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Paper

INNOVATIVE LIQUID IMPACT BASED MATERIAL MICRO FORMING TECHNOLOGY

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ABSTRACT

The objective of this study was to investigate micro scale metals deformation in the course of a high-speed (>1500 m/s) water impact. An experimental setup for projectile fabrication was constructed and a series of experiments involving micron scale metal forming and extrusion was performed. The geometry and topography of the generated samples was investigated using advanced surface examination techniques and the feasibility of the liquid impact based microforming technology was demonstrated

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1. INTRODUCTION

A water projectile impacting a solid surface at the speed of 1000 m/s and more acts as an explosive, which detonates on the target's surface. Advantages of the impact based forming [6] as well as the explosive forming [7-9] are well understood and documented. In a number of applications, however, the use of an explosive is difficult if not impossible. In this case the high-speed liquid projectiles can be used as a forming or welding tool. Previous research showed the feasibility of the application of the liquid impact to metal forging, stamping, coining and extrusion [10, 11]. The most promising application of the liquid projectile, however, is mass production of MEMS parts. The proposed technology involves impacting a workpiece supported by a die by a high-speed (1000-1750 m/s) water projectile (an impulsive jet) [1-5]. The projectiles are generated by a launcher (a water cannon), which constitutes a modified gun, loaded by a round where a solid slug is replaced by a container with a liquid, e.g. water (Fig.1). The powder explosion accelerates water and at the end of the barrel the water speed is comparable with that of the solid projectile. The further acceleration occurs in a nozzle attached to the barrel. This enables us to increase significantly the water speed. In the previous experiments, a water velocity of 1750 m/s was achieved. Computations show that it is possible to achieve water speed as high as 3-4 km/s. At the speed of 1500 m/s the pressure exerted on a target at the impact zone is in an order of 1 GPa. At such a pressure a metal target impacted by the liquid projectile acquires a shape of the supporting die. Thus the liquid impact can be used for metal forming and the high speed liquid projectile can replace a punch.

The previous research demonstrated the feasibility of the use of high speed projectiles as a punch in conventional metal forming operations. The objective of this study is to expand the range of the application of the liquid impact to micro forming operations. The performed study involved micro- stamping and extrusion of various metals. The feasibility to generate a desired micro scale deformation of a target material using the liquid impact was demonstrated by the performed experiments.

2. EXISTING MICRO FORMING TECHNOLOGIES

Research in micro and meso manufacturing area is being conducted by a team lead by Kuniaki Dohda [12] , Gifu University, Japan. Micro pressing technology has been developed. This technology involved formation of the ultra fine holes in aluminum samples using 15 μ SiC fibers as a punch. Micro forging was used to die forge micro parts out of amorphous alloy. Micro extrusion of aluminum alloys was investigated as well. A single process system was designed and used for each application (micro press, micro extruder). Development of a system which could be used for more than a single micro forming application and which would have higher efficiency was addressed by a group of Hye-Jin Lee of Korean Institute of Industrial Technology, Korea [13]. Study of forming of the sub millimeter metal parts is currently being carried out in the Friedrich-Alexander University, Germany [14]. A Group Mass-micro of Dr. Jiangho Lin, (U of B), is currently working on the development of technologies of mass production of micro parts. [15]. While the teams above are involved in one or another miniaturization of forming facilities, the objective of the proposed study is modification of the mode of the generation of the stress field in a target.

The study involved filling cavities by a target material and stamping a die shape on the target surface. The filling of the semi closed cavities (groves on the workpiece surface) and metal extrusion into open micron scale slots was examined. Stamping using simple (cylindrical wires) and complex (a coin) dies was also investigated. Targets were fabricated from copper, brass, aluminum and steel. In one of the performed experiments extrusion of an alloy used for fabrication of Ukrainian coins was studied.

3. EXPERIMENTAL TECHNIQUE

An experimental setup (Fig.2), for the study of the liquid impact based forming was designed and constructed. In this setup samples to be processed were mounted on a heavy ballistic pendulum which was displaced by the water impact. The angular displacement of pendulum was measured in each experiment and the projectile impulse and momentum were calculated by the use of the measured pendulum displacement. During an experiment the water cannon was placed at a desired distance from a sample which then was impacted at selected conditions. In the course of the impact the target acquired a shape of a supporting die. The principal challenge in the die fabrication was formation of the micron scale cavities using conventional machining facilities (lathe, milling machine, etc.) During each experiment the values of water mass, powder mass, standoff distance and pendulum displacement were measured and the acquired data was incorporated into a global matrix of the investigation. Upon completion of an experiment generated samples were examined visually and then sample characterization, involving scanning electron microscopy, infinite focus microscopy, optical microscopy, 3-D digital microscopy, 3-D digital profiler, was carried out.

An exit diameter of the nozzle utilized in the performed experiments was 15 mm, the diameter of barrel was 20 mm and the total length of the launcher was 80 cm. Amount of water used for the projectile formation ranged between 30 g and 350 g. Water was propelled by the products of the combustion of 30 g powder. The standoff distance was 16 cm in all experiments. Calculated outflow velocity of the projectile head ranged between 850 m/s and 1566 m/s. Calculated maximal pressure inside the nozzle ranged from 341 MPa and 843 MPa. At these conditions the pressure excerted on the workpiece varied from 0.35 GPa to 1.2 Gpa.

4. MICRON SCALE FORMING

The objective of the performed experiments was to form micro channels on the surface of different metals. During the tests individual micro channels and micro channel’s networks were formed on the surface of cooper, brass and steel samples. High ductility steel having 46% elongation, tensile strength of 325 MPa, and yield strength of 195 MPa was utilized in this study. A tungsten wire was used as a die. The wire diameters were 7 μ and 40 μ. In each experiment the wire was attached by glue to a polished surface of a metal sample in order to form a desired network. Samples were mounted on a heavy pendulum with the wire side facing the pendulum. Water projectiles impacted opposite side of the sample and as a result much harder wires were driven into softer materials of samples creating a desired network of micro channels. In the course of experiments 230 g of water were propelled by 30 g of a gun powder at a standoff distance of 16 cm.

Geometry of the generated micro channels was examined by optical microscopy, infinite focus microscopy, scanning electron microscopy, 3-D digital microscope and surface profiler. Scanning electron microscope was used to investigate surfaces of formed micro channels.

Intersection of two micro channels formed by 7 μ diameter tungsten wire on brass sample is depicted on Fig.3. Examination showed that formed channels are approximately 8 μ wide. A view and dimensions of 7 μ diameter tungsten wire imbedded into brass sample are shown on Fig.4.

Infinite focus microscopy was used to perform topography, profile, waviness and roughness analyses. Intersection of two micro channels formed on brass by 40 μ diameter tungsten wire is shown on Fig.5.

Three dimensional microscope was also used for examination of the formed micro channels (Figs.6 and 7). Generated 3-D images of channels were further used for profile analysis and the results complied with previously conducted infinite focus microscopy analysis. A 3-D image of a section of the micro channel formed on the brass sample by 40 μ diameter tungsten wire is shown on Fig.6 and a 3-D image of an intersection of micro channels formed on the brass sample by 40 μ diameter tungsten wire is shown on Fig.7. Extensive examination of formed micro channels confirmed geometrical reproducibility and the exceptional surface quality.

