Forming of micro gears by compressing a pure copper sheet through its thickness

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Abstract. Currently, micro gears are mostly fabricated by LIGA technology and micromachining. These processes have some limitations. Forming processes not only satisfy mass production and appropriate productivity rate but also present superior mechanical properties. A major problem preventing the bulk micro metal forming is the preparation of micro billets and their precise transfer between the forming stages. The purpose of this study is developing a method to form a micro gear without the need to a separate micro billet preparation. In this paper, pure copper sheets were compressed into the predetermined micro gear profiles though their thicknesses, so that there is no need for preparation of micro billets and also its troublesome transforming. The tests were performed at room temperature, in two cases of single extrusion process and extrusion-forging process. Micro gears with 6 teeth and 250μm in module were formed completely with good repeatability in both the cases. A major advantage of the proposed study compared with the blanking process is that, in blanking, the process is merely cutting the edges, while here the material fills the die by deformation. Thus, better mechanical properties will be achieved. Measuring the micro-hardness of the formed parts in comparison with raw material, verified this point. In general, the micro-hardnesses of combined extrusion-forging parts were higher than those of single extrusion ones in the same positions on the micro gears surface.

keywords: Micro forming, Extrusion, Micro gear.

1 Introduction

Due to the wide applications of small gears, there are various methods for the production of micro gears in industries [1]. Among of all, LIGA and micromachining are advanced techniques for producing metallic parts. Nevertheless, these processes challenge with some limitations. On the other hand, microforming techniques are able in mass production with high productivity rate, near net shape manufacturing and better mechanical properties [2, 3].
The first definition of microforming was presented by Geiger et al. [4] as the production of parts with at least two dimensions in the sub-millimeter range [5].
Saotome and Yavazaki [6] produced micro gear shafts from a super plastic of aluminum alloys by means of extrusion process at elevated temperatures. Wang et al. [7] formed a micro gear from bulk metallic glasses by a hot embossing process. After the process, they used a chemical solution to solve the silicon die for ejecting the micro gear. Chen and Qiu [8] studied the forming of micro stepped gears by forging process. Dong et al. [9] used hot extrusion and investigated microstructure and micro-hardness of 7075 aluminum alloy micro gears. They reported that the micro-hardness at the teeth are lower than that of the center of specimens. Chang and Cuo [10] investigated the effects of temperature and grain refinement on the closed-die forging of copper micro gear by ECAPed and anealed material. Kim et al. [11] used ECAPed 6061 aluminum alloy to form micro gears by means of extrusion process. Guo et al. [12] forged micro gears from Zr-based metallic glass. They also measured the nano-hardness of the formed part and reported that the core of micro gear has the maximum of nano-hardness.
In the above researches, micro billets were prepared separately and were positioned in the die before each test. Meanwhile, one of the main problems of industrializing the micro bulk forming is preparing and controlling of billets between the forming stages. This is because at micro scale, the workpiece tends to stick to the grippers [13]. Also, there would be some other questions that must be addressed, for example, in an extrusion of a micro gear shaft how an extruded part would be cut into small ones or how to prepare a micro billet without using separate process to circumvent the problem of positioning and handling.
This experimental study tries to address the mentioned questions based on the concept of progressive microforming of bulk parts using directly sheet metals [14]. In this type of controlling, micro parts are attached to the sheet and in the final stage, the ejection is performed. [15, 16]. On the other hand, it is ideal that a process chain for micro-manufacturing should be short

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as much as possible [17]. Therefore, in this research, the die was designed to perform the forming operation and ejection without transforming the formed part. In fact, at the center of a blanked sheet, extrusion occurs and material will be compressed through thickness to the predefined gear profile. When forming was finished, the ejection was performed by means of a torsion operation of dies which departs micro gear from sheet. In addition, conventional ejection was done too. The torsion method and investigstion of its feasability was performed for the first time in this paper.

