the formation of the metallurgical bond along joining interface. In this work an investigation of the metal welding by the water impact was performed with the objective to explore experimentally joining of two or more similar (same) and dissimilar (different) metals by the water projectile impact.

An experimental setup for the study of the water projectile impact-based joining was designed and constructed (Fig. 1). The setup contained a laboratory scale prototype of a launcher (Ref 2, 14). The launcher operated in an extruder and water cannon modes (Ref 2, 14). Diameter of the cannon's nozzle used in all experiments was 15 mm. The targets were mounted on a heavy pendulum (Fig. 1). An angular displacement of the pendulum was measured in each experiment. This enabled us to estimate the impact impulse and therefore the impact momentum. For each experiment the water cannon was placed at a desired distance from the samples and water projectile impact operation was conducted. Each experiment was performed by a single impact of water projectile.

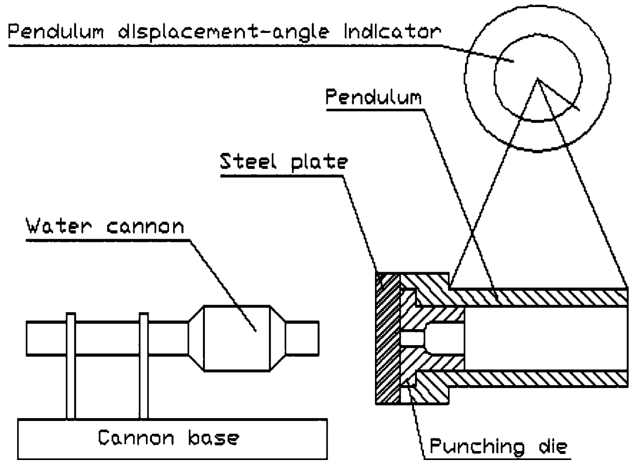

Fig. 1 Schematic of the experimental setup. Notice that mounting of the target on a ballistic pendulum allows measuring the impact momentum

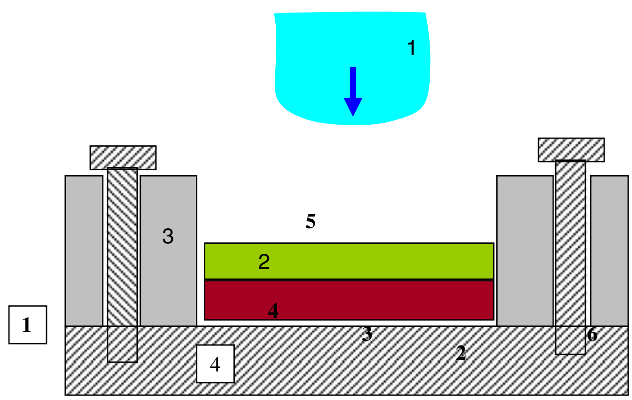

Fig. 2 Schematic of impact zone for a nested experimental setup: 1—water projectile, 2—nested metal samples to be welded, 3—fasteners, and 4—back support

In this part of investigation joining of similar metals (copper-copper, brass-brass, and steel-steel) and combinations of dissimilar metals (copper-steel, copper-brass, and brass-steel) were tested. Circular and square metal samples were used. The metals tested included copper, brass, a nickel alloy, and high-ductility steel which have elongation of 46%, tensile strength of 325 MPa, and yield strength of 195 MPa. Thickness of the copper samples used in this study was 1 mm while the brass samples have thickness of 1 mm and 1.5 mm; the thickness of the steel samples was 2.75 mm.

The experiments were performed with and without a distance between plates to be welded. The no distance joining (Fig. 2) involves a single impact of a sandwich-type structure by an incoming projectile. Process in this case is determined by the waves generated in the adjacent plates by the liquid impact (a single impact process). In the performed study of the welding of the adjacent plates, a nickel-based alloy (a coin) was placed between two other metal plates with no distance between the components.

If, however, there is a distance between the plates to be welded, the liquid impact results in an acceleration of the impacted plate which, in turn impacts the rest of the sandwich (double impact). Process in this case is determined by the waves generated in the impacting and impacted metal bodies.

