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Paper

INNOVATIVE JETBASED MATERIAL PROCESSING TECHNOLOGY

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The feasibility of material processing using high speed (1400- 1750 m/s) liquid impact was investigated. The demolition of the brittle materials and disintegration of the explosive devices was demonstrated during the previous study. The principal objective of these experiments was investigation of the impact based material forming. In the course of the performed experiments steel and aluminum samples supported by a die were impacted by the high speed liquid projectiles. The energy released in the course of the powder combustion was used for water acceleration. While the die geometry varied in a high range, the projectile properties at the exit of the water cannon (velocity, pressure, and diameter) were almost identical. It was shown that the material forming can be precisely controlled by the die geometry and the impact conditions. For example, the feasibility of the formation of various opening in steel works by the change of the die geometry was shown. Other experiments included material extrusion and forging. Particularly, the feasibility of the precision forming (coining) was demonstrated. The feasibility of improvement existing and development of entirely new manufacturing technologies using high speed liquid projectiles was demonstrated.

1. INTRODUCTION

Main objective of this study was to investigate the substrate deformation occurring during a liquid impact and to achieve better understanding of generation and utilization of high speed water projectiles. Several modifications of the waterjets have been adopted by industry. Continuous waterjets found wide applications in cleaning, cutting, transportation etc. The use of the pulsed streams instead of the continuous one 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 [1], and mining [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. Exploration of the potential applications of the liquid projectiles is objective of this study. The performed experimental study showed that high speed liquid projectiles are an effective material processing tool. Particularly, the objective of this study was to investigate the substrate deformation occurring during a liquid impact. The effect of the standoff distance and the target thickness on the workpiece deformation was investigated. Such processes as punching of circular and complex shape openings in steel plates, liquid impact based forming, stamping and coining as well as liquid projectile based solid state joining and cladding were explored. Experimental data acquired in the course of the performed experiments was incorporated into the knowledge base of the material processing by high speed water projectiles. As a result of the performed experiments feasibility of the use of high speed water projectiles for a number of material processing operations was demonstrated.

2. EXPERIMENTAL PROCEDURE

An experimental set for the study of the impact based forming was designed and constructed (Fig.1). With minor modifications this setup was used in all performed experiments. Laboratory scale prototypes of the water cannon [1, 2] were used in this study. The targets were mounted on a heavy pendulum (Fig.1). Angular displacement of pendulum was measured in each experiment. This enabled us to estimate impact impulse and therefore impact momentum. For each experiment water cannon was placed at a desired standoff distance from the sample and particular water impact operation was performed. Experimental data collected in the performed experiments was used for the study of material deformation and processing by high speed water projectiles.

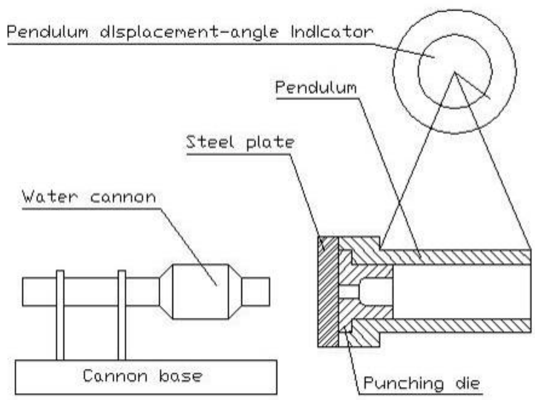


Figure 1. Schematic of the experimental setup. Notice that mounting of the target on a ballistic pendulum allows measuring the impact momentum.