2 Experimental procedures

2.1 Material and die setup

Pure copper sheets with the thickness of 3mm were used as received material. The sheets were annealed at 700°C and cut into disc shape to the diameter of 44mm. To eliminate the oxide layers on the sheet surfaces and also for the reduction of thickness to 2.75mm, the discs were grinded. The micro-hardness of the annealed material was measured 55HV.
Either at micro or macro scale, providing a billet is mandatory for the processes like extrusion and forging. But at micro scale, the sheet can be used as a raw material to form a micro gear. The idea is that the material of the sheet which is in the deformation zone, plays the role of micro billet. As illustrated in Fig. 1, the material above the die cavity and beneath the punch exists in the deformation zone. Thus, a fraction of blank is used instead of a longer micro billet which should be cut from a wire and positioned with too much difficulty in the die. The rest of material plays carrier role for material at the deformation zone like a gripper.

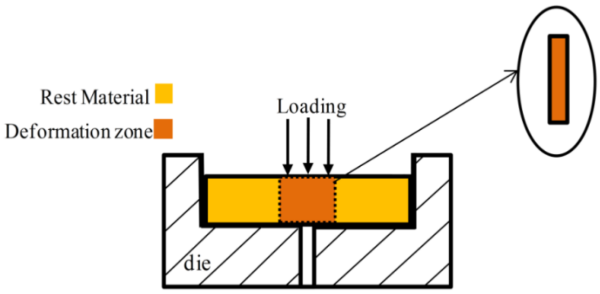


Fig. 1. Material in deformation zone as a micro billet

The schematic of the die set and experimental procedure are shown in Fig. 2. The components of the die set are punches, blank holder, blanking die, inserts and insert holder, and bottom plate. The experimental procedures have two stages for both single extrusion and combined extrusion forging processes. The first stage of each process relates to fine blanking of the sheet with the diameter of 12mm, Fig. 2-a. The extrusion of the material at the deformation zone of the blanked part into the predefined micro gear cavity is done for the second stage, Fig. 2-b or 2-c. Since the two extrusion processes, including single extrusion or combined extrusion-forging, are performed for the second stages, two kinds of inserts were designed. Single extrusion test was designed to determine the maximum capacity of the copper sheet under this test situation and combined extrusion-forging insert was designed to produce a final part from the copper sheet. The thickness of the insert for combined extrusion-forging was considered 2.25mm, Fig. 3. A hard stopper was used to change the extrusion process to the forging one.

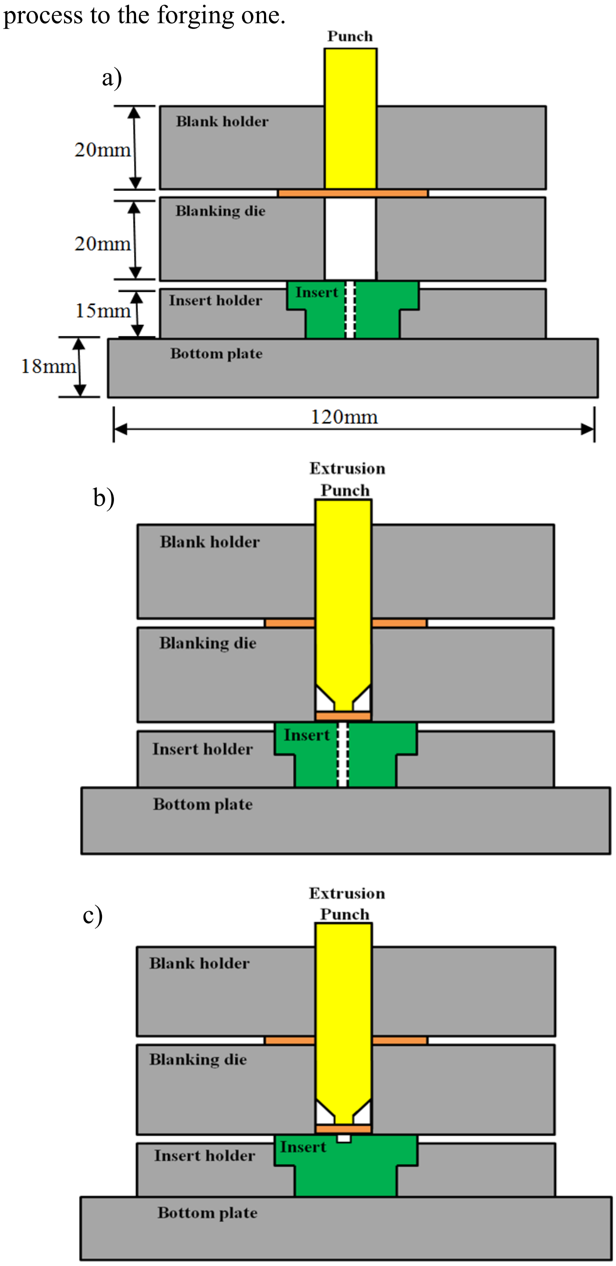


Fig. 2. Schematic of the die and experimental procedure a) blanking operation, b) single extrusion and c) combined extrusion-Forging