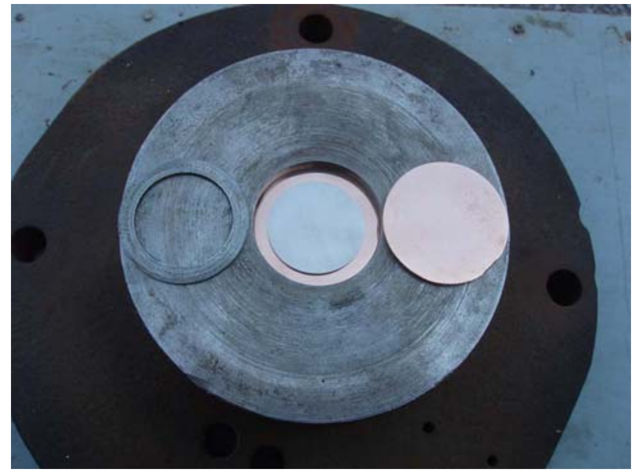

Fig. 3 Front view of nested experimental setup prior to assembly for welding. 1—back support, 2—rear copper plate to be welded, 3—middle layer to be welded (nickel alloy coin), 4—separation ring, 5—fastener, 6—impact side copper plate to be welded

In this case two impacts are contributing to the welding process. Welding with acceleration of a part of a target was carried out by separating metal samples to be welded by steel separation rings (1 mm and 2 mm thick).

The tests were also carried out with no radial constrains to the reflected jet and with fasteners preventing the radial water outflow (Figs. 2 and 3). Experimental conditions were selected as following: 350 g of water propelled by 25 g of gun powder at a stand of distance of 16 cm for the copper-nickel coin-copper combination, and 350 g of water propelled by 35 g of gun powder at a stand of distance of 16 cm for the brass-nickel coin-brass and steel-nickel coin-steel combination. The acquired experimental data collected in the performed experiments was used for the study of the process feasibility.

3. Experimental Results

The results of all performed experiments, successful and failed, are depicted in Tables 1 and 2. The presented experiments were carried out at different setup design and different operational conditions. Consistency of operation was confirmed by sufficient repetition of experiments. Initially the experiments were carried out using super high-speed shooting mode (1500 m/s) where 240 g of water was driven by combustion of 30 g of a gun powder (Experiments 1–4, Table 1.). After an initial investigation of samples including visual observation and forceful mechanical separation of several welded samples, it was estimated that a lower projectile speed (750–850 m/s) delivered stronger joint. However, a single impact resulted in adequate joining, e.g., formation of a sandwich with a nickel alloy in the middle; better results were attained at a double impact (Table 1).

It was also found that an extruder mode (launcher barrel completely filled with liquid) of the launcher operation brings about better results. Samples were less deformed and well joined.

Several material examination techniques were used to characterize the developed seams. Figure 4 shows micrograph of the interface between copper and nickel-based alloy plates

Table 1 Experimental results of welding by water projectile impact

Exp.#	*M*, g	*m*, g	*H*, cm	*I*, kg·m/s	*V*, m/s	R	Comments
1	30	240	16	251	1500	G	Cu-Ni-Cu, wavy interface
2	30	240	16	264	1500	G	Cu-Cu, wavy interface
3	25	350	16	394	750	G	Cu-Ni-Cu, wavy interface
4	25	350	14	356	750	G	Cu-Ni-Cu, wavy interface
12	25	350	16	314		E	Cu-Ni-Cu, no shield with 1 mm thick ring in the front
13	35	350	16	369		V	Br-Ni-Br, no shield with 1 mm thick ring in the front, warped
14	35	350	16	327		P	St-Ni-St, no shield with 1 mm thick ring in the front, supporting Al plate is wrapped
15	25	350	16	237		N	Cu-Cu, no shield with 3×1 mm thick rings in the front
16	35	350	16	369		P	Br-Br, no shield with no separation and with 1 mm thick ring in the front
28	30	350	16	169		G	Cu-Cu, 1 mm thick ring between and in the front
29	30	350		378		P	Br-Br, no shield with 1 mm thick ring between and in the front
40	30	350	16	466		E	Br-Br, 1 mm separation ring
41	30	350	16	217		E	Br-Br, 2 mm separation ring
42	30	350	16	442		E	St-St, 1 mm separation ring
43	30	350	16	430		E	Cu-St, 1 mm separation ring
44	30	350	16	N/A		E	Cu-Br, 1 mm separation ring placed between them
45	30	350	16	N/A		E	Br-St, 2 mm separation ring placed between them