Profile analysis performed by the infinite focus microscopy revealed steady geometry of the formed channels. An example of the channel profile (Fig.8) indicates that both the depth and the width of formed channels are approximately 40 μ. Curvature of the 7 μ wire has better imprint on all of tested materials. This is demonstrated by two profiles which have depth and width in the range of wire diameter. At the same time the curvature of the generated channel is completely determined by the geometry of the wire (Fig.9). Profile of same section of the channel is also shown on Fig.10.

Additional analysis of the profile and roughness of channels was conducted by a table version white light non contact three dimensional optical profiler. This instrument was used to scan surfaces with embedded micro-channels. This analysis yielded results compatible to those obtained by the infinite focus microscopy. This confirmed consistency of the forming

An example of profile of two adjacent channels (40 μ and 7 μ wide) is shown on Fig.11 while an example of the surface roughness measured on the bottom of the 40 μ wide channel is depicted on Fig.12. As it is shown by this figure the surface roughness did not exceed 0.002 μ.

In the course of the surface, study by the 3-D profiler three dimensional images of sections of the micro channels were reproduced and compliance between the die and the work piece geometries was demonstrated for all three tested materials. The roughness, waviness and profile analyses yielded satisfactory results.

As it is shown on Fig.13 the brass surface contains a rectangular network of channels which is bordered by two intersecting 40 μ wide channels (Fig. a). The thin lined rectangle represents 7 μ wide channel network. Figure .13 a) is accompanied by a color bar which depicts a range of the depth of the formed channels. Figure 13 a) also demonstrates that a channel section shown on this figure has a depth of approximately 40 μ along the all length of the wider channels. The 3-D view of the same part the network (Fig. 13b) provides more details about the channels geometry. Particularly comparative depth of two channels is illustrated.

The zoomed views of the 40 μ channels intersection (Fig.14) depict fine details of channel's features. Particularly it is shown that the edges of the channels have round segments. The straight walls and the bottom of the channels are clearly shown on the 3-D image.

Roughness of the channel's surfaces was analyzed by the profiler, the infinitive focus microscopy and the 3-D digital microscope. All three techniques yielded almost similar results. For example the average roughness of 1.2 mm long segment of 40 μ wide channel was 1.6 μ (Fig.15 a), and the average roughness of 530 μ long segment of 6 μ wide channel (Fig.15 b) was 2.53 μ .

5. MICRON SCALE EXTRUSION

The objective of this study was to investigate extrusion of metals by filling a space between cylindrical and plane walls. The distance between the walls ranged from 10 to 50 microns, while the wall width was in order of several centimeters and the height was in order of several millimeters. Thus, process involves filling a semi-infinite micron scale gap by an impacted metal. Copper, brass and high ductility steel samples were used. Also, some of the samples were made from an alloy used for fabrication of Ukrainian coins. Two types of dies were designed and manufactured. The first kind of dies entails 2 concentric rings and a solid cylinder. The heights of the rings and the cylinder were almost precisely equal. In the course of the die assembly the cylinder was tightly fitted into a cylindrical ring of the precisely same height. Then the obtained assembly was tightly fitted into another ring also having the same height (Fig.16). The rings and the cylinder were fabricated so that in the course of the assembly micron scale gaps were formed between the cylindrical surfaces on the forefront base of the cylindrical assembly. The base of the constructed die was placed against a target. By exposing a target to the water projectile impact, a target material was being extruded into the gap between the cylindrical surfaces creating rings (Fig.16). While the thickness of the rings was in order of microns, the height and the diameter were in order of millimeters. Thus micro extrusion with comparatively high extrusion ratio was accomplished.

Maximal extrusion ratio of 130 was achieved in a section of a cooper ring, and maximal extrusion ratio of 100 was obtained in a small section of the brass ring (Fig.17). A segment of the extruded ring reproduced by the infinite focus microscopy is shown on the Fig.18. A selected profile of the same segment has 1500 microns height and approximately 150 microns thickness (Fig.19). The extrusion ratio 10 observed in this case was substantially lower than the average one. Infinite focus microscopy was used to evaluate waviness and roughness of selected samples (Figs 20, and 21).

As it is shown on Figs 17-19 brass extruded at comparatively high extrusion ratio forms rings having almost straight wall and almost plane surface. The surface topography was also adequate. According to Fig. 20 the roughness of a sample was less than 1 μ while the waviness was approximately 10 μ (Fig.21). The performed profile and roughness analyses demonstrated that the extruded rings had stable micro geometry. A segment of the extruded copper ring reproduced by the infinite focus microscopy is shown on Fig.22. A selected transversal cross section of the segment (a foil profile) is 250 μ high and 50 μ thick

(Fig.23). A segment of the extruded steel ring is shown on the Fig.24 and a selected profile form the segment 400 μ high and 90 μ thick (Fig.25).

The second die was used for the study of the formation of plain foils having the micron scale thickness. In order to fabricate a die the calibration strips (15 and 25 microns thick) were placed between 1 cm thick tool-steel slabs. This die assembly had 6 mm deep gaps which were 15, and 25 microns wide. The die was fastened by a plane support. A high strength alloy used for fabrication of the Ukrainian coins was used as a target. The target materials were extruded into the gaps (Fig.26) and the extrusion ratio between 100 and 200 was attained in the course of these experiments.

6. DISCUSSION OF RESULTS

The liquid impact based forming has unique technological advantages. For example, similarly to the explosive forming, 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. Contactless mode of the launcher-work piece interaction, ability of a liquid projectile to adjust to any geometry of a die, simplicity of process control assures the flexibility of the impact based micro forming. While the previous research [9] showed effectiveness of the application of high speed liquid impact to conventional forming operation, this study demonstrated feasibility to extend this application to micro forming.

In the course of the performed study totally 12 testing of extrusion into closed cavities, 12 testing of extrusion into open slots, 8 testing of micron scale stamping and 11 tests of micron scale forming were carried out. All of these tests involved deformation of various metals including steel and a special alloy at an extremely high rate determined by the speed of the water projectiles. The tests included formation of rather complex patterns such as networks of the micro scale channels 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. Even at these conditions only 2 tests did not result in completion of the selected forming operation. In the rest of 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 the development of manufacturing technology will involve mass production of the precision low cost micron scale parts out of various engineering materials or formation of the micron scale pattern of the surfaces of regular parts. The performed experiments demonstrate feasibility of the use of high speed projectiles for fabrication of micro scale parts. It was shown that liquid impact driven micro forming has a potential of becoming technology of choice for micro parts fabrication. Indeed, the feasibility to generate micro scale (down to 6 microns) parts with an adequate surface topography was demonstrated. The facilities are comparatively simple and process productivity is determined by the firing rate of the launcher. For simplicity sake in the performed experiments a powder was used as an energy source. It is expected that in a manufacturing environment the chemical energy of a powder will be replaced by electrical or magnetic energy. In this case the firing rate can be as high as 1 kHz. Then it can be expected the speed of the projectiles to be increased up to 2-3 km/s and the accuracy and the strength of the dies will be significantly enhanced. This will enable us to generate more complicated and more accurate parts.

