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Paper

INVESTIGATION OF METAL PROCESSING USING A HIGH SPEED LIQUID IMPACT

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ABSTRACT

Metal deformation and welding in the course of an impact of high speed liquid projectiles (impulsive jets) was investigated experimentally. The projectiles were generated by a launcher where the chemical energy of a powder was converted into the kinetic energy of a projectile and were used as a punch, while the die geometry determined the final shape of a workpiece. The deformation and welding of steel, copper and bronze samples was investigated experimentally. Selected samples underwent forging, stamping and extrusion operations. It was shown that the deformation was carried out at the extreme high speed and the shape of the die determined the geometry of a generated part at desired accuracy. Joining of same and dissimilar materials using the liquid impact was also studied. Ultrasound examination showed the continuity if the joint generated in the course of the impact. Potential application of the liquid impact for metals processing is discussed.

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1. INTRODUCTION

The objective of the proposed study was to investigate a novel high productivity technology for parts fabrication. The technology involves impacting a workpiece by high speed liquid projectiles. The stresses developed in a target in the course of the impact exceed the strength of the target material while the force exerted on the workpiece drives the material into die cavities. Compression and rarefaction waves developed in the course of the impact bring about joining of similar and dissimilar materials subjected to impact. Thus room temperature forming and welding of metals become possible [1-8]. Because the duration of deformation or joining is equal to or less than the duration of the projectile-workpiece interaction, the rate of the deformation in the course of the impact based forming or welding is extremely high. The effectiveness of the high rate material processing, such as explosive forming and welding, is well understood and documented. [e.g. 9-13]. While the effect of the liquid impact on a target is similar to that of an explosive, as it will be shown below, in some applications the use of the liquid impact is more effective.

The principal element of the technology in question is the high speed liquid projectiles. The theory of the projectile formation and a launcher for their generation were developed earlier [14-18]. The launcher application for metal deformation was discussed in [1-8]. The presented study is concerned with the further investigation of the impact based forming. The principal attention in this study, however, is paid to the demonstration of the feasibility of the liquid impact based welding.

2. EXPERIMENTAL PROCEDURE

An experimental setup for the study of the impact based forming and welding was designed and constructed (Fig.1). A detail description of the setup is given in [8]. The principal part of this setup was a laboratory scale launcher for projectile generation. In the course of the experiments the targets were mounted on a heavy pendulum (Fig.1). An angular displacement of the pendulum was measured and used for estimation of the projectile momentum. The standoff distance of the launcher changed in a wide range. Circular or square steel, copper and brass plates were used as targets. The plates' thickness was in the range of 1-3 mm. In the course of forming experiments a target was supported by a die. In the course of the study of joining special sample holders (Figs. 2, 3) was used. This holder enabled us to test joining of different sets of samples at a different distance between the samples. Particularly, joining of attached samples was investigated. This experiment was especially important, because explosive welding can be carried out at a certain distance between parts to be joint.

Welding experiments were also carried out at different conditions of the water removal. Free water outflow from the impact zone as well as complete water containment were tested. The acquired data was used to evaluate the feasibility of industrial use of liquid impact forming and welding.

3. INVESTIGATION OF MATERIAL FORMING

3.1 Formation of Sub Millimeter Scale Grooves. The experiments involved the study of formation of sub-millimeter circumferential ridges on the target surface. For this study, a die with concentric groves was designed and manufactured (Fig.4)**.** In the course of experiments a metal plate was placed on a die and impacted by a projectile. The impact forced the target material to fill the die grooves. Thus a set of ridges and groves was formed on the target surfaces. Compliance between the geometries of the die and workpiece surfaces constituted the criterion for evaluation of the performed forming operation. In the course of the experiments 200 g of water was propelled by 30 g of gunpowder at a stand-off distance of 16 cm. The performed computations showed that at these conditions the projectile velocity at the impact was 1500 m/s.

In order to quantify the accuracy of forming the microscopic evaluation of a workpiece was carried out using optical microscopy, 3-D digital microscopy, and infinite focus microscopy. Optical microscopy (x200) was used for visual examination of the generated surfaces. The performed examination confirmed that at the existing tolerances of die fabrication there is sufficient compliance between the desired die geometry and the actual geometry of a work piece.

The surface geometry generated in the course of an impact of a brass sample is shown in Figs. 5 – 8. A close-up view of the segment containing three ridges reproduced by 3-D digital microscopy (Fig. 5) confirms compliance of the shapes of the die and the workpiece The generated workpiece surface was a mirror view of the corresponding die section. Similar result was obtained for 10 different sections of the workpiece surface.

A general view of the surface of a brass target generated in the course of forming is shown in Fig. 6. As it follows from this figure the geometries of the die and the work piece complied sufficiently well and the geometries of the grooves and ridges on both surfaces are almost identical. This accurate reproduction of the die geometry was observed in all sections. An infinite focus microscopy was used for quantification of the workpiece surface topography. Profiles of four neighboring ridges formed on the brass surface are shown in Fig. 7. As it is shown in this picture, the height of a one of the depicted ridges was approximately 140 μ while the neighboring ridge has height of approximately 200 μ. The difference in size of these ridges was the same as that of the corresponding parts of the die and was caused by an unstable process of the die machining. The infinite focus microscopy was also used for analysis of the surface waviness and roughness of all generated samples. As it follows from Figs 8a and 8b the waviness of the generated surfaces was below 2 μ and the roughness was below 0.04 μ.

A general view of the groves and ridges formed on the surface of copper sample is shown in Fig. 9. Notice that the desired surface geometry was accurately reproduced in the course of the impact. This compliance is also demonstrated by a close-up view of a segment containing three ridges and reproduced by 3-D digital microscopy (Fig. 10). The infinite focus microscopy was used to examine the topography and profile of a copper sample. It was found that the waviness of the generated surface was below 2 μ (Fig. 11) and roughness was below 0.1 μ (Fig. 12).

3.2 Fine Stamping. The objective of these experiments was the study of formation of rather complex patterns on the target surface. In this case a conventional coin was used as a supporting die. Target materials included copper, brass, aluminum and high ductility steel. The steel had

46% elongation, tensile strength of 325 MPa, and yield strength of 195 MPa. Thickness of the copper and brass samples was 3 mm and steel samples were 2.5 mm thick.

A Ukrainian coin was used as a die for investigation of the fine stamping. As a result the coin image was stamped into copper, steel and aluminum plates. In the course of the experiments 350 g of water were propelled by combustion of 35 g of gun powder at a stand off distance of 16 cm. A calculated impact velocity was 850 m/s. Geometry of the coin was accurately reproduced on all aluminum, steel and copper samples. Quality of the reproduced surface was characterized by two methods, infinite focus microscopy and 3-D profile analysis. Measurement of parameters of the surface geometry was performed and it was demonstrated that the coin geometry was reproduced sufficiently accurate on the surface of all targets

General view of the coin images stamped on the surface of aluminum and copper samples is shown in Fig. 13. An image of the coin stamped on the surface of a steel sample and generated by the 3-D profile analysis is shown in Fig.14. The depth of the depression of the work piece surface was approximately 130 μ. As it was demonstrated by measurements, this corresponds to the topography of the coin. In addition to the profile and depth features, top view of the work piece geometry was compared to the corresponding view of the die. The performed measurements showed almost mirror-like reproduction of the die geometry on the workpiece surface. Example of a profile of the coin (Fig.15) shows fine stamped features with the maximum height range of 90 μ and the roughness below 1 μ (Fig. 16).