Tests were done at room temperature. For dry lubrication condition, the die was cleaned by acetone solution before each test. The ram speed was considered 25mm/min for blanking process, and 3mm/min for extrusion processes. Low speed of extrusion processes was for better controlling and preventing die damage. The size of the blanking clearance was 0.02mm which created a blank with smooth edge. In fact, a fine blanking was occurred. This smooth edge helps to prepare a good lateral constraining and completely blockage of the lateral movement of material. Components of die were manufactured from K100 steels by machining.

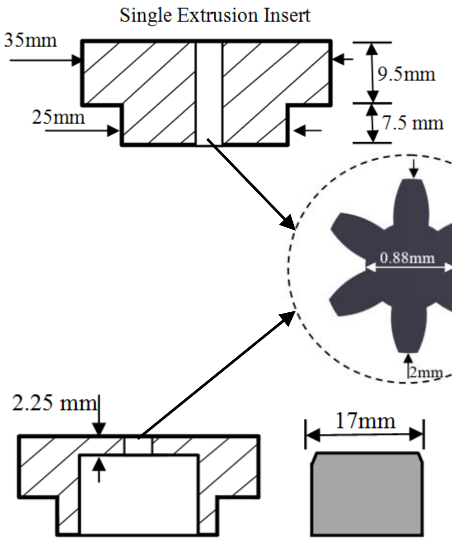


Fig. 3. Inserts a) Single extrusion b) Combined Extrusion-Forging

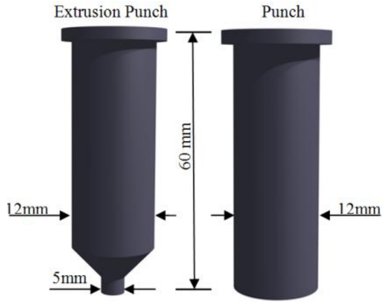


Fig. 4. Schematic and size of punches

The gear female die with 6 teeth and 250μm in module was machined on the inserts by Wire Electro Discharge Machining (WEDM). The tip of extrusion punch is 5mm in diameter which is more than 3 times the micro gear pitch circle diameter. This creates enough material and makes a significant deformation zone for micro extrusion. Schematic of punches are shown in Fig. 4. The die assembly and components of die are shown in Fig. 5.

2.2 Ejection Methods

The ejection of micro parts has been performed by means of torsion operation. The principle of this operation is simple and needs no extra tool which is very significant, because designing and manufacturing of gear shaped punch for blanking needs high precision at micro scale.

Since the micro parts are very small, they could be departed from the sheet at low forces. So, when the insert holder and subsequently inserts keep constant, if the blanking die twists through its axis, the formed part will be departed from the blank, Fig. 6.