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

7. CONCLUSIONS

It was shown that forming of micro scale can be accomplished by high speed water projectiles. Original concept of micro machining process is validated. It was shown that micro forming can be accomplished by a single water projectile impact. It was shown that it is possible to generate a single micro object as well as an assembly of such objects, e.g. a network of micro channels. The obtained extrusion ratio shows feasibility to fabricate micron scale foils. Since commercial low cost metals were used in this study it can be suggested that the use of super-plastic materials would yield parts having grain scale dimensions. The performed experiments show that liquid projectiles have a potential of becoming a competitive micro forming tool.

8. ACKNOWLEDGEMENTS

The support of NSF (Award DMI-9900247) and CRDF (UE2-2441-DO-02 Q2) in performing of this study is acknowledged. The state of the art instrumentation techniques was provided by EXCEL Technologies, Enfield, CT 06083; Hitachi High Technologies America, Inc, Gaithersburg, MD 20878; Micro Photonics Inc. Irvine, CA 92618;ADE Phase Shift, Tuscon, AZ85706.

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10. FIGURES

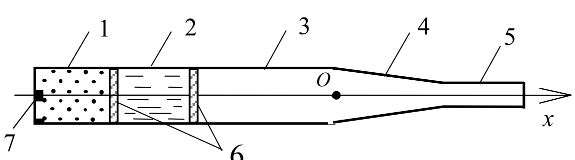

Figure 1. Schematic of Water Cannon. 1-powder charge, 2-water load (projectile), 3-barrel, 4-nozzle, 5-cylindrical attachment (collimator), 6-partitions, 7-primer.

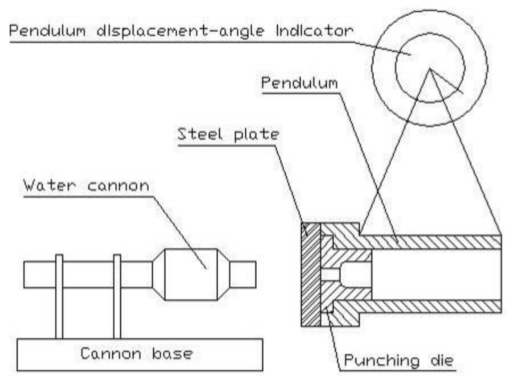

Figure 2. Schematic of the experimental setup. Notice that mounting of the target on a ballistic pendulum allows measuring the impact momentum.

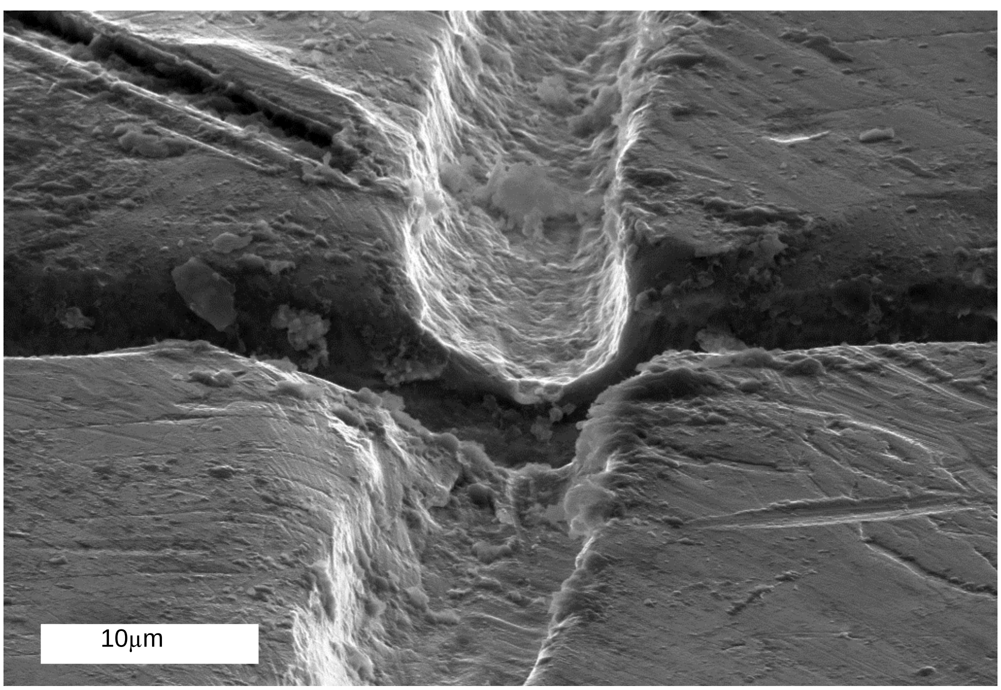

Figure 3. Intersection of two micro channels formed on the brass surface by 7 μ diameter tungsten wire.

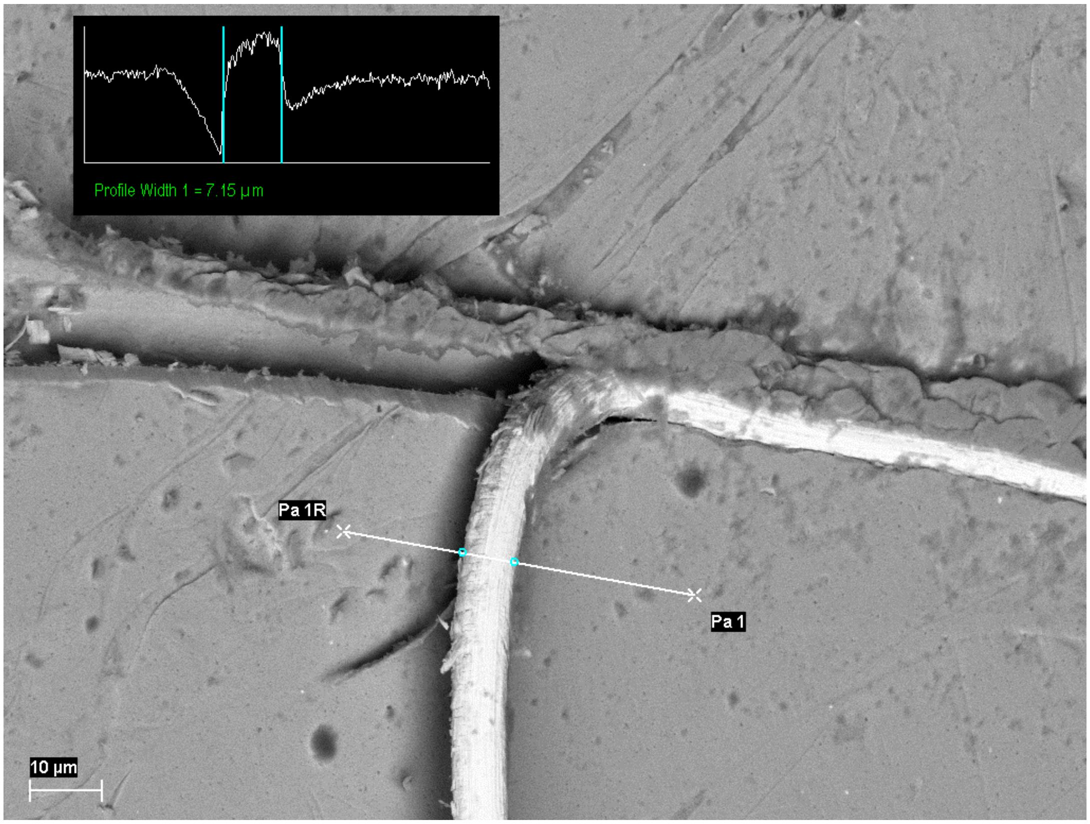

Figure 4. A view of the 7 μ tungsten wire embedded into brass surface generated by SEM.