3. EXPERIMENTAL INVESTIGATION OF PUNCHING OF STEEL PLATES

Three objectives were pursued in this study. First, the feasibility and limits (maximal plate thickness, minimal punched opening diameter and maximal punched opening diameter) of the operation were explored. Second, punching of complex shape opening in steel plates of various thicknesses was studied. The third objective was to investigate punching of multiple holes by a single water projectile impact. A close up schematic of the impact zone

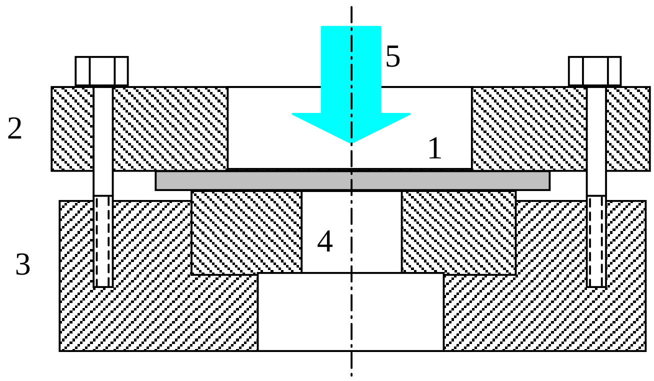


Figure 2. Sample-1, clamping plate-2, die holder-3, die-4, high speed liquid projectile-5.

subassembly is shown on Figure 2. In this investigation the exit diameter of the launcher was 15 mm.

A hot rolled carbon steel with 0.22% of the carbon content which has the tensile strength of 450 MPa, the yield strength of 320 MPa and the maximal elongation of 26% was used in the first series of the experiments. . Plates of 2.5, 4.2, 6, 8 and 10 mm thicknesses were tested. In each experiment the steel sample was tightly attached against the die and mounted on the pendulum. A water load of 200 g was propelled by combustion of 40 g of powder. The standoff distance was 16 cm in each experiment. Dies with round openings of 16.5 and 25 mm diameter were used in this part of investigation. Against both dies circular openings were created in plates of 2, 4, 6 and 8 mm. The opening of 25 mm in diameter was created in the 10 mm thick plate while the opening of 16.5 mm in diameter was not completed in the similar plate. In this case the deformation process on the impact side has been initiated and shearing cutting on the die side was started but not completed. Entering side of each opening has slightly rounded edges due to the flow of punched potion of material and exiting side of circular opening has sharp edge which was cut against the die. Calculated velocity of the projectile head prior to the impact was 1500 m/s.

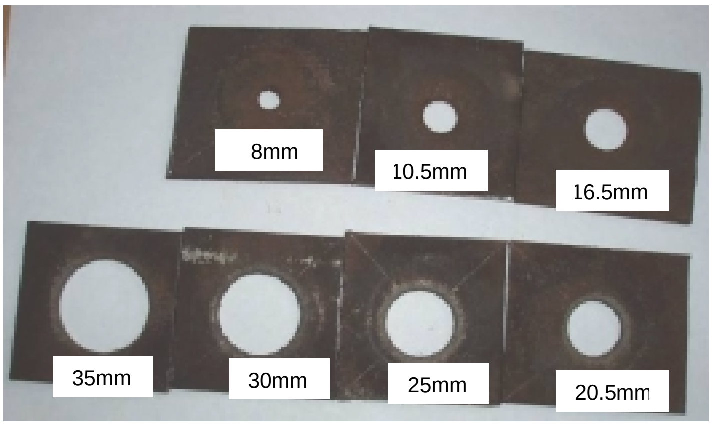


Figure 3. Piercing of 4mm steel plates. Notice feasibility of generating different openings using the same jet.

Another series of experiments involved evaluation of the maximal opening generated by the impacting jet. In these experiments the 4 mm thick steel plates were punched against dies with the openings of 4, 8, 10.5, 16.5, 20.5, 25, 35, 40, and 45 mm. The water projectiles of 200 g were propelled by 40 g of powder and at the standoff distance to the target of 16 cm. An array of clean cut openings was created against dies with: 4, 8, 10.5, 16.5, 20.5, 25, 30, and 35 mm diametric openings (Fig.3). The attempt to generate the opening of 40 mm failed. The sample was not pierced and it failed in petaling mode. Diametric opening of 45 mm was punched around ¾ of circumference and punched portion of the material was still holding on ¼ of circumference. In this part of investigation D/d=2.5 was reached and maximal thickness of h= 0.67d was punched. Here D is the opening diameter, mm; d is the projectile diameter, mm and h is the standoff distance.