3.3. Discussion of results. The liquid-impact-based forming has unique technological advantages. For example, similarly to the explosive forming [10, 11], it requires a single die. The second die is replaced by a liquid punch. This simplifies the forming facilities and reduces its cost. A water projectile (liquid punch) could be applied to several processing operations and rapid execution of tasks would enable mass production of various parts. All of the performed tests involved deformation of various metals including steel and a special alloy at an extremely high rate determined by the impact of high-speed water projectiles. The tests included formation of rather complex patterns such as sub-millimeter scale grooves or an image of a coin. The facilities used in this study (launcher, dies, targets, fixture) were fabricated using conventional machine shop capabilities and conventional materials. No special provisions for fastening a die, target or launcher or preventing die deformation were available. In all of the performed experiments the results of forming were satisfactory. The desired shapes were generated, surface topography of the targets was quite adequate, no defects or damage generated in the course of deformation was observed. Formation of shapes having a size of 6 microns was achieved.

It is expected that the development of manufacturing technology will involve mass production of the low-cost precision parts out of various engineering materials or formation of precision pattern of the surfaces of regular parts. The performed experiments demonstrate feasibility of the use of high-speed projectiles for fabrication of desired parts. It was shown that liquid impact driven fine forming has a potential of becoming technology of choice for precision parts fabrication. Indeed, the feasibility to generate precision parts with an adequate surface topography was demonstrated. The required facilities are comparatively simple and process productivity, determined by the firing rate of the launcher, is extremely high. For simplicity sake in the performed experiments a powder was used as an energy source. It is expected that in the manufacturing environment the chemical energy of a powder will be replaced by the energy of an electrical discharge or magnetic field. In this case the firing rate can be as high as 1 kHz. Then it can be expected to increase the speed of the projectiles up to 2-3 km/s and the accuracy and the strength of the dies will be significantly enhanced. This will bring about emerging of a technology for mass production of complicated and precision parts.

The performed experiments also indicate that there is a possibility to apply a proposed technology to precision forming of difficult to process materials, such as glass or ceramics. Unique advantages of the liquid impact based fine forming define the effectiveness of its application, while the performed experiments show its feasibility.

4. EXPERIMENTAL STUDY OF WELDING OF SIMILAR AND DISSIMILAR METALS

4.1 Experimental results

Initially experiments were carried out at the projectile speed of 1500 m/s (Figs 18, 20, 21). Initial examination of a successfully joined structure showed, however, that the projectiles having speed of 750-850 m/s deliver weld of higher strength (Fig. 17). This range of lower water speed was used in the further experiments. By repetition of experiments consistency of operation was confirmed. After initial investigation it was estimated that separation of the parts to be jointed provides better conditions for welding than joining without separation. It was also found that if the launcher barrel is completely filled by water prior to the process initiation, a stronger joint was developed. Consistency of joining was confirmed by sufficient repetition of experiments. Each of the performed tests resulted in welded assembly of investigated combinations. Some results of the selected experiments are given in the Table 1.

Table 1. Experimental results of welding by water projectile impact

Exp.#	Mp [g]	Impulse[kgm/s]/* α[deg]	Metals Combination
12	25	314/*45.5	Copper-Nickel-Copper
13	35	369.1/*54	Brass-Nickel-Brass
28	30	169/*24	Copper-Copper
43	30	430.81/*64	Copper-Steel

Ultrasonic technique was employed for examination and characterization of welded interface-interface region. All joined samples were scanned automatically and metallurgical bonding and integrity of all joined structures was confirmed. General view of brass-nickel alloy-brass welded sandwich in Fig. 17 shows single structure integrated out of three plates. All three plates were welded and integrated into a single structure by the water projectile of velocity around 750 m/sec. Such welded structures were generated in each experiment. Example of ultrasonic scan of copper-nickel alloy-copper welded sandwich is shown in Fig. 18 with the ultrasonic scan shown below. All joined samples were scanned automatically and metallurgical bonding and integrity of all joined structures was confirmed.

Sample of ultrasonic verification of metallurgical bonding and integrity of welded copper-nickel-alloy-copper plates obtained during experiment shown in figure 19. The time differential of ultrasonic reflection peaks is the time needed for the sound to travel through entire thickness of the structure with no interference caused by a poor joint. This confirms integrity and metallurgical bonding of plates. Two more examples of ultrasonic verification of the metallurgical bonding are shown in figures 22 and 23.

4.2 Discussion of results

In this study a novel welding technology was investigated. Mechanical separation of several welds revealed evidence of melted layers in each of the welded samples. It appears that melting of extremely thin layers at the interface takes place and results in metallurgical welding of joined metals. Duration of the process is of order of microseconds during which micro-diffusion may take place as well and may be a contributing welding mechanism as well.

Out of 20 performed experiments only one was not successful. It was shown that process result is determined by the distance between the joining items, momentum and direction of the projectile, kind and thickness of the joining components, duration of the impact. The process variables in the performed experiments change in a wide range. For example, the projectiles impulse ranged from 170 to 465 kg m/s. A number and range of the process variable enable us to optimize process results. Because of this, the liquid impact welding is more effective technology then the explosive welding [12, 13]. While the explosive welding can be carried out only at a separation of the joining parts, the joining via the liquid impact can be brought about without and with the components separation. While the best results are achieved at 90 degree impact, the process can be carried out at the inclination of the projectile trajectory.

It is suggested that the welding during the liquid impact is due to the superposition of the compression and rarefaction waves generated by the impacting projectiles. Propagation of the waves through a multiphase region causes melting of very thin layers at the interface of plates to be joined. This results in forming a metallurgical bond along the phase boundary.

5. CONCLUDING REMARKS

The feasibility of the material forming and welding using high-speed liquid projectiles was demonstrated. It was shown that a comparatively simple device, the presented launcher, can be used for both forming and joining. These two rather different applications are attained just by change of the process conditions. This launcher capability constitutes the primary advantage of the proposed technology.

6. REFERENCES

1. Petrenko, O. P., Geskin, E. S., Atanov, G. A., Semko, A. N., Goldenberg, B. (2004). "Numerical Modeling of Formation of High-Speed Water Slugs". *Transactions of ASME, Journal of Fluids Engineering*, 126(2).