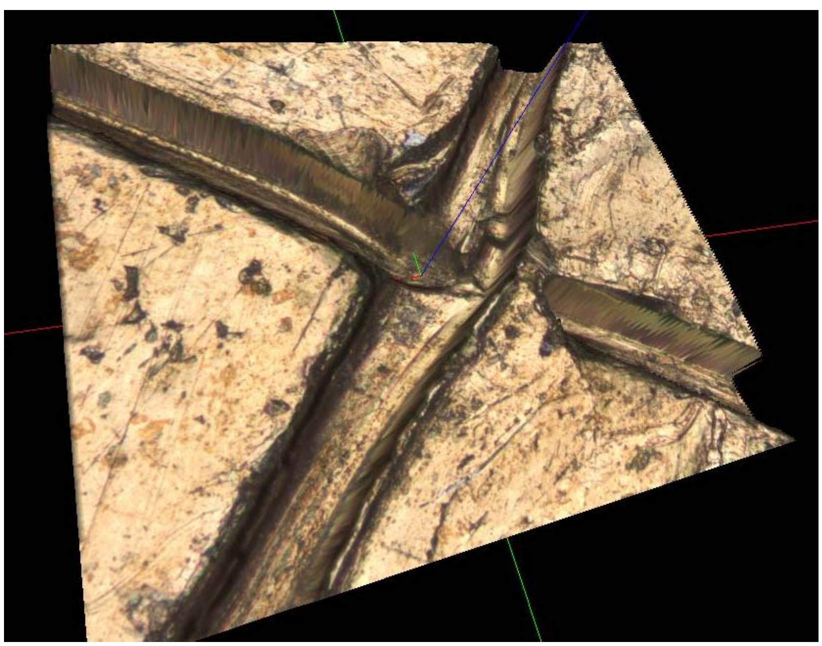

Figure 5. Intersection of two micro channels formed on a brass sample by 40 μ diameter tungsten wires.

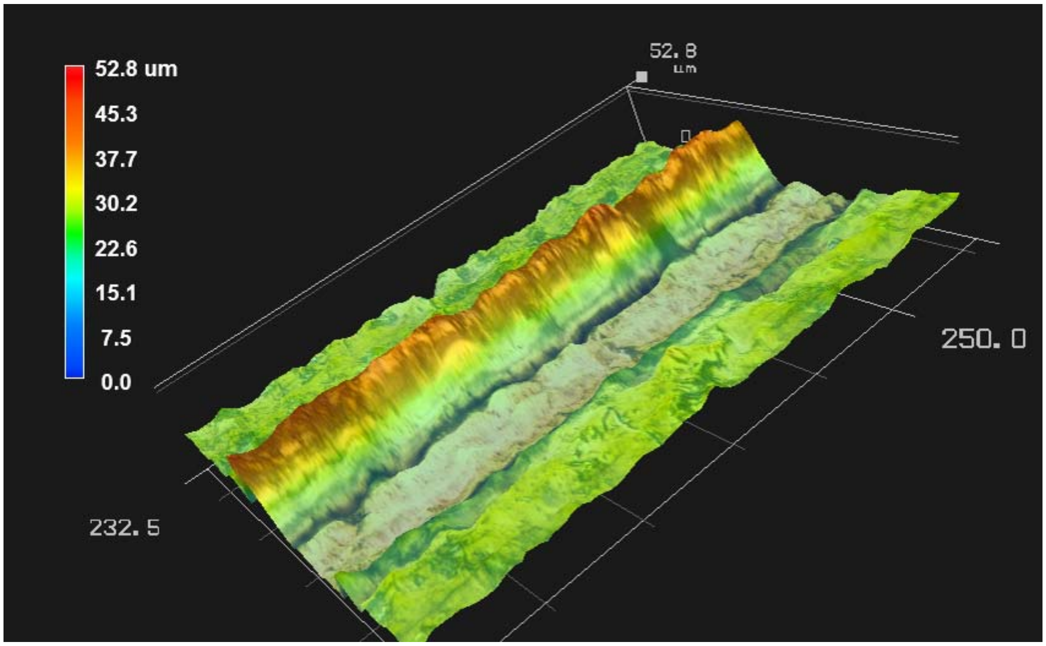

Figure 6. A 3D image of a section of the micro channel formed on a brass surface by 40 μ diameter tungsten wire; the image is generated by the 3-D digital microscope.

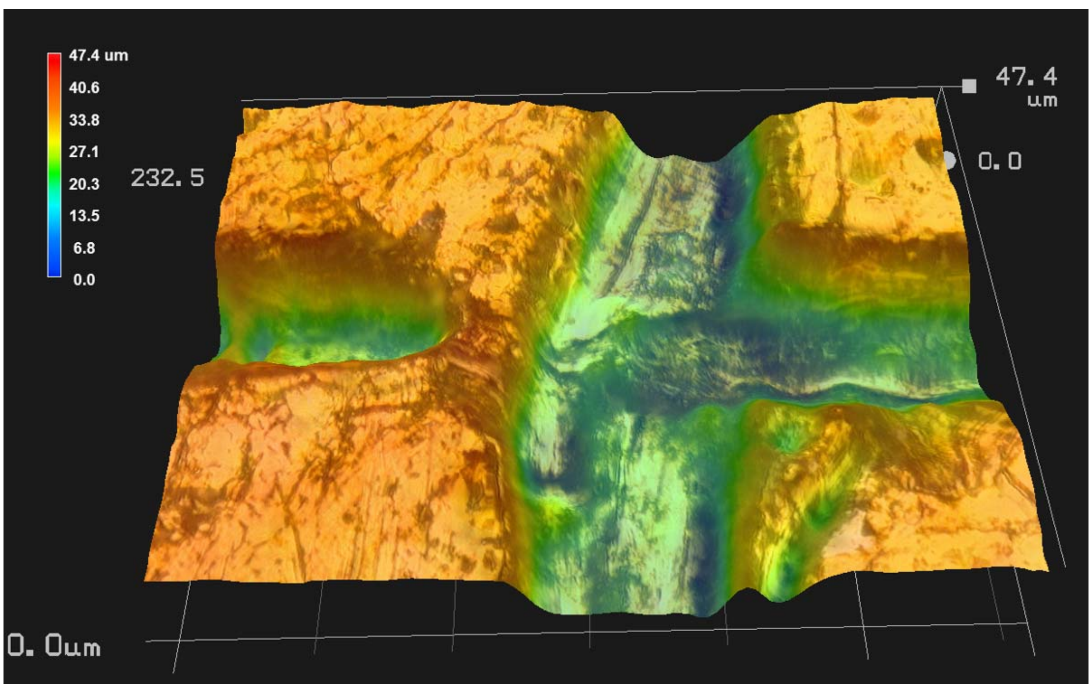

Figure 7. A 3D image of an intersection of the micro channels formed on a brass surface by 40 μ diameter tungsten wire; the image is generated by the 3-D digital microscope.