Note: M: gun powder mass; *m*: water projectile mass; *H*: standoff distance; *I:* impulse; *V:* impact velocity; R: result; E: excellent weld; G: good weld; P: partial weld; N: no weld

Table 2 Combinations of welded metals

Similar/No acceleration	Similar/With acceleration	Dissimilar/With acceleration	Dissimilar-multilayer/No acceleration
Copper-Copper	Copper-Copper	Copper-Brass	Copper-Nickel alloy-Copper
Brass-Brass	Brass-Brass	Brass-Steel	Brass-Nickel alloy-Brass
Steel-Steel	Steel-Steel	Steel-Copper	Steel-Nickel alloy-Steel

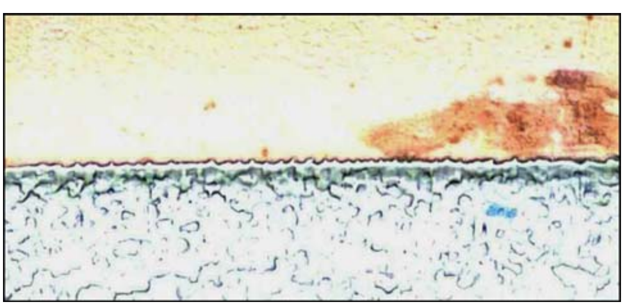

Fig. 4 Micrograph of wavy interface of joined copper-nickel alloy plates. Notice waves at the generated interface

generated by the projectile velocity of 1500 m/s (Table 1, Experiment 3). Here the seam exhibits wavy appearance such as commonly observed in the joints generated by the explosive welding (Ref 3-5).

Figure 5 shows micrograph of the welded interface between two copper plates (Table 1, Experiment 2), where a side view of joined plates is shown in Fig. 5(a) and micrograph of section of wavy welded seam is shown in Fig. 5(b). Figure 6 shows a long segment of the same section of a wavy welded seam where stable wavy pattern of the welded seam along an entire welded section is observed. The performed microscopic examination revealed the wavy interface of the joined plates where the wave length has a magnitude of the grain size of the used materials.

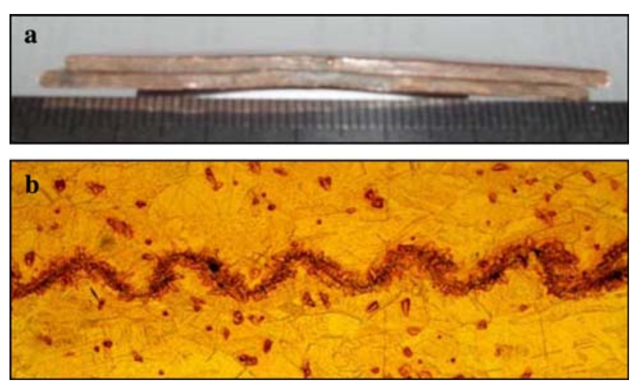

Fig. 5 (a) Copper plates welded by the water-projectile impact at the water velocity 1500 m/s and *h* = 3 mm. (b) Zoomed-in section of a micrograph of wavy interface of joined copper plates

Fig. 6 Two copper plates welded by a water-projectile impact at the water velocity 1500 m/s and *h* = 3 mm. Notice uniformity of wavy seam along entire bond length (×100)

4. Ultrasonic Examination

The ultrasonic technique was employed for nondestructive testing examination and characterization of the welded interface region. Welded samples were submerged into water-filled tanks and exposed to automatic ultrasonic scanning. The automatic ultrasonic scanning (A, B, and C-scans) was used to examine the integrity of the welded seam and metallurgical bonding. The performed examination confirmed formation of metallurgical bonds for all of tested combinations. Examples of the results of the ultrasonic examination are given in Figs. 7-14. In these figures the continuity of the green areas and the intensity of the green color show strength of the ultrasound waves passing through a sample. The intensity of the green color is determined by the strength of the sound wave reflected from the samples. The ultrasound wave passes almost unabated through a continuous metal and then is reflected by the sample base. There is no wave dissipation at the interface if the metallurgical bonds are developed, but metal irregularities at the joining attenuate the waves. Thus the strength of the green color is an indication of the continuity of the generated seams.