In the performed experiments an array of various round openings was created at a single (15 mm) projectile diameter. This shows that a high speed water projectile is an effective punching tool. Thus, a novel material processing operation has been demonstrated.

4. EXPERIMENTAL STUDY OF COMPLEX SHAPE OPENING IN STEEL

The next series of the experiments involved investigation of punching of complex shape opening. Steel plates of various thicknesses were punched against dies of three different shapes. In the first series of experiments a die contained three overlapping circulars having the same diameter of 15 mm. The second die had the triangular equilateral opening with 20 mm side. Third, a die with multiple 4 mm diameter holes placed at 4 mm distance from each other, was used. Experiments with composite circle and triangular openings were performed with steel plates of thicknesses: 4, 6, 8, and 10 mm (Figures 4 and 5). In each test 200 g of water was used and a standoff distance was 16 cm. For punching of plates of 4 and 6 mm thickness 40 g of powder was used which was sufficient to punch the tested plates. For 8 mm thick plates it was necessary to use 45 g of powder in order to create the openings. For 10 mm thick plates 50 g of powder was used, however this charge was not sufficient to create an opening. With both dies material was extruded to slightly more than 50% of original thickness of the plate. For punching of multiple circular openings of 4 mm diameter 3.2 mm

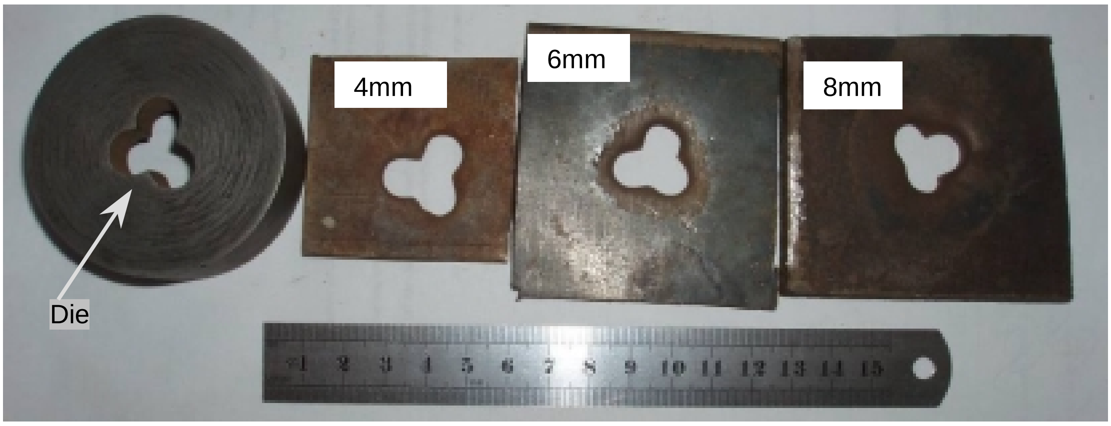


Figure 4. Formation of shaped openings using a round jet. Notice that the workpiece thickness does not affect the accuracy of the piercing.

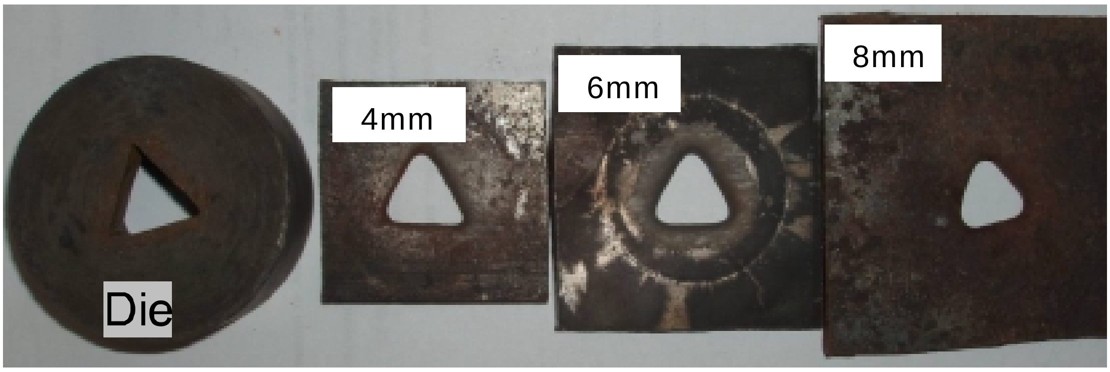


Figure 5. Formation of triangular openings using a round jet. Notice that the workpiece thickness does not affect the accuracy of the piercing.