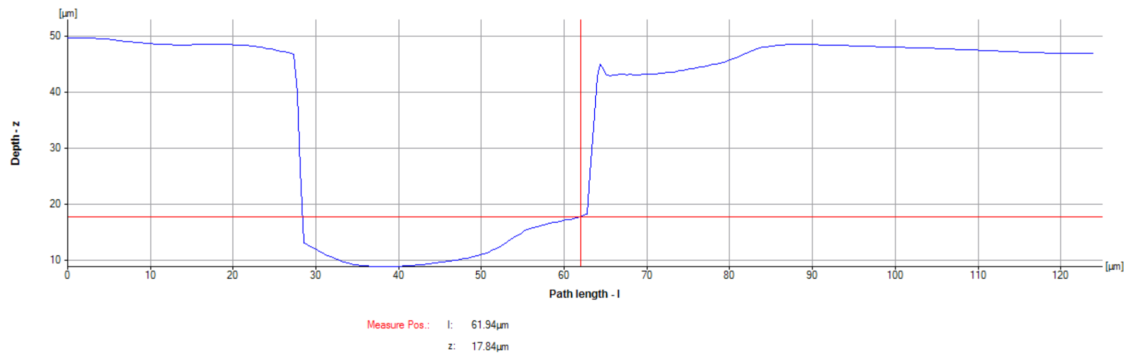

Figure 8. A profile of the channel formed on a brass sample by the 40 μ wire. Notice that the depth and width of the channel are approximately equal to the wire diameter.

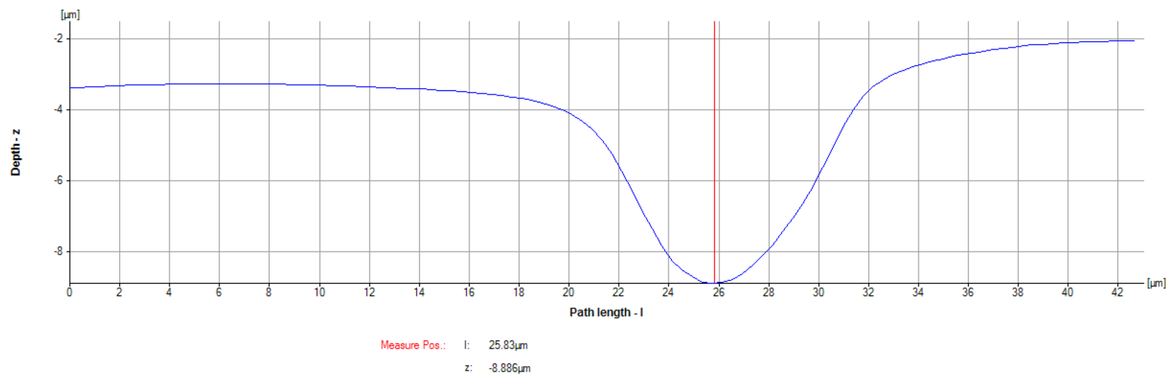

Figure 9. Profile of the channel formed by a 7 μ diameter wire. Notice the compliance between profile of the channel and the die.

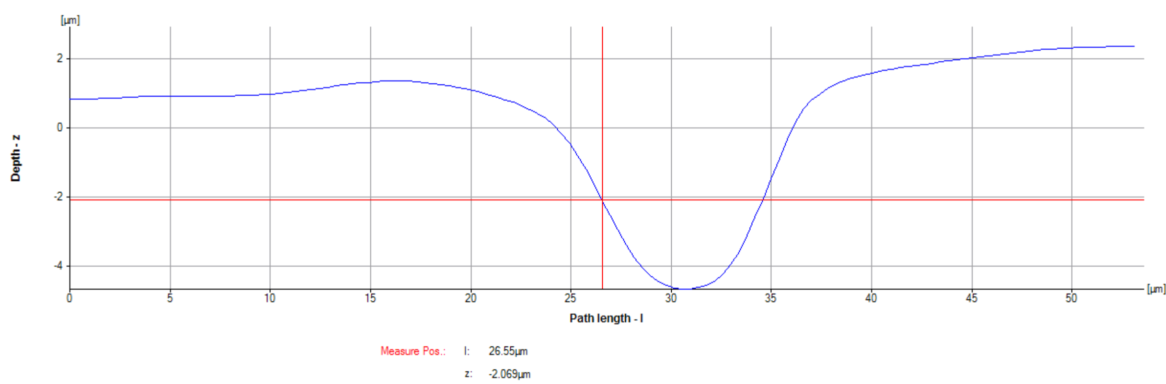

Figure10. Profile of the channel formed by 7 μ diameter wire. Notice the compliance between profile of the channel and the die and almost identity of profiles Figs.23 and 24.

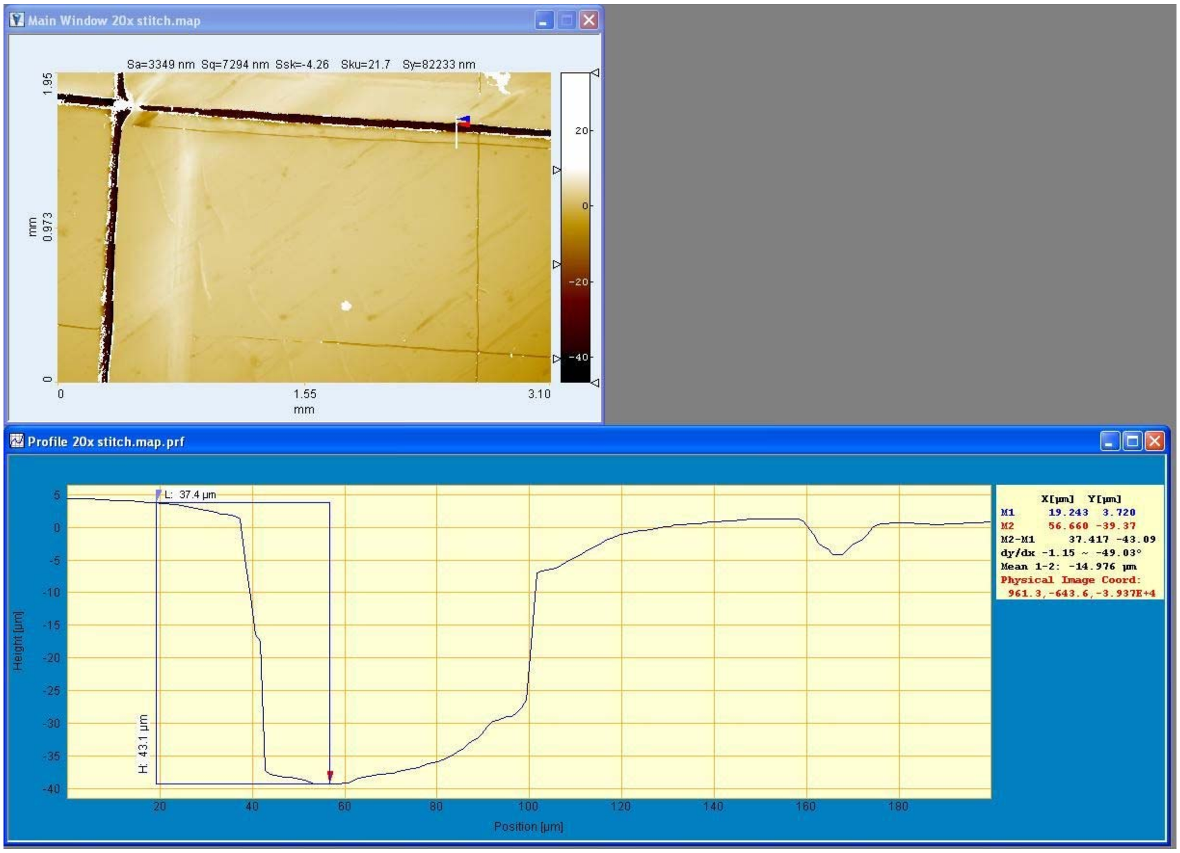

Figure 11. Profiles of two adjacent channels 40 μ and 7 μ wide.