Figures 7-9 show generation of continuous seams at the almost all impact area excluding some areas at the sample periphery. Especially, representative is the scan shown in Fig. 9 where welding took place over almost entire coin surface which was sandwiched between two brass plates. Green color represents excellent metallurgical bond. Figures 10-14 exhibit a partial joining which, probably, is determined by the imperfection of the samples surfaces; however, at least partial welding was observed at all examined samples.

Another way of verifying the integrity of the formed structure and metallurgical bonding using ultrasonic beams is examination of the peaks of the reflected sound beams. The time difference between these peaks is the time needed for the beams traveling from the top to bottom surfaces of the generated samples. If the seam is ideal and there is no beam attenuation the time difference between the peaks is almost equal to the time of the beam traveling through the metal and the peaks amplitude is almost the same. If, however, there are discontinuities at the joints the second peak is weak or disappears all together. The application of this technique is

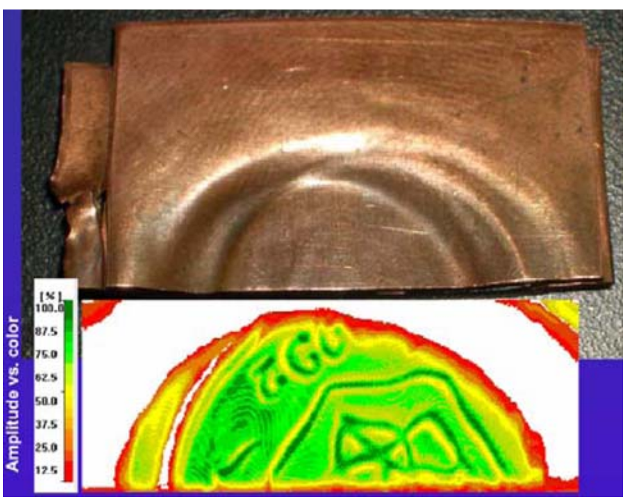

Fig. 7 General view and the ultrasonic scan of the copper-nickel alloy-copper plates welded by the water projectile impact at the water velocity 1500 m/s (Exp. 2, Table 1)

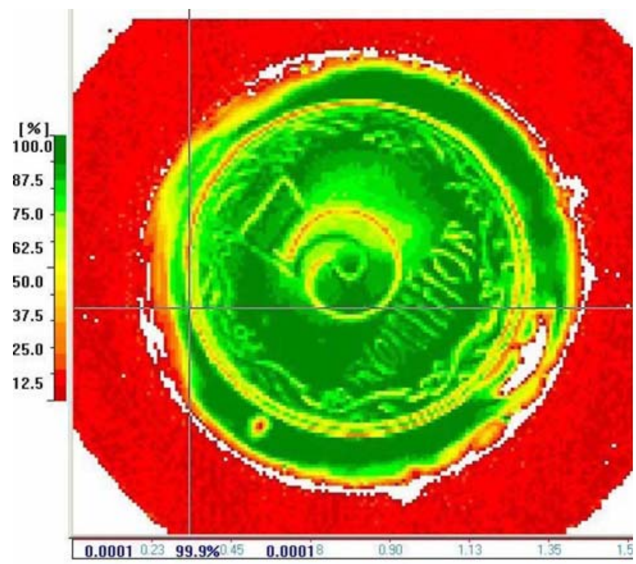

Fig. 9 Ultrasonic scan of welded structure obtained in experiment 13. Brass-coin-brass combination