2. V.Samardzic, E.S. Geskin ,G.A. Atanovv, A.N. Semko, A. Kovaliov,(June 2007). "Liquid Impact Based Material Micro-Forming Technology". *Journal of Materials Engineering and Performance,16(3)*

3. Geskin, E. S., Goldenberg, B., Petrenko, O. P., V. Samardzic, Atanov, G. A., Semko, A. N. (Jan. 2002). Investigation of Material Fracturing by High-Speed Water Slugs. Presentation at *Annual Meeting of National Science Foundation Division of Design Manufacturing and Innovating Engineering*. San Juan, Puerto Rico.

4. Geskin, E. S., Goldenberg, B., Petrenko, O. P., V. Samardzic, Atanov, G. A., Semko, A. N., (Jan 2003). Investigation of Material Fracturing by High-Speed Water Slugs. Presentation at *Annual Meeting of National Science Foundation Division of Design Manufacturing and Innovating Engineering*. Birmingham, AL.

5. Geskin, E. S., Goldenberg, B., Petrenko, O. P., V. Samardzic, Atanov, G. A., Semko, A. N. (Jan 2004). Investigation of Material Fracturing by High-Speed Water Slugs. Presentation at *Annual Meeting of National Science Foundation Division of Design Manufacturing and Innovating Engineering*, Dallas, TX.

6. V.Samardzic, O.Petrenko, E.S.Geskin, G.A.Atanov, A.N.Semco "Innovative Jet-based Material Processing Technology",2005 WJTA American Waterjet Conference&Exhibition, ST Louis, MO

7. V. Samardzic, Petrenko, T,Bitadze, E.S. Geskin, GA. Atanov, A.N. Semko, A.N. Kovaliov and O.A. Rusanova (2005) "Feasibility Study of Free Form Fabrication of the Heterogeneous Structures Using the Liquid Impact", Proceedings of 2005 DMII NSF grantees conference, Scottsdale, AZ

8. V.Samardzic, O.P. Petrenko, E.S.Geskin G.A. Atanovv, A.N. Semko, A. Kovaliov, (2005) "Innovative Jet Based Material Processing Technology", in proceedings of *Waterjet Technology Association Conference , Editor M. Hashish, August, Houston , TX; paper 2A-2*

9.M.D. Verson, (1969) *Impact Machining*, Verson-Allsteel Company

10. .J.S. Reinhart. (1963), *Explosive Working of Metals*, Macmillan.

11 .A.V. Krutin et.al. (1975). *Exlosion Deformation of Metals*, Metallurgia, Moscow (in Russian)

12. B.Crosssland, (1982) "Explosive Welding of Metals and its Application", *Clarendon Press, Oxford, Oxford University Press,NY*

13. T.Z. Blazinski , (1983) "Explosive Welding, Forming and Compaction", *Applied Science Publishers, London and New York*

14.G.A., Atanov, (1987), *Hydroimpulsive installations for rocks breaking*. - Kiev, Vystcha shkola. 1987 (in Russian.).

15.G Atanov. (1996), “The Impulsive Water Jet Device: A New Machine For Breaking Rock “, *International Journal of Water Jet Technolgy. Vol. 1, No 2, p.. 85 – 91*

16,.W.C. Cooley and W.N. Lucke (1974), “Development and Testing of a Water Cannon for Tunneling”. *Proceedings of the 2nd International Symposium on Jet Cutting Technology.* Cambridge, England, Paper J3

17.B.V Voitsekhovsky, (.1967), “Jet nozzle for obtaining high pulse dynamic pressure heads”, *U.S. Patent № 3, 343, 794*, 26 Sept..

18 .G.A., Atanov, , V.I., Gubskiy, A.N., Semko, (1997) “Internal ballistics of the powder hydrocannon”, *Izvestia RAN*, MZhG, № 6,. – P. 175-179 (in Russian).

7. ACKNOWLEDGMENTS

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7. FIGURES

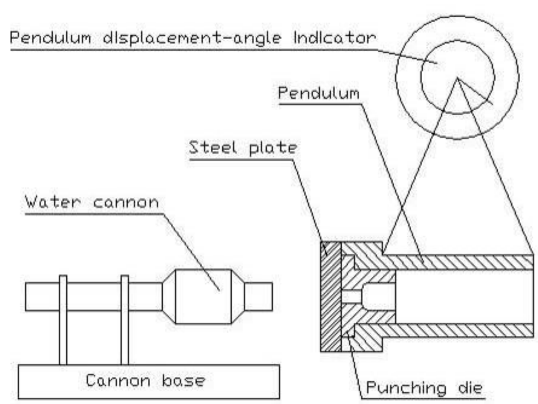

Figure 1. Schematic of the experimental setup. Notice that mounting of the target on a ballistic pendulum allows measuring the impact momentum.

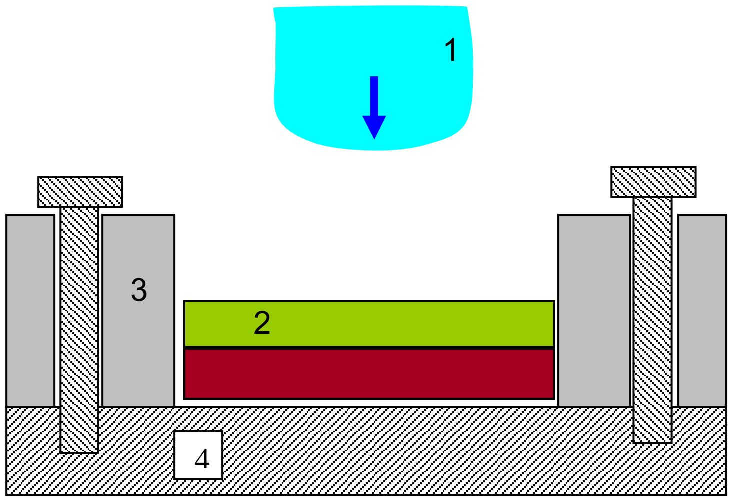

Figure 2. Schematic of nested experimental setup for welding. 1 –water projectile, 2 –nested metal samples to be welded, 3 – fasteners, 4 –back support