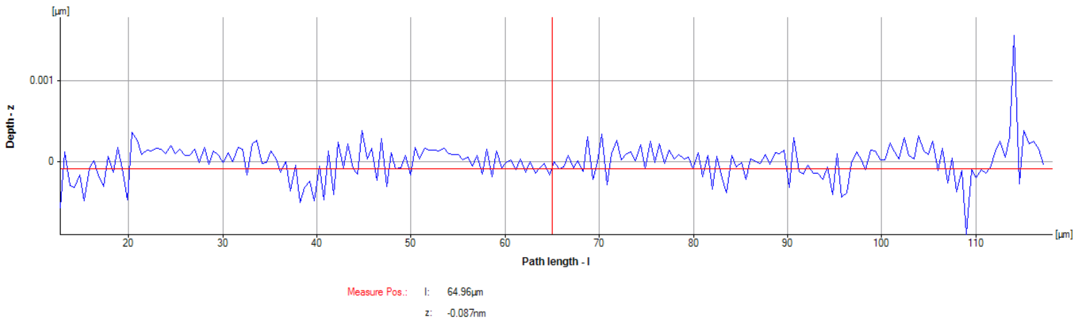

Figure 12. Surface roughness of a channel formed by the 40 μ wide wire.

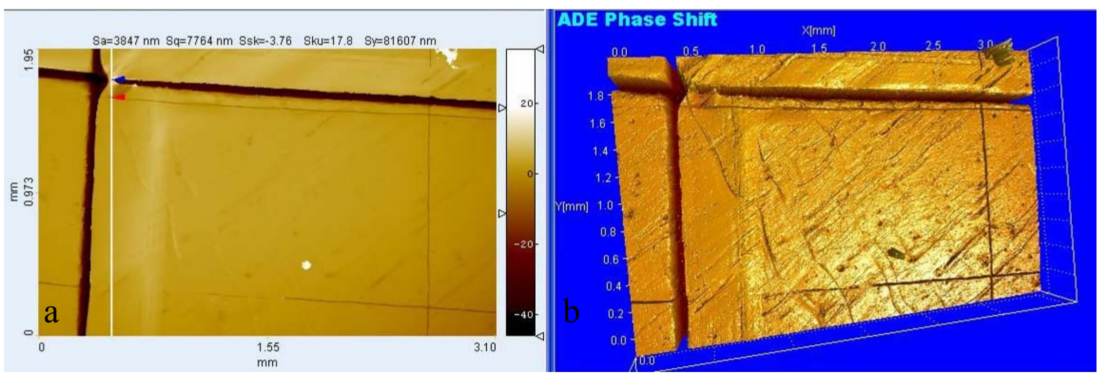

Figure 13. A channel network on the surface of the brass sample, a) 2-D image, b) 3-D image, 20x.

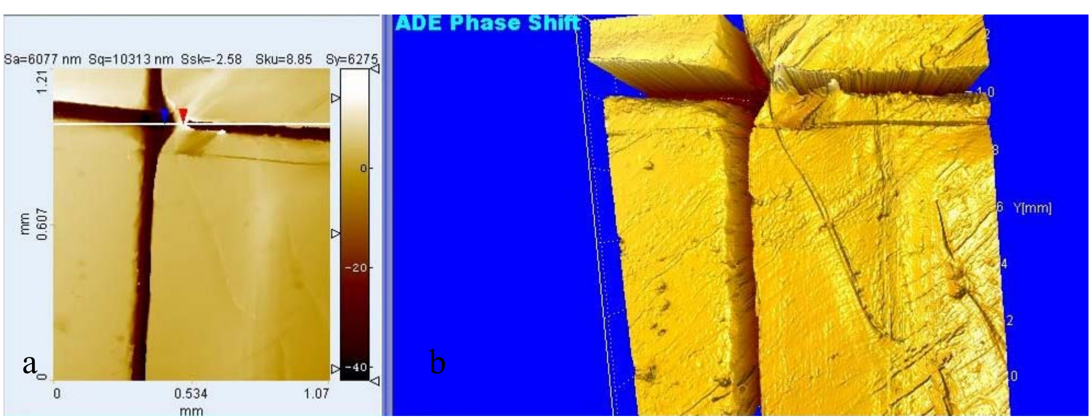

Figure 14. Zoomed in view of the portion of channel network shown on Fig. 27, a) 2-D image, b) 3-D image,20x. Notice rectangular shape of the channel.