thick steel plate was impacted by 200 g of water. Impact was carried at the standoff distance of 16 cm and the powder charge of 40 g. As a result, 8 openings were created in the central region of the impact zone and 37.5 mm round depression was forged by the impact (Fig.6). Repeatability of the results was demonstrated on the various samples

Figure 6. Formation of the multiple openings by a single impact of a round jet. Steel sheet thickness is 2.5 mm and the opening diameter is 4 mm. Notice that the liquid penetration into the workpiece can be controlled by the impact condition.

The performed experiments show that complex shape openings other than circular can be reproduced by the impact of the circular projectile. Feasibility of new technology introduced in previous part of this work was broaden by this study.

5. EXPERIMENTAL STUDY OF FORGING BY HIGH SPEED WATER PROJECTILES

The objective of this study was to demonstrate the potential of the application of liquid projectiles for forging and stamping. In the first series of experiment three dies of various surface geometries were designed and manufactured. Material of targets used for this part of the investigation included copper, an aluminum alloy and a high ductility steel. The steel sample has elongation 46%, tensile strength of 325 MPa, and yield strength of 195 MPa. Forming against shallow (Fig. 7) and medium depth dies was carried out. The launcher (water cannon) was loaded by 230 g water and 30 g powder. The standoff distance was 16 cm. Thickness of the steel samples used in this study was 2.5 mm.

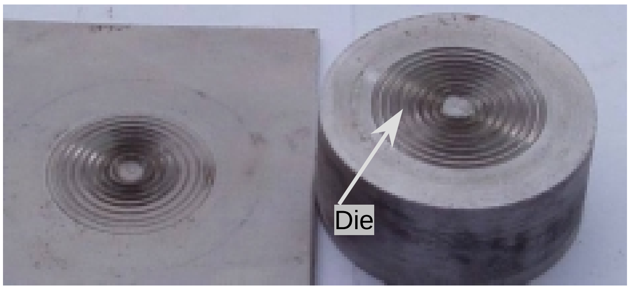


Figure 7. Concentric grooves (1mm deep, with 2 mm pitch and 90 degrees inclination) on a 2.5 mm thick steel plate formed by the impact of 200 g of water against the die. Notice the compliance of the die and the part geometry.

Figure 8. Formation of a 3D shape in the course of the liquid impact (h=2.5 mm, D=25 mm, max. depth 10 mm). Notice the compliance of geometries of the die and the generated part.

As a result of the impact a shallow die geometry having concentric grooves of 1 mm deep, 2 mm pitch and 90 degrees inclination (Fig.7) was precisely reproduced on the central portion of the surface of the steel target. The obtained results show that the impact pressure is inverse proportional to the distance of the impact center. While at the center of the target the geometry of generated grooves accurately reproduces the geometry of the die, as the distance from the center of the impact increases the compliance between the die and the workpiece reduces and reproducibility of the die image weakens. This experiment demonstrates that there is a zone in the vicinity of impact where precise reproduction of the shape of a die is possible.