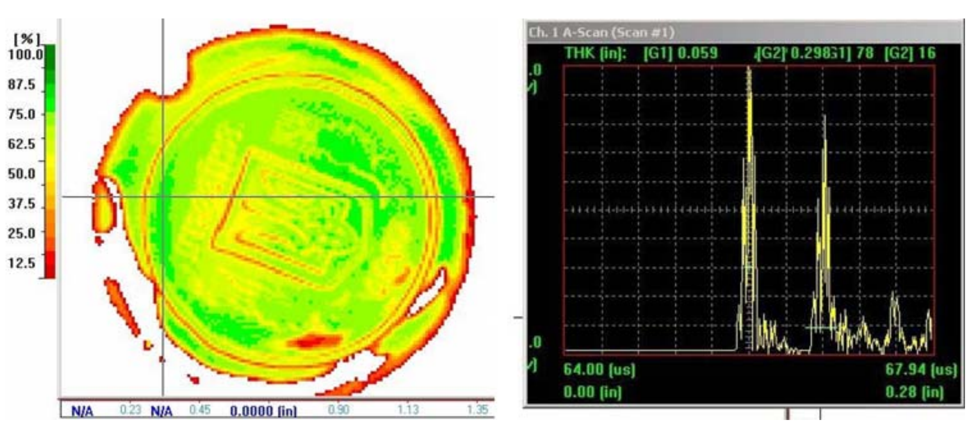

Fig. 8 Ultrasonic verification of integrity of formed structure and metallurgical bonding of plates welded in experiment 12 (Table 1)

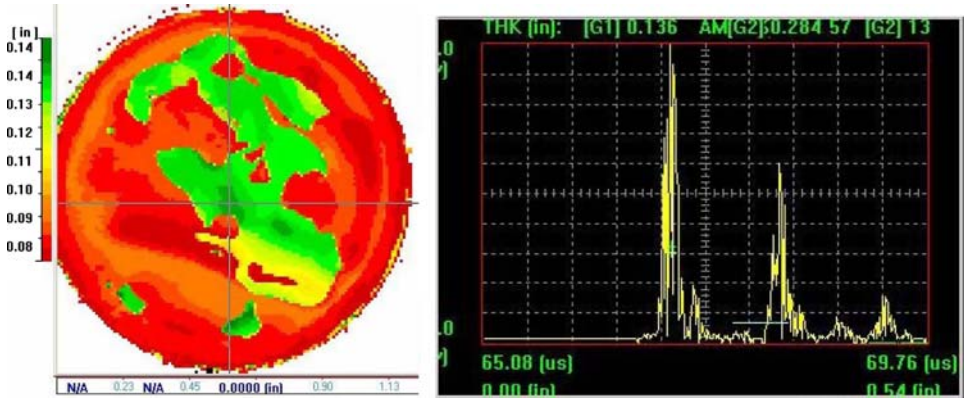

Fig. 10 Ultrasonic verification of integrity of formed structure and metallurgical bonding of plates (Exp. 44. Table 1)

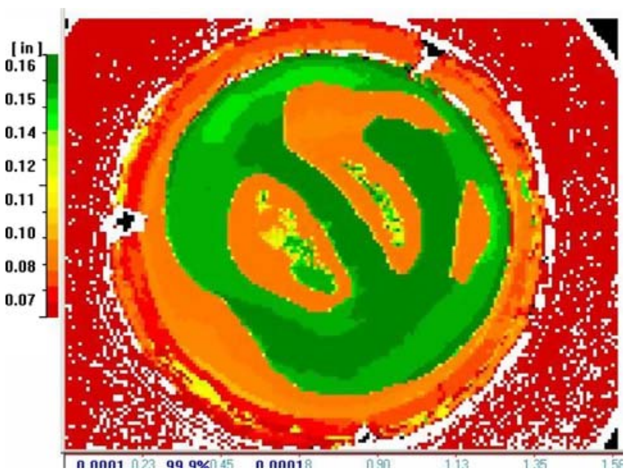

Fig. 11 Ultrasonic verification of integrity of formed structure and metallurgical bonding of two brass plates (Exp. 41. Table 1)