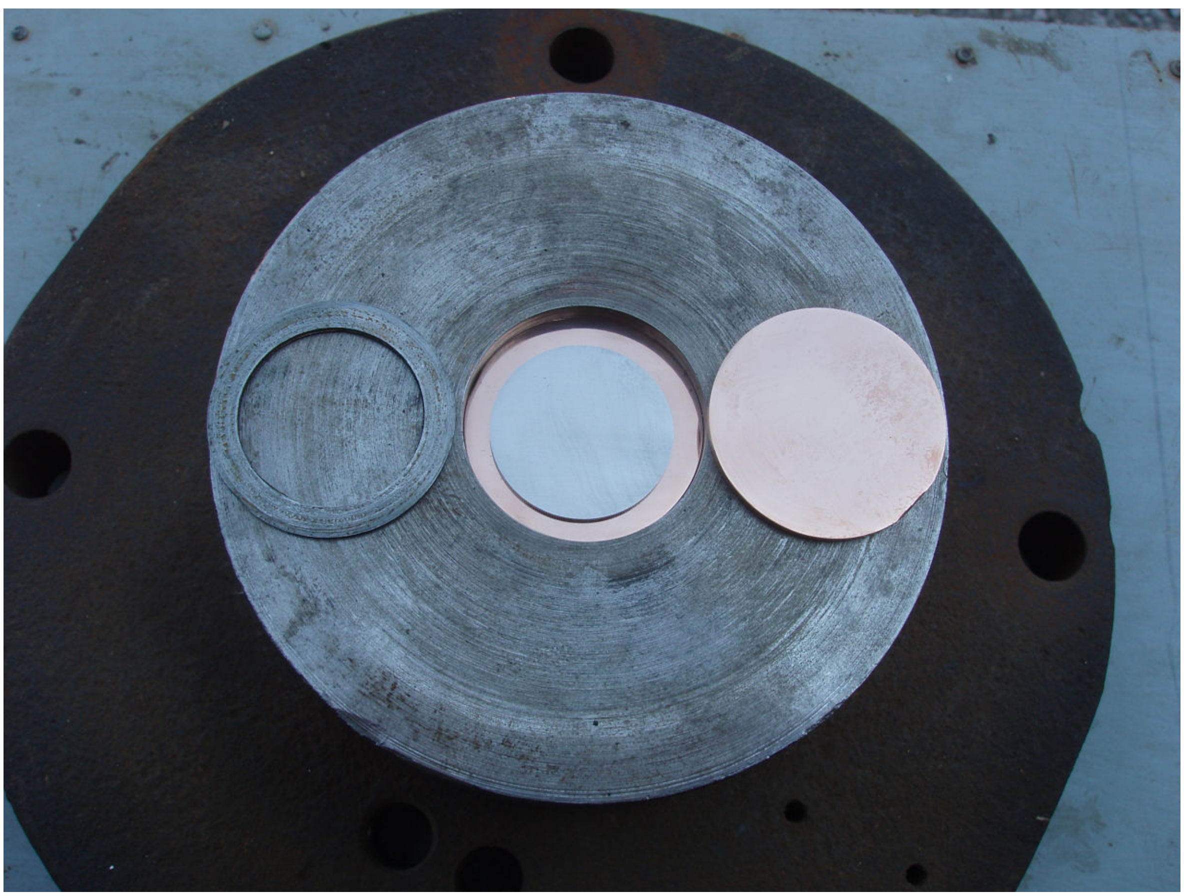

Figure 3. Components of a nested experimental setup prior to assembly for welding. 1 – back support, 2 –rear copper plate to be welded, 3 –middle layer to be welded (nickel alloy coin), 4 –separation ring, 5 –fastener, 6 – impact side copper plate to be welded.

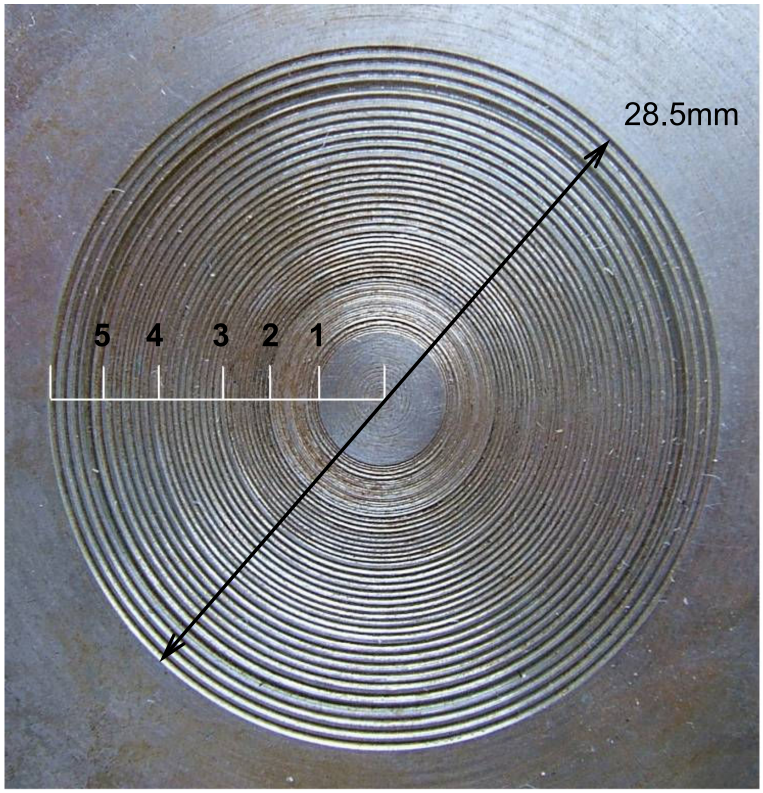

Figure 4. General view of the die used for fine forging of samples. Notice complexity of die geometry. Numbers 1-5 show number of the section on the die surface. The ridges geometry of different section (Table 1) is different.

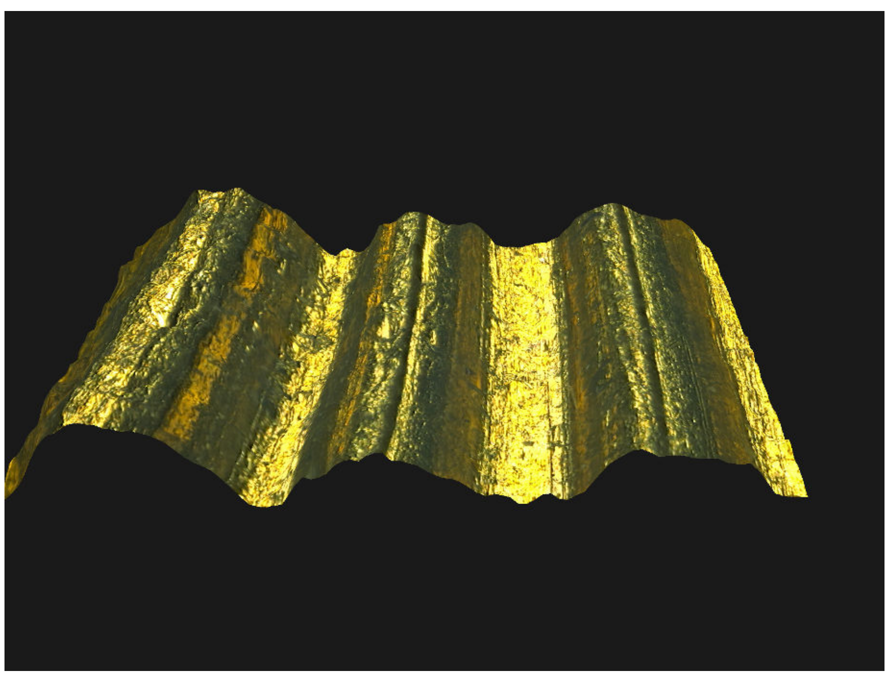

Figure 5. Segment of concentric grooves and ridges formed on brass. Notice that ridges and grooves of the work piece surface have the forms of a trapezium which is similar to a corresponding segment of the die.