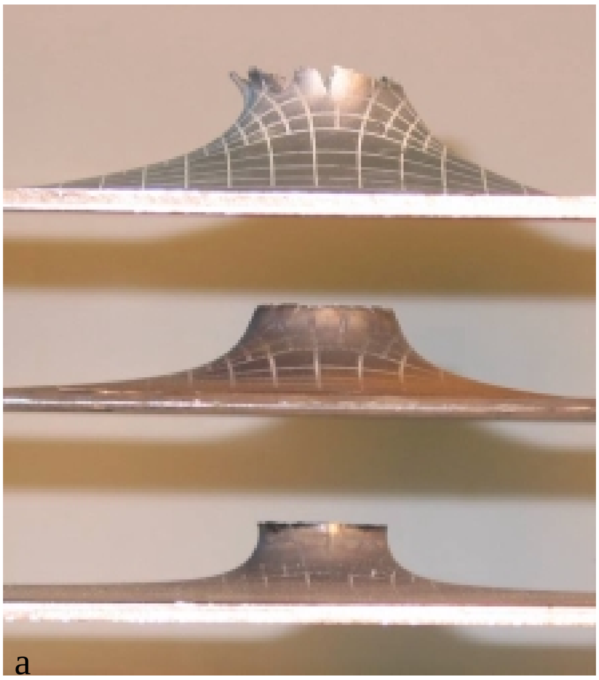
Another experiment involved the study of the deep forging (Fig. 8). The samples were impacted by 350 g of water which was propelled by 30 g of powder at the standoff distance of 16 cm. The calculated impact velocity was 700 m/s. This experiment showed that forming of deep and complex 3-D parts can be accomplished by the high speed liquid impact. The impact intensity can be controlled by sizing the powder and water loads as needed for a particular task. Changing the standoff distance is another way to control the impact effect. Consistency of forming operations was confirmed by repetition of this experiment. The stable output was obtained at each test. Again, the proposed material processing technique was validated.

Figure 9. Printing of a coin (24 mm diameter and 1mm thick) against 2 mm aluminum alloy (left) and 1 mm copper (right) sheets. Notice precision reproduction of the die geometry.

For investigation of fine forging and coining two kinds of dies were used. First, a die with fine concentric ridges 0.1 mm wide was manufactured and in the second experiment coins were used as dies for forging. In this investigation 350 g of water was propelled by 25 g of powder at a standoff distance of 16 cm. Investigation of fine forging was carried out by impacting the aluminum alloy plate against the die. As a result, fine ridges were precisely reproduced. The coins were printed on the copper samples as well with the fine accuracy under same experimental conditions (Fig. 9). Each test was repeated three times in order to confirm consistency of results. Extremely high hydrostatic pressure (1-10 GPa) developed in the impact zone increases metal plasticity during the deformation [3, 4]. This enables us to generate precision parts having the complex geometry. Thus, the high speed projectiles can be used for rapid prototyping and near net shape forming. In combination with welding facilities they can be used for solid state forming of heterogeneous structure. High plasticity of the metal will enable filling of fine cavities. Task of validation of water projectile impact based fine forging and coining was accomplished.

6. METAL PIERCING

The piercing of heavy steel and aluminum plates was investigated in order to investigate potential material deformation capability. For this experiment two different targets were exposed to the impact of ultra high speed water projectiles. First, a composite target made of combined three 4.8mm thick A36 hot rolled steel plates was used. This target was exposed to the impact of 230 grams high speed water projectile, which was propelled by combustion of 65 grams of rifle powder. The stand of distance was 2.5 cm. As a result, the composite target was successfully pierced (Fig 10). All three plates have a bottle neck type deformed section with an opening.



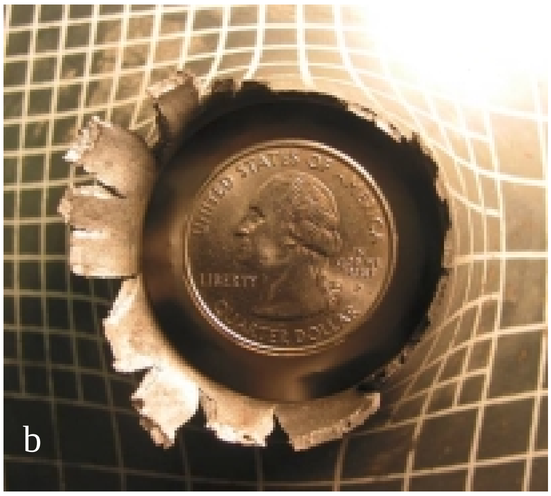


Figure 10. a)Side view of three 4.8 mm steel plates simultaneously pierced by 230g water projectile with 64.69g of riffle powder charge; b) Top view back plate.