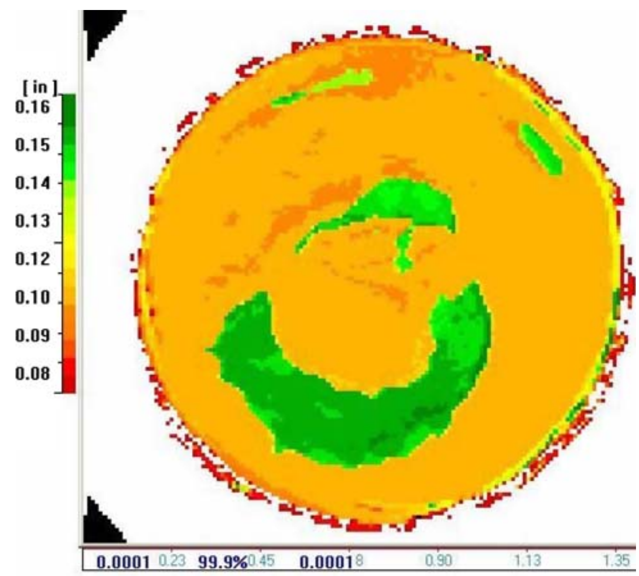

Fig. 12 Ultrasonic verification of integrity of formed structure and metallurgical bonding of copper and steel plates (Exp. 43. Table 1)

shown in Figs. 8, 10, and 13. The strength of two peaks in Fig. 8 is almost equal, while Figs. 10 and 13 show beams attenuation at the seams. This attenuation is weak in Fig. 10 and stronger in Fig. 13. All samples, however, exhibit at least partial samples joining.

A typical view of the generated samples is shown in Fig. 15. As it is illustrated by this figure the impact of the projectiles does not result in the macroscale target deformation. An exception is shown in Fig. 16, where the impact results in the bending of plates.

5. Discussion of Results

In the course of the performed experiments 20 out of performed tests exhibited at least partial welding while only one test did not bring about plates joining. These results were achieved while no special surface preparations common in conventional joining operations were performed. By a single water projectile impact welded surface to nozzle cross section surface ratio up to 2.5 was achieved. Welding of larger areas can be conducted by scanning of water launcher and performing multiple impacts. In this case existing industrial robots can be used for guiding the water launcher. It was suggested that welding in the course of the liquid impact is due to the microscale melting and subsequent solidification of the melted layer. In the case of the unsuccessful welding slight melting of the adjacent surfaces was observed. The role of melting in the performed experiments was demonstrated by mechanical separation of several welded parts which revealed evidence of melted layers on each of the adjacent surfaces. These parts were severely damaged beyond presentational value by mechanical forces of separation so those cannot be shown here. This illustrates that melting of extremely thin layers takes place at the joining interfaces and results in metallurgical bonding of the joined metals. Of course other phenomena, such as the microscale diffusion can contribute to the welding as well. The estimated process duration is in the order of microseconds, thus diffusion in the adjacent layer may be a factor. Mechanical properties of welds were not quantified since existing methods for mechanical testing of welds could not be applied.

It was found that the process is determined by several control variables. In addition to the obvious control variables

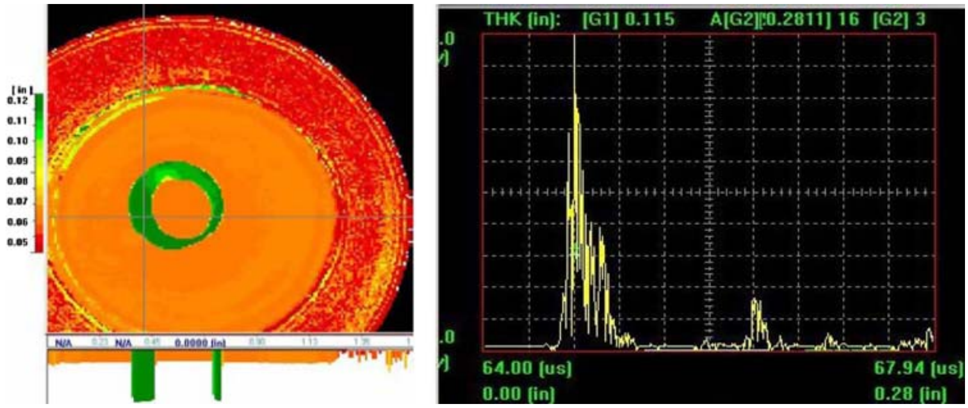

Fig. 13 Ultrasonic verification of integrity of formed structure and metallurgical bonding of two steel plates (Exp. 42. Table 1)