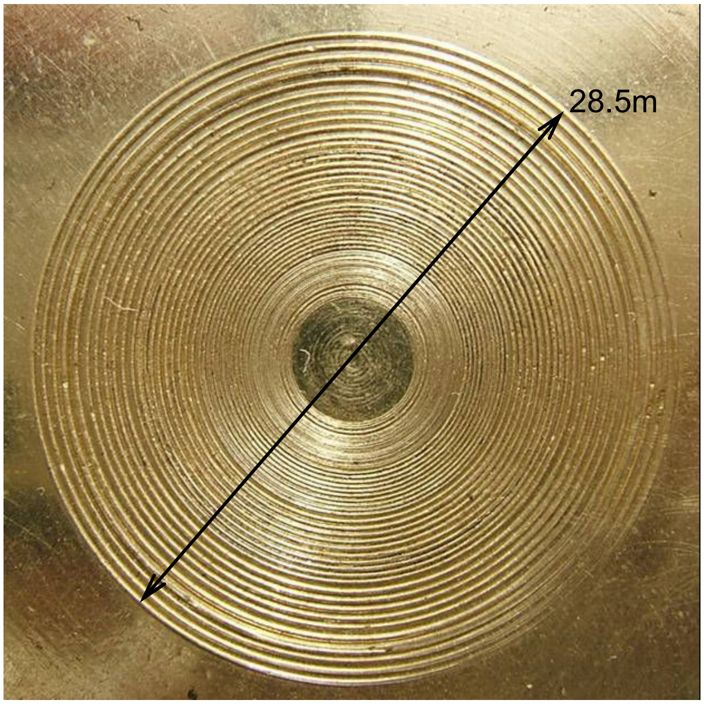

Figure 6. General view of concentric grooves and ridges formed on the surface of brass sample. Notice precise geometry of the generated grooves.

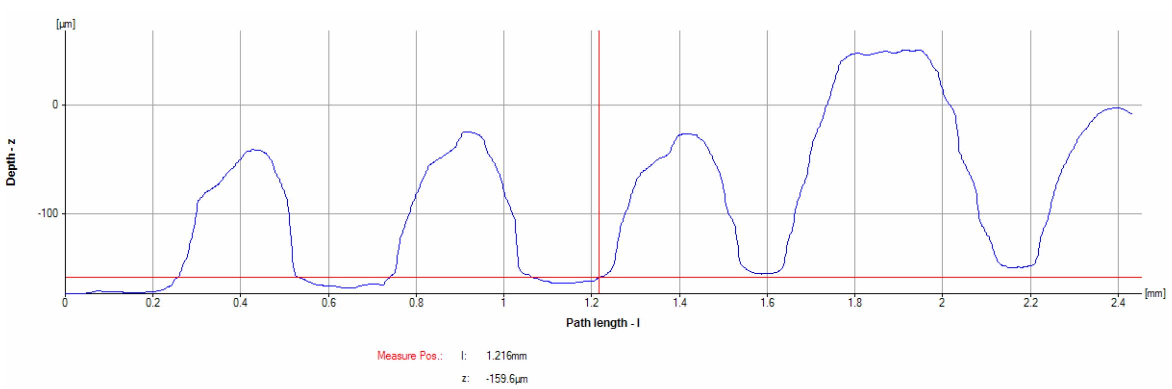

Figure 7. The profile of concentric grooves and ridges formed on a brass sample.

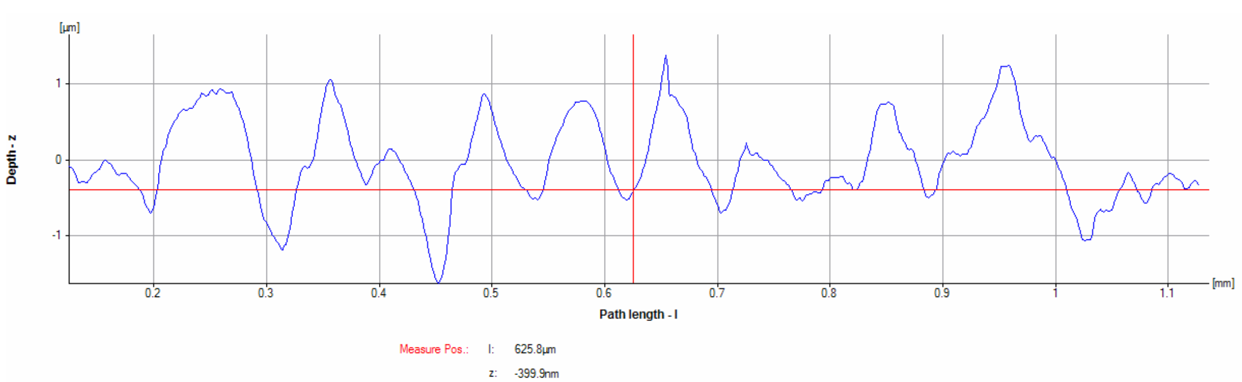

Figure 8a. Surface waviness of grooves formed on a brass sample.

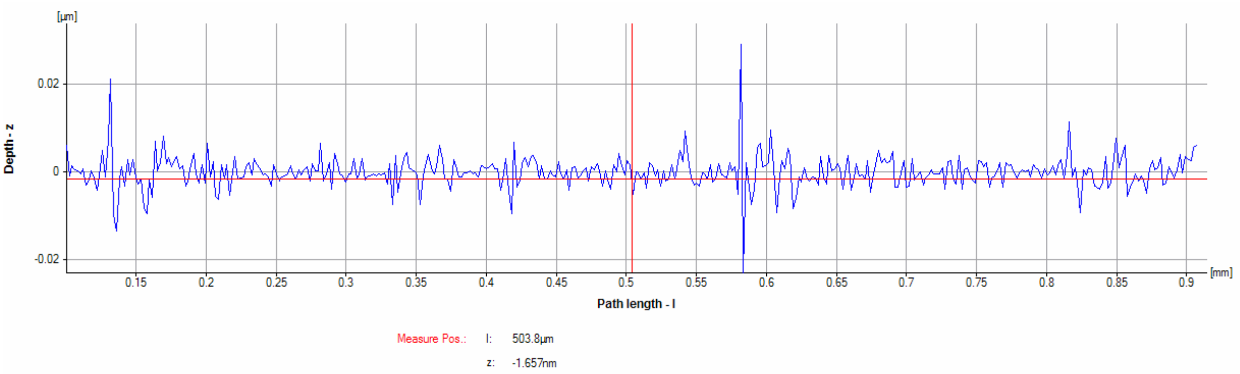

Figure 8b. Surface roughness of groves formed on a brass sample.