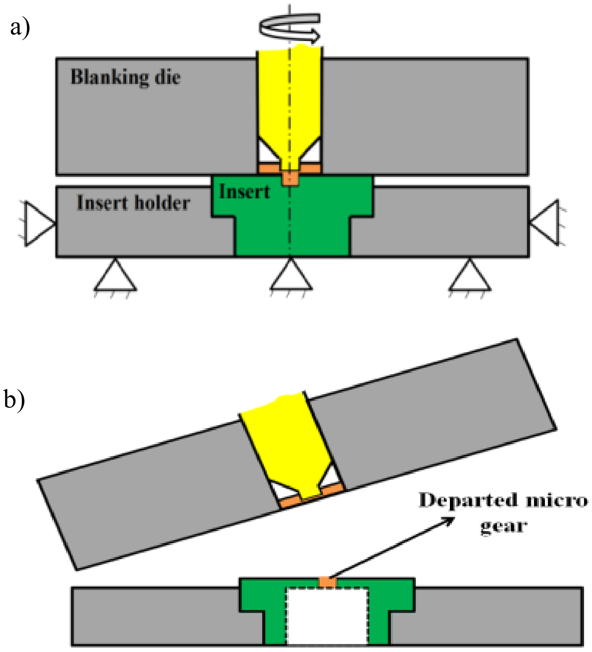
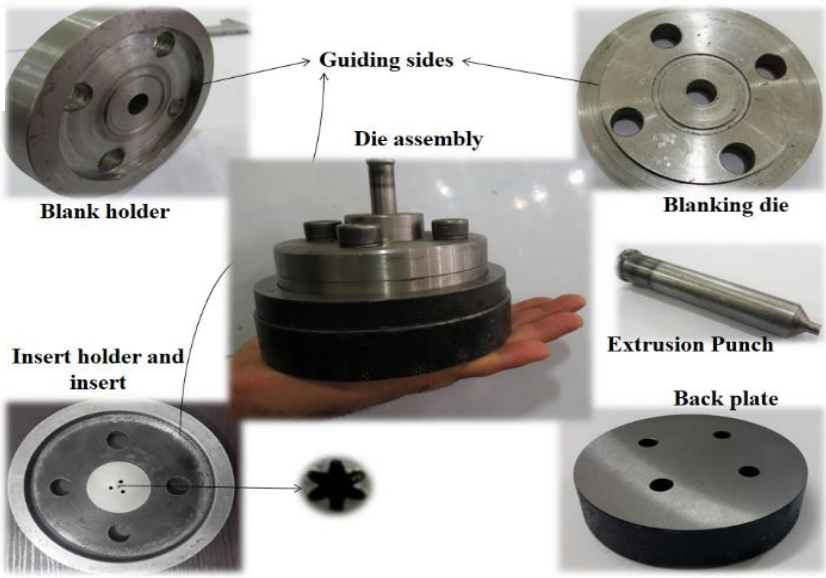


Fig. 6. Torsion operation a) keep constant of lower die and twisting of upper die b) picking up the upper die

Fig. 5. die assembly and components of die



The conventional ejection of micro gears was also done to show the result of tests and to bring out the attached formed part with blank. For this purpose, 3 pins were used to push up the blank, Fig.7. Through this movement, the micro gear that is connected to the blank, exits from the die cavity.

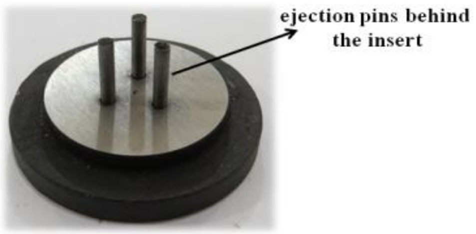


Fig. 7. conventional ejection by three pins

3 Results and discussion

Because of passing the material through a shaped die, extrusion process is one of the manufacturing methods in which parts replicate the geometrical features very well. Therefore, the manufacturing accuracy of the die features intensively affects the quality and accuracy of final parts. Due to the actual difficulty of the WEDM to create sharp corners in the die, the corners were produced by a wire with the radius of 0.06 mm. This affects the accuracy of the die geometry. The tests were done successfully and the micro gears were formed completely.

Images of micro gears produced by single extrusion and combined extrusion-forging are shown in Figs. 8 and 9, respectively. The bulged area around the bottom of micro gears attributes to the lack of vertical constraining of blank during compressing. The punch stroke was 4.15mm which is 150% of the sheet thickness. The reason of the longer stroke was aggregation of material under the punch during the forming operation. This observation was previously reported in reference [16]. As the figures show, there are no defects on the surface of the micro gears and the lines that are observed on the lateral surfaces of the part, parallel to the extrusion direction, were caused by the roughness of the die machining during WEDM. Since the material in the deformation zone must pass a vertical path to enter into the die cavity, a large strain was occurred at the edge of die entrance. Increasing of the stresses leads to increase the strains and furthermore, material flow interference caused a mass of material at the entrance of the die cavity. An appropriate radius at the edge of material flow into the cavity could improve the process and caused better material flow. On the other hand, high ratio of extrusion punch diameter to micro gear pitch circle diameter and dry lubrication condition can be other reasons of material accumulation at the entrance of the cavity. Separation and cutting of these areas from the whole deformation zone, especially the material around the die cavity at the longer stroke, prevents the process to achieve a higher micro gear shaft.