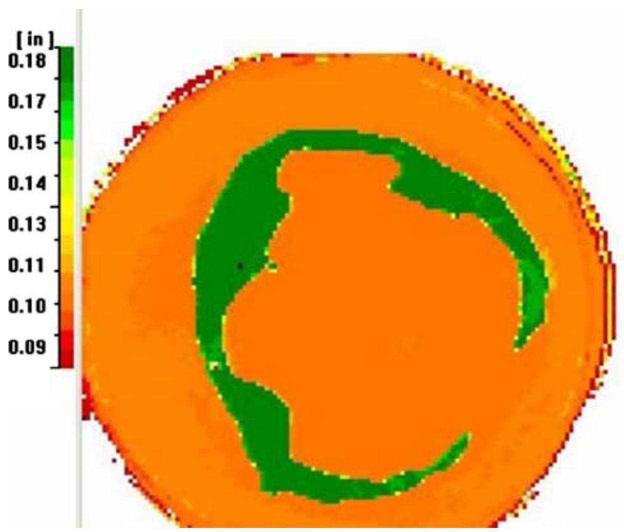

Fig. 14 Ultrasonic verification of integrity of formed structure and metallurgical bonding of two brass and steel plates (Exp. 45. Table 1)

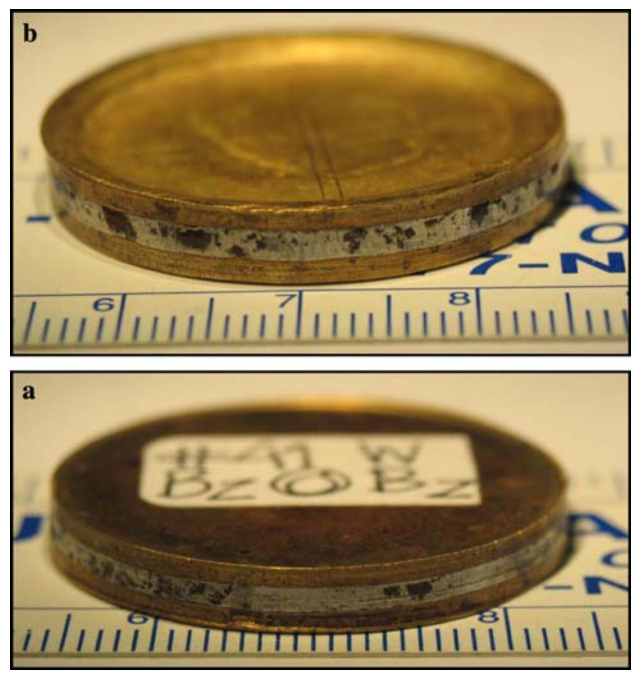

Fig. 15 (a) General view of impact side of two brass plates welded by the water projectile impact at the water velocity 750 m/s; (b) Back side view of same structure (Exp. 41. Table 1)

Fig. 16 General view of nickel alloy coin and steel plate welded by the water projectile impact at the water velocity 750 m/s (Exp. 14. Table 1)

such as the mass of water and powder and stand off distance, the positioning of the plates in the course of impact has crucial role. While joining of plates with no separation is possible, it was observed that a distance between joining parts enhances welding process. For example, two copper plates were not welded using no acceleration setup at reaction impulse of 237.69 kg·m/s while the same combination was well welded with 1 mm separation ring at significantly lower reaction impulse of 169 kg·m/s. While parts separation affected results of the performed experiments, unlike similar conventional welding such as explosive welding which needs separation distance between items to be welded, water projectiles can conduct welding without and with the separation distance.

Process results are also affected by the impact angle. The best results were achieved at 90° incidence impact angle; however, it was observed that projectiles carry sufficient energy to conduct welding of metals at angles smaller than 90°.

Feasibility of novel technology was validated which is that similar and dissimilar metals can be welded by high-speed water projectiles impact. Metallurgical bonding was confirmed for all of tested combinations of metals.

6. Conclusions

The performed experimental study demonstrated feasibility of the use of water projectile impact for similar and dissimilar metal welding. Welding of ten metal combinations was demonstrated. Metallurgical bonding was confirmed for each of these combinations. Industrial needs for consecutive stitch welding when large plates does not need to be joined in a continuous weld seam fashion can be met by water projectile stitch weld processing. Welding of large metal plates can be effectively performed by generation of weld-stitch seams by use of consecutive water projectile impacts. Feasibility of development of novel manufacturing technologies was demonstrated.

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