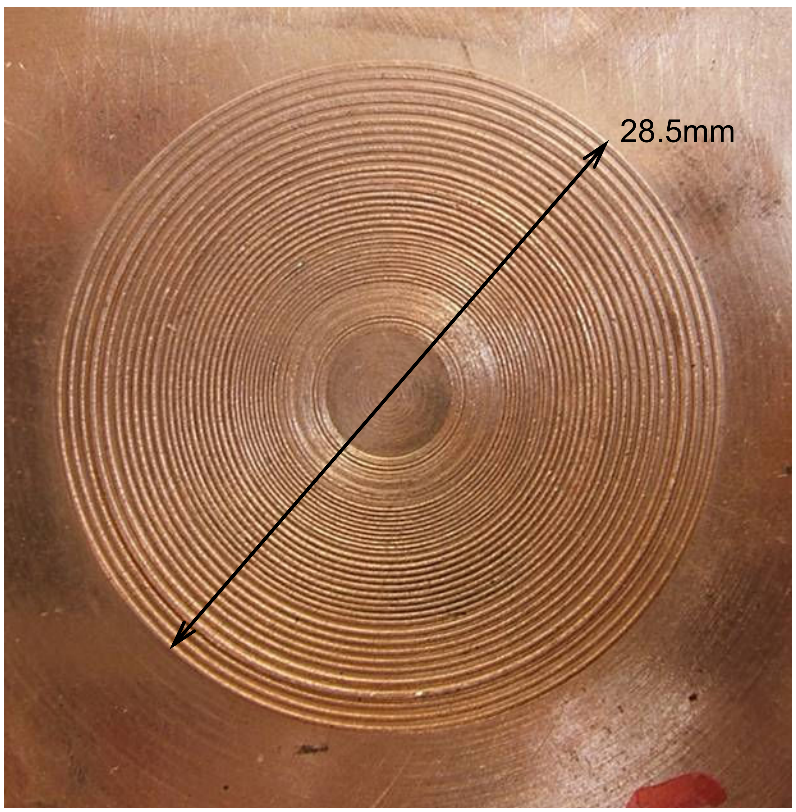

Figure 9. General view of concentric grooves and ridges formed on the surface of a copper sample.

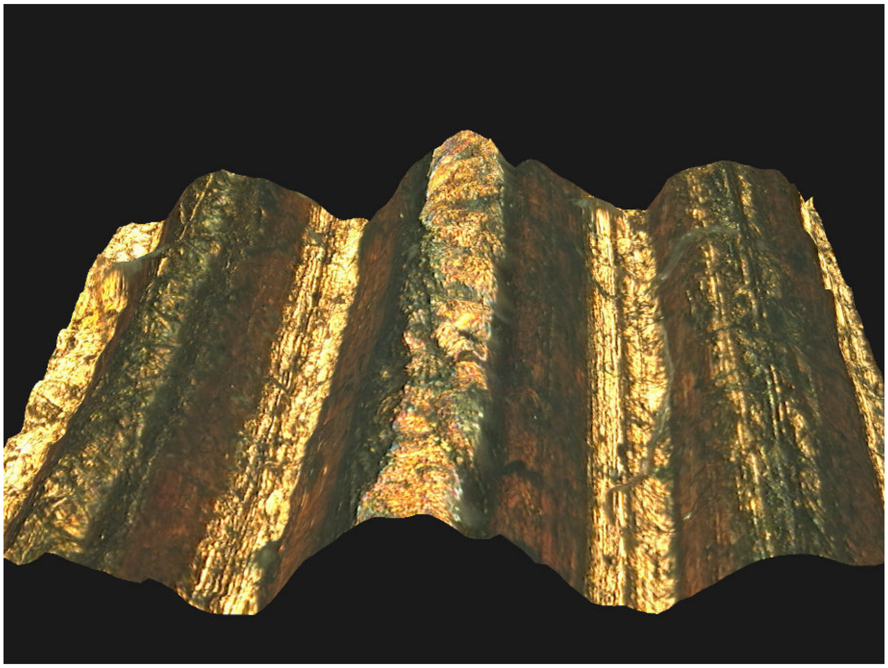

Figure 10. Segment of concentric groves and ridges formed on a copper sample

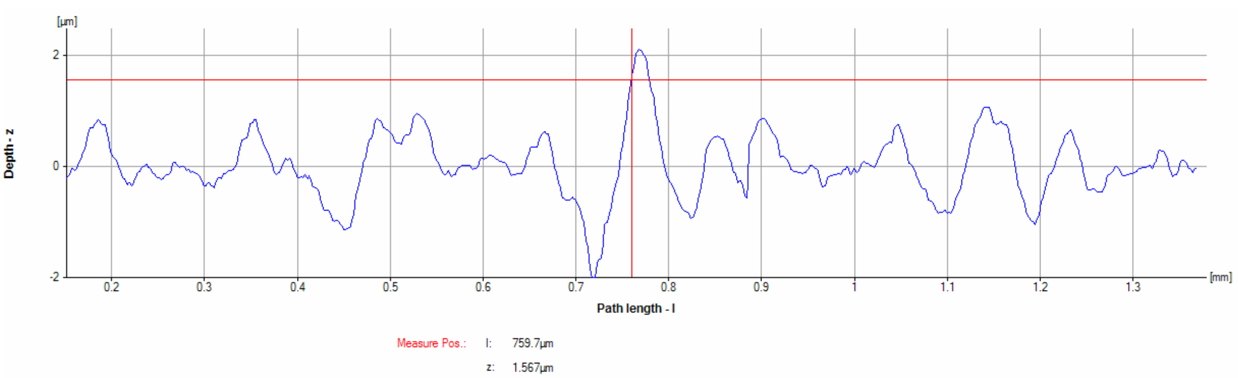

Figure11. Surface waviness of groves formed on a copper sample.

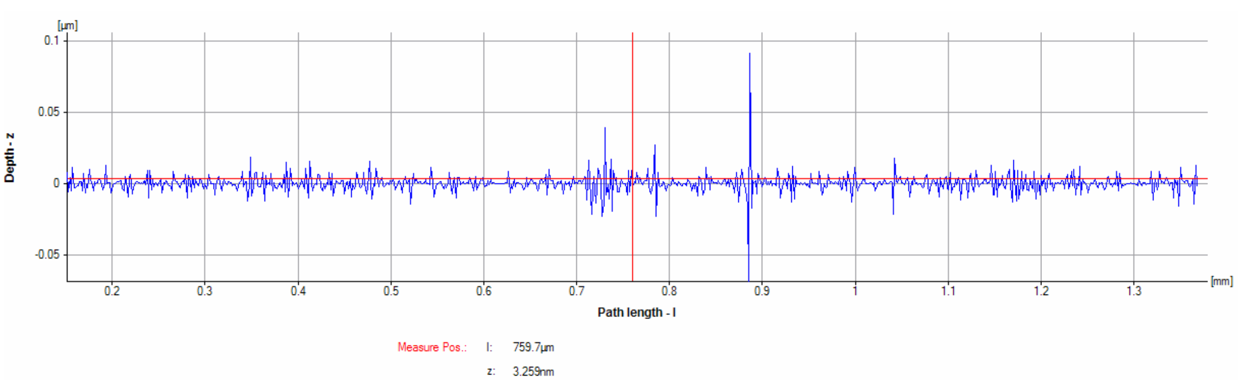

Figure12. Surface roughness of a grove formed on a copper sample.