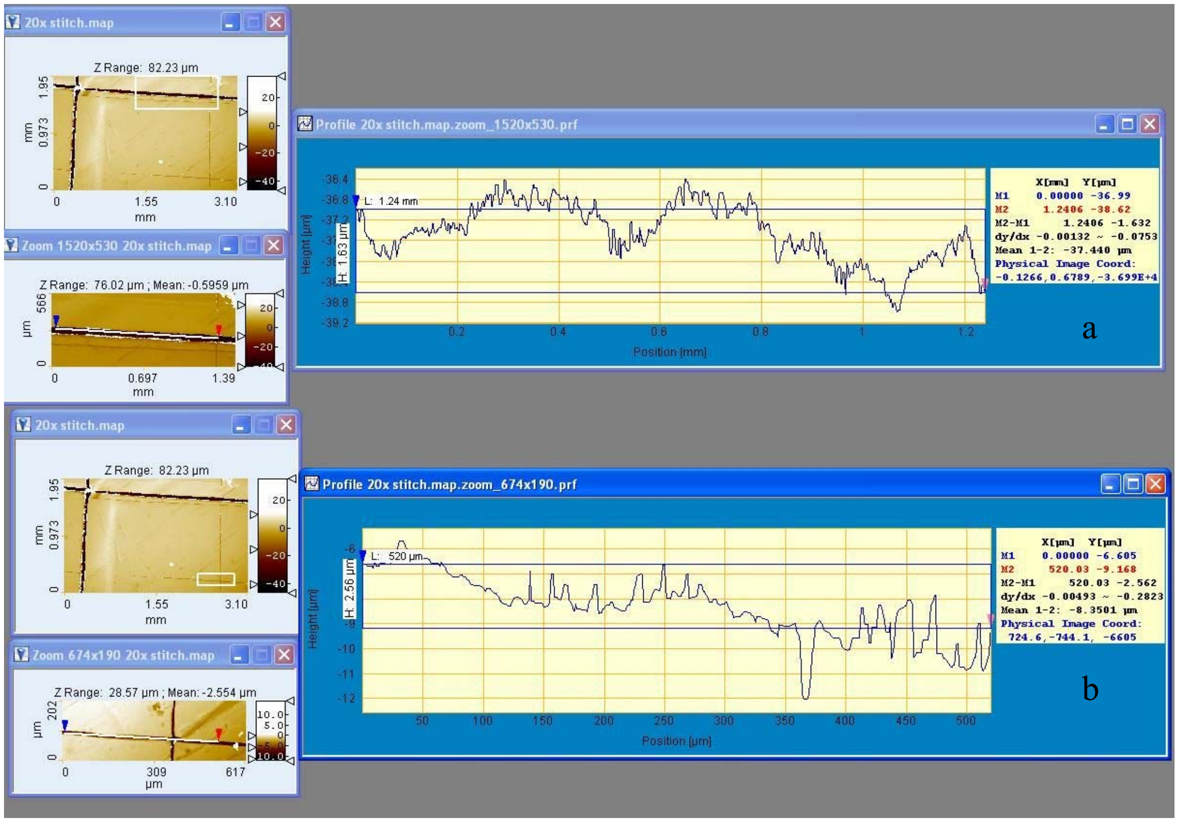

Figure 15. Average roughness of selected segments of channels,
a) average roughness of 1.2 mm long segment of 40 μ wide channel was 1.6 μ ,
b) average roughness of 530 μ long segment of 6 μ wide channel was 2.53 μ

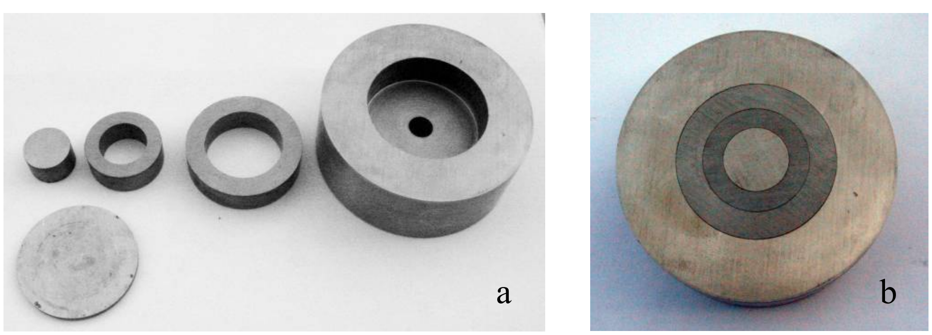

Figure 16. A die for ring formation: a) disassembled, b) assembled.

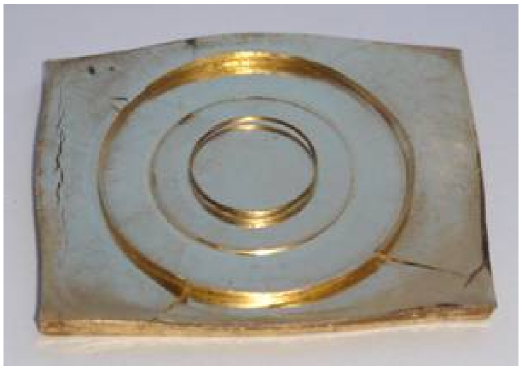

Figure 17. Extruded circular brass rings.

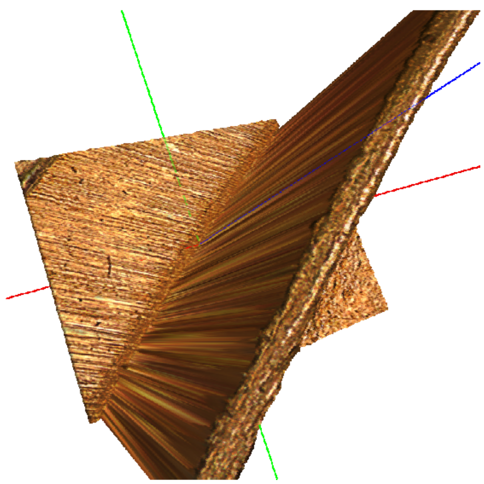

Figure 18. 3-D image of a section of the extruded brass ring, the section is 1500 μ high, 150 μ thick.

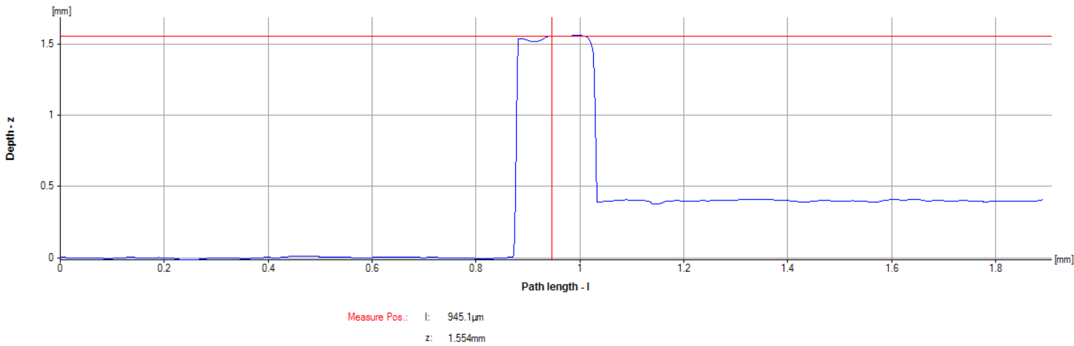

Figure 19. Profile of a section of the extruded brass ring, the section is 1500 μ high, 150 μ thick.

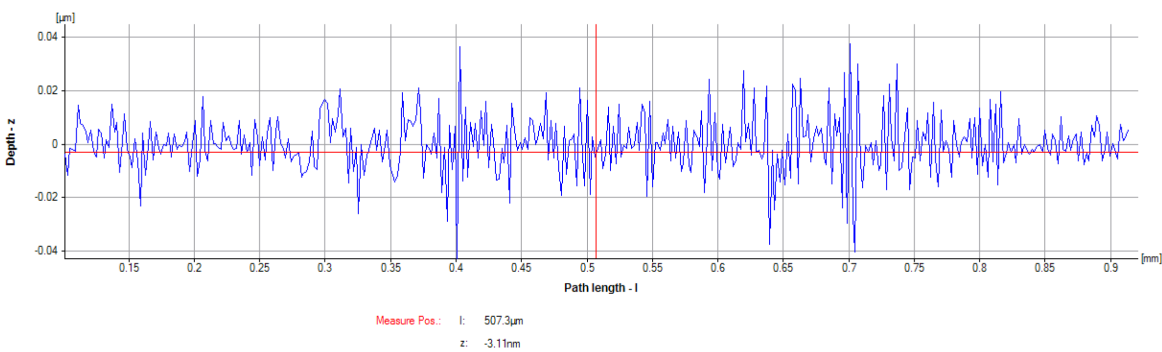

Figure 20. Roughness of a section of the extruded brass ring.