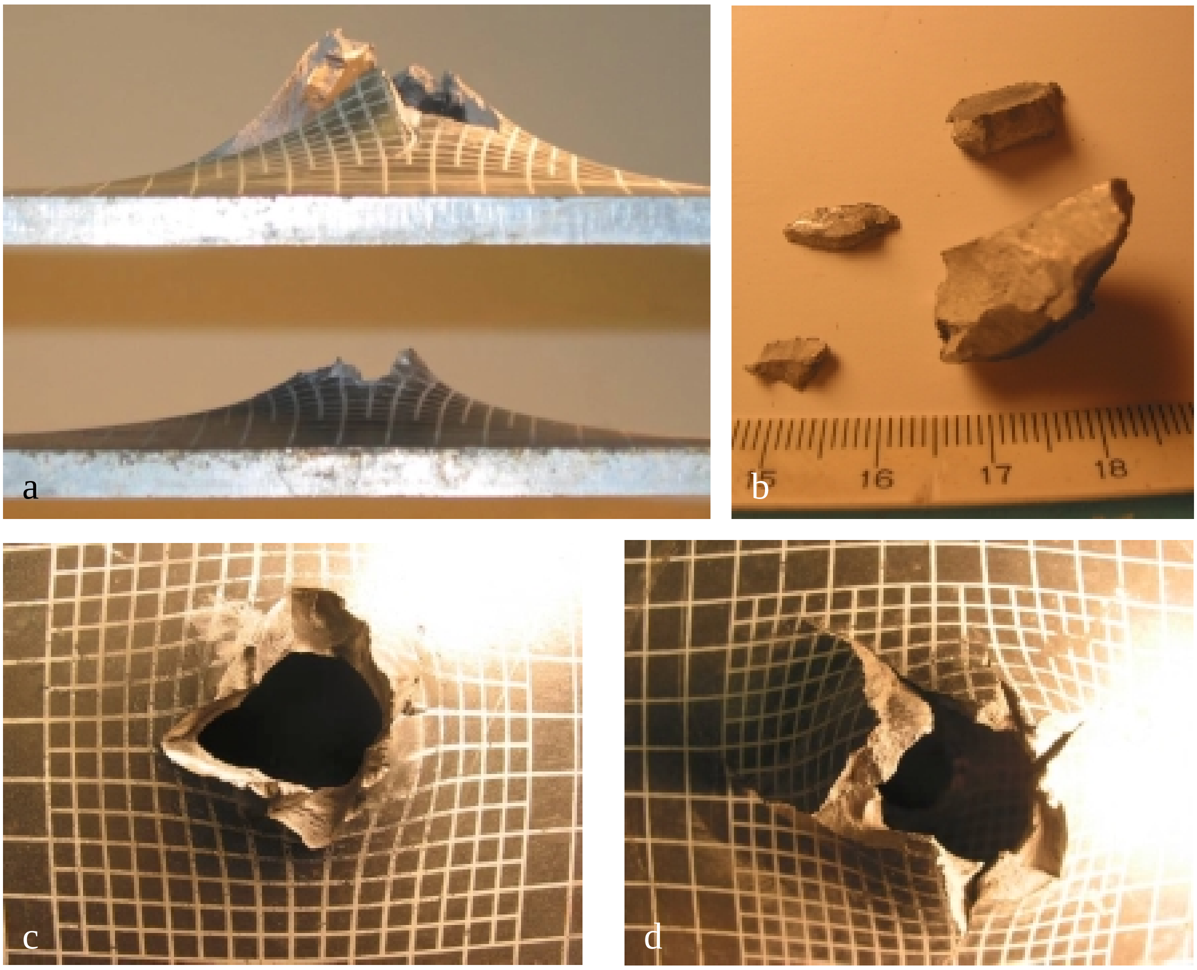


Figure 11. a) Two 9.9 mm thick Aluminum plates simultaneously pierced by 230g water-projectile with 57 g of riffle powder charge; b) Captured fragments; c) Top view of front plate; d) Top view of back plate.