Figure 13. General view of a coin stamped on aluminum and cooper samples. Notice reproduction of fine details of the coin on the sample surface.

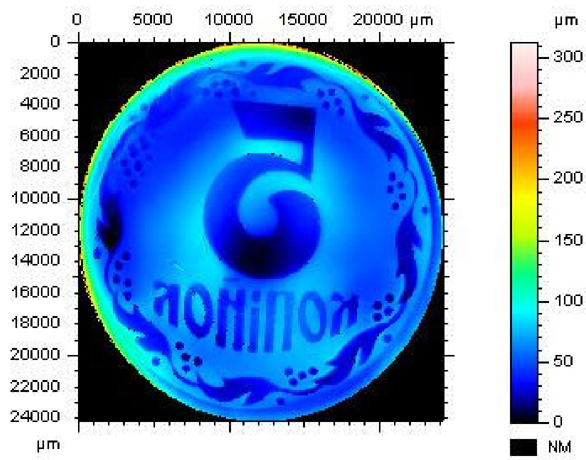

Figure 14. Image of coin stamped on steel created using 3-D profile analyzer.

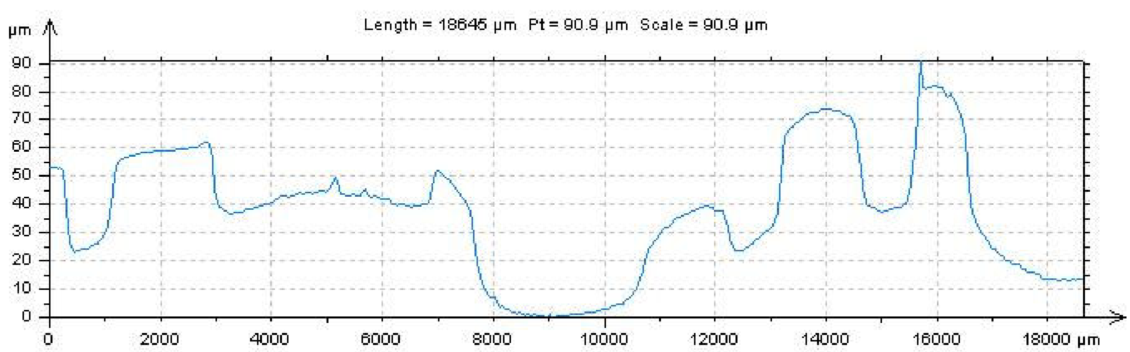

Figure 15. Example of profile of a coin stamped on a steel sample.

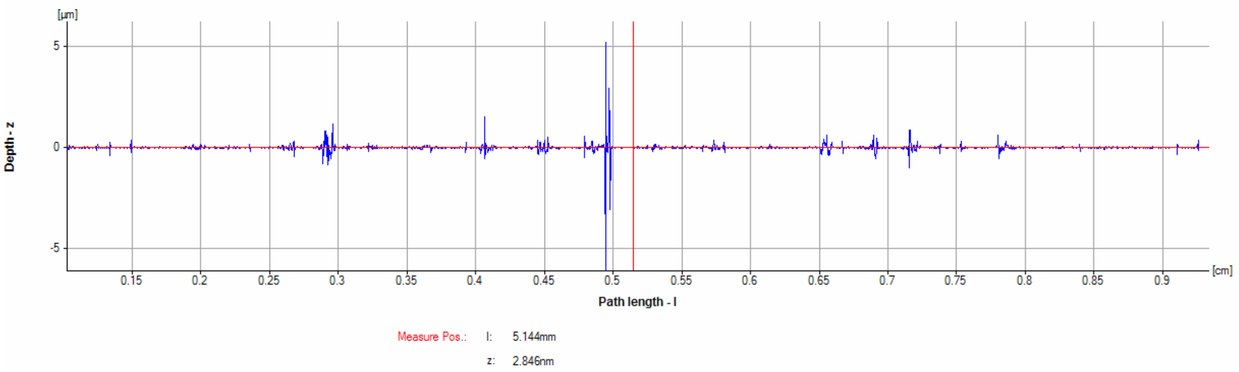

Figure 16. Roughness of the surface of steel sample stamped by a coin.

Figure 17. General view of brass-nickel-alloy coin-brass plates welded by the water projectile impact in at the water velocity 750 m/sec (Table 1, Exp. #13).

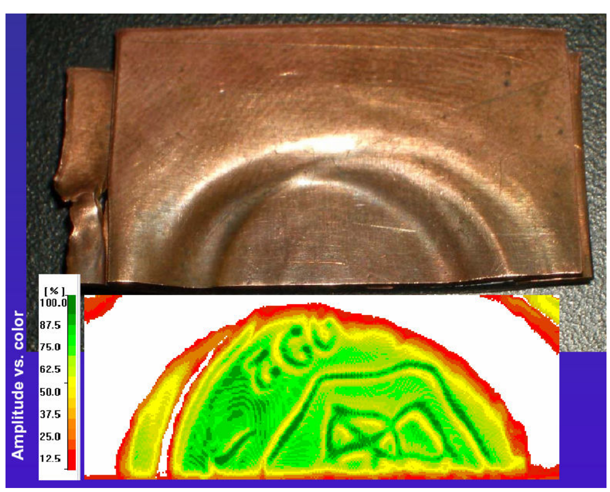

Figure 18. Copper –nickel alloy-copper plates welded by the water projectile impact at the water velocity 1500 m/sec, and ultrasonic scan of welded plates.