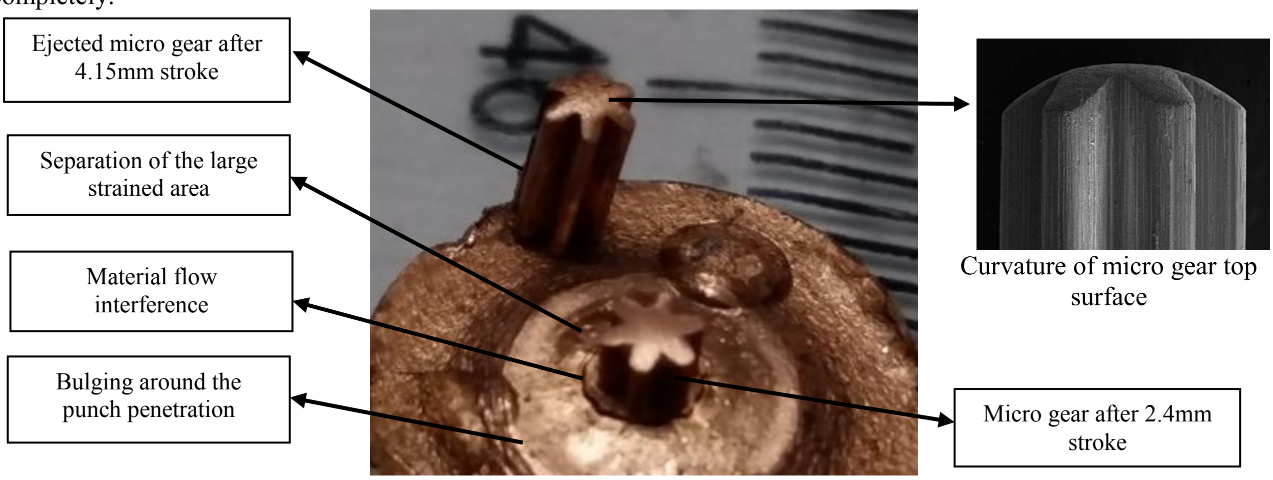


Fig. 8. Micro gear formed by single extrusion process at 2.4mm and 4.15mm stroke

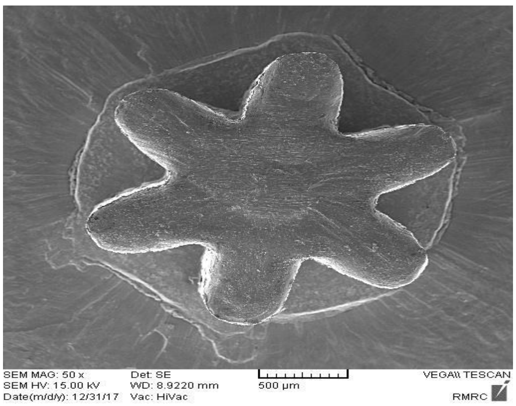


Fig. 9. eliminating the curvature of micro gear top surface by hard stopper

Fig. 10. inscribed Hexagon on the teeth and secondary bulging after 4.15mm stroke

Squeezing the separated area, shaped a secondary bulged area around the micro gear and an inscribed hexagon on the micro gear teeth, Fig. 10. However, maximum capacity of the 2.75mm copper sheet under the situation of this test at the stroke of the 4.15mm created 5mm micro gear shaft height.

The curvature of the micro gear at the top surface was caused by the frictional force of the side wall in the single extrusion process, Fig. 8. This curvature was eliminated in combined extrusion-forging process, Fig.9, by applying the hard stopper on the path of the micro gear.

The measurement of the outer diameter and root diameter size of micro gear by SEM image showed that the features of the cavity were more than the size of the design. Outer diameter was 2.08mm and root diameter was 0.89mm. Also, the walls of micro gear did not conform to the involute curve. The accuracy of the die was directly affected by WEDM accuracy and its setup parameters.

3.1 Load- displacement curve