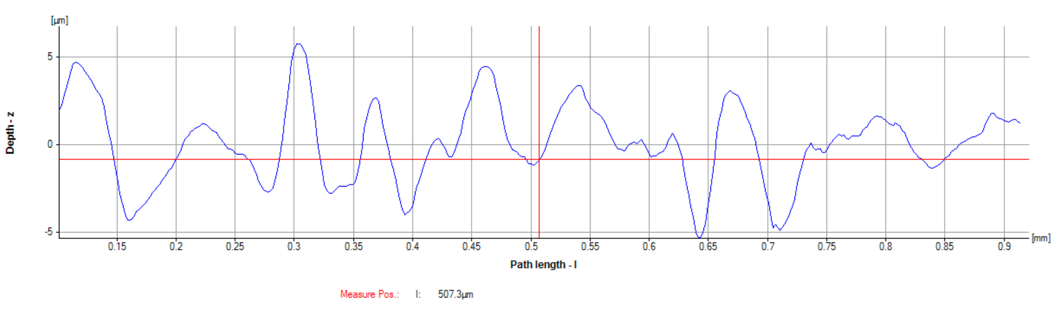

Figure 21. Surface waviness of brass wall section.

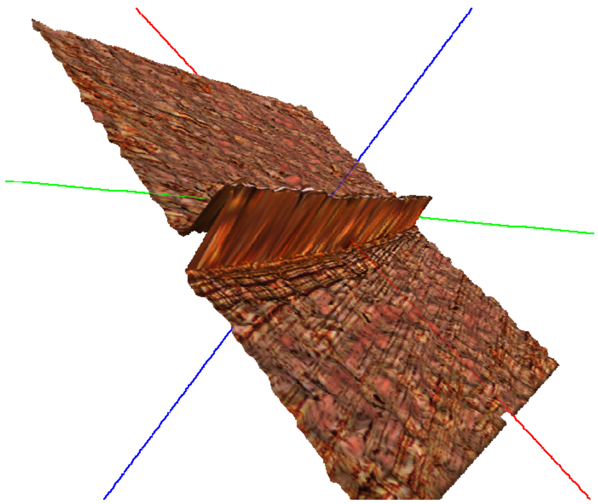

Figure 22. 3-D image of a section of the extruded copper ring. The section is 250 μ high, and 50 μ thick.

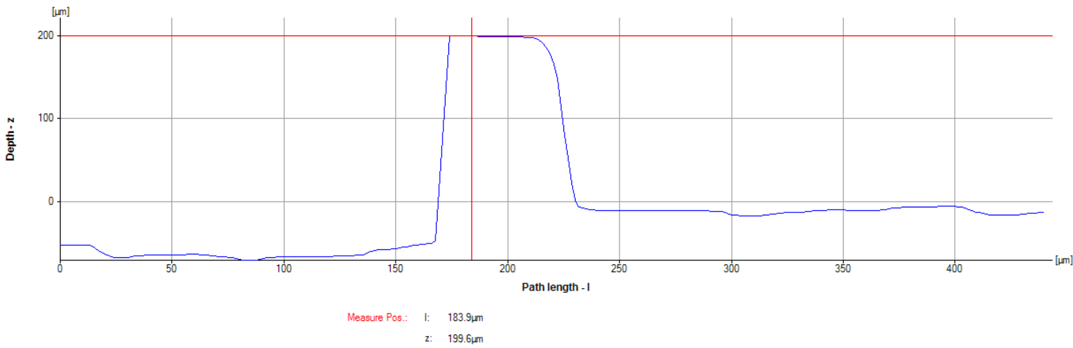

Figure 23. Profile of a section of the extruded copper ring. The section is 250 μ high, and 50 μ thick.

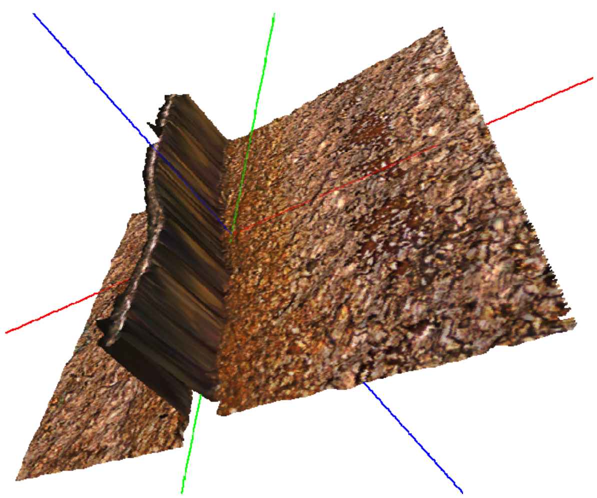

Figure 24. 3-D image of a section of the extruded steel ring. The section is 400 μ high, 150 μ thick.

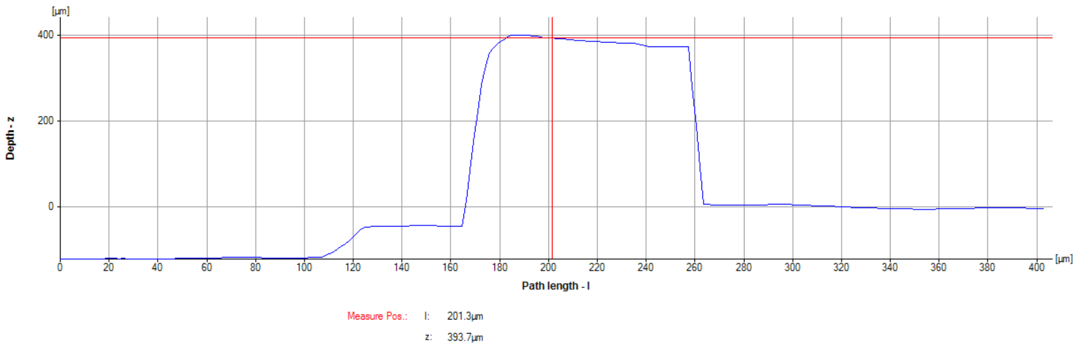

Figure 25. Profile of a section of the extruded steel ring. The section is 400 μ high, and 90 μ thick.

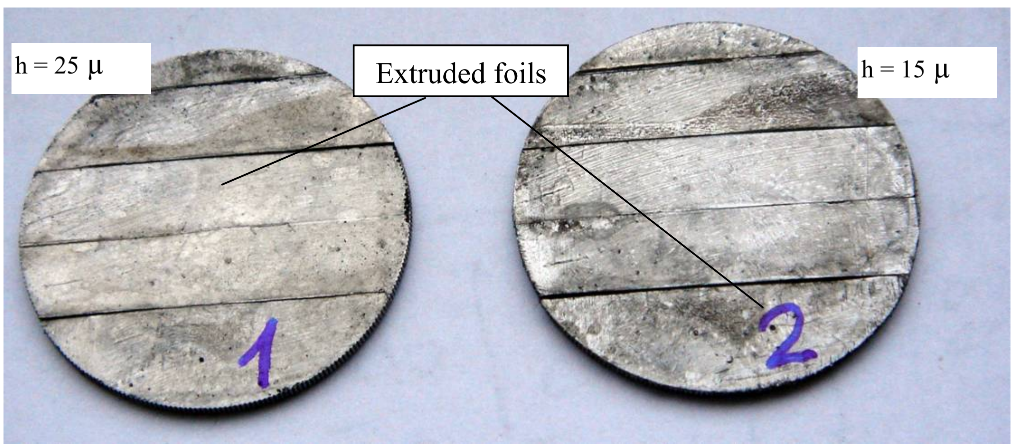

Figure 26. Extruded plain foils of nickel based alloy.