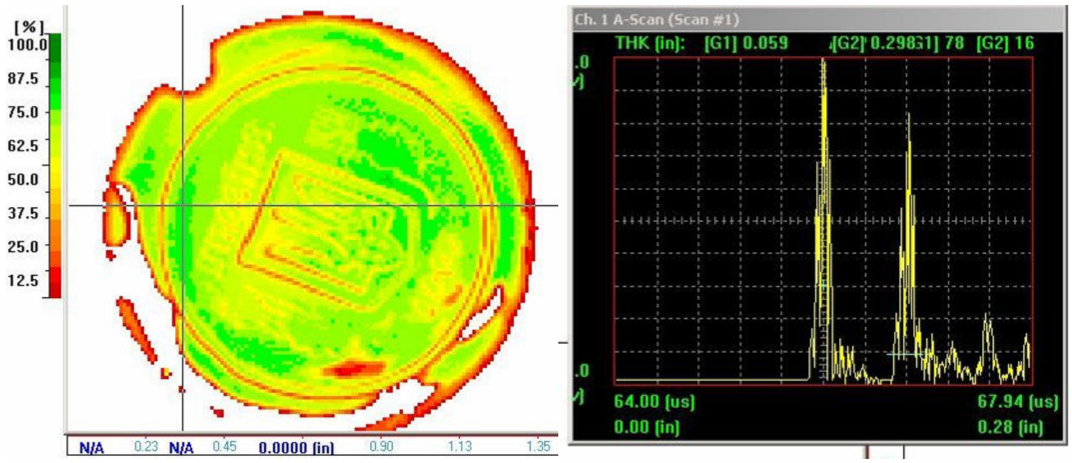

Figure 19. Ultrasonic verification of integrity of formed structure and metallurgical bonding of plates welded in experiment 12 (Table 1).

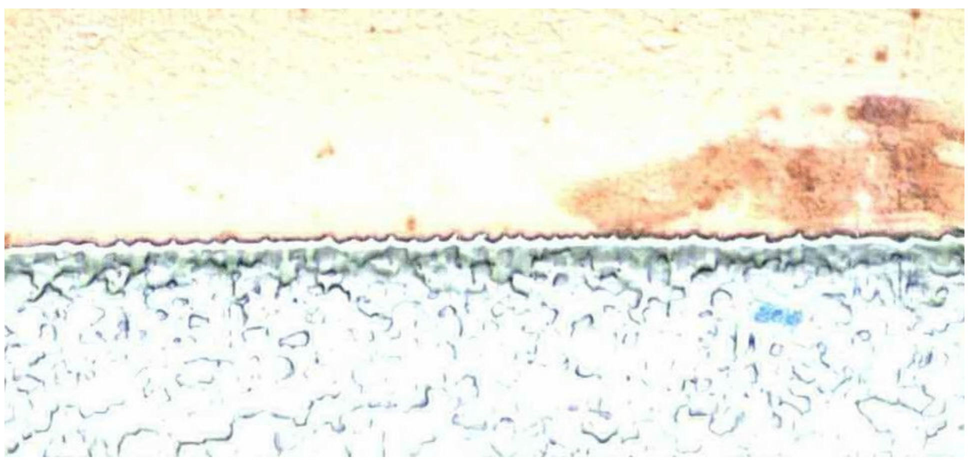

Figure 20. Copper and nickel-alloy plates welded by the water projectile impact at the water velocity 1500 m/sec. Micrograph of wavy interface of joined copper-nickel plates.

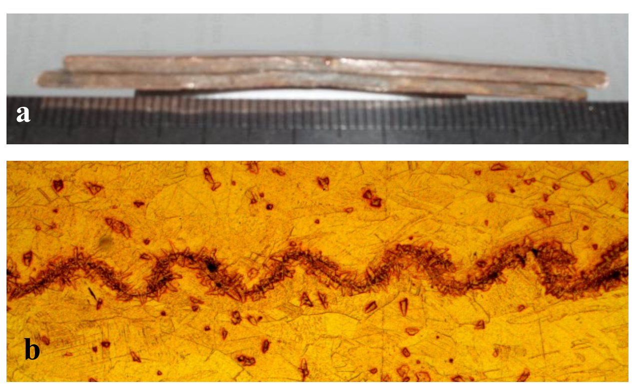

Figure 21. a) Copper plates welded by the water-projectile impact at the water velocity 1500 m/sec and h=3 mm. b) Zoomed-in section of micrograph of wavy interface of joined copper plates.

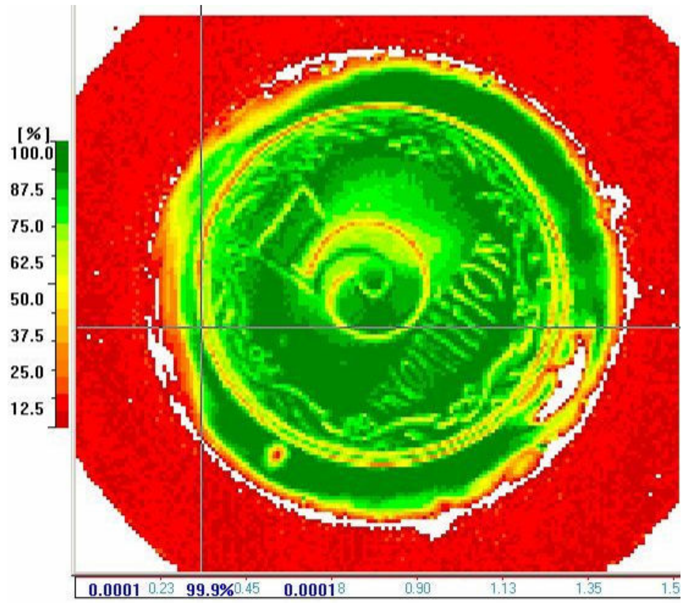

Figure 22. a) Ultrasonic scan of welded structure obtained in experiment 13 (Table 1.). Brass-coin-brass combination.

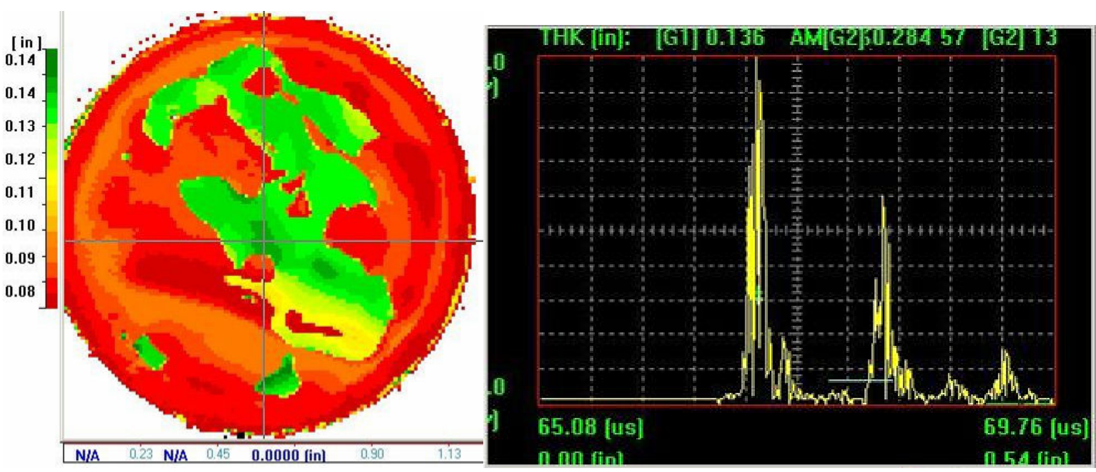

Figure 23. a) Ultrasonic verification of integrity of formed structure and metallurgical bonding of plates in exp. 44. (Ta