In the second experiment the composite target was made of two combined 9.9 mm thick aluminum alloy plates. This target was exposed to the impact of 230 grams ultra high speed water projectile which was propelled by combustion of 57 grams of rifle powder. These plates failed in a manner similar to that of the steel plates and have a bottle neck type deformed area (Fig. 11).

As expected, the results of all performed experiments were that rather high energy ultra high speed water projectiles definitely constitutes an effective metal forming tool.

7. EXPERIMENTAL STUDY OF SOLID STATE JOINING BY IMPACT OF HIGH SPEED WATER PROJECTILES

Supersonic and hypersonic water projectiles provide comparable conditions at impact interface to those provided by detonation waves generated by explosives in explosive forming and welding. In order to apply this phenomenon for material processing solid state metal joining by impact of water projectile was investigated. First, two copper plates (each 1 mm thick) were separated by 1 mm thick coin and mounted as a composite target on the heavy pendulum. This target was impacted by 350 g of water which was propelled by burning of 25 g of powder at standoff distance of 16 cm. As a result all three items were joined to each other. By repetition of experiments consistency of operation was confirmed. Another experiment on joining was performed by impacting of the target composed of two 3 mm thick copper plates (Figure 12). Experimental conditions were identical to those for previous task. As a result plates were joined over interface boundary, shown on Fig.12. This interface exhibits the wave geometry typical to the explosion welding.

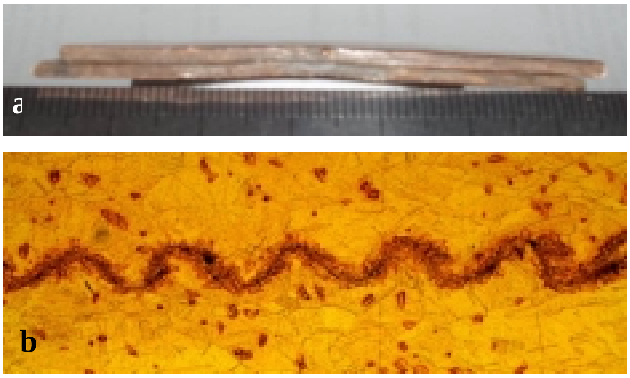


Figure 12. a) Copper plates joined by the water impact at the water velocity 1500 m/sec and h=3 mm. b) Micrograph of wavy interface of joined copper plates.

8. CONCLUSIONS

The performed experiments demonstrated feasibility of the use of water impact for metal punching, piercing, forming, stamping and joining. All of these operations were validated. A new lead for development of novel impact based technology was identified. Target deformation by the impacting projectile is due to the energy transfer from the water to the solid via the liquid-solid interface. However, in the course of deformation, the boundary position changes. Thus, modeling of the metal deformation involved simultaneous description of the motion of the liquid and solid and the position of the phase boundary. The equations representing these processes were obtained and the numerical procedure for process simulation was conceptually developed. Feasibility of development of novel manufacturing technologies was demonstrated.

9. ACKNOWLEDGEMENTS

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10. REFERENCES

[1] Atanov, G.A. (1987) "*Hydro-Impulsive Installations for Rocks Breaking*", Vishaia Shkola, (Russian), Kiev, USSR

[2] Atanov, G.A. (1977) "*Internal Ballistics of Hydro Cannon and Impulsive Water Extruder*", Donetsk State University (Russian), Donetsk, USSR

[3] P.W. Bridgman. (1951), "The Effect of Pressure on the Tensile Properties of Several Metals and Other Materials". *Journal of Applied Physics*, V 24, # 5. May, pp. 560-570.

[4] P.W. Bridgman, (1952)."*Studies in Large Plastic Flow and Fracture with Special Emphasis on the Effect of Hydrostatic Pressure*", McGraw-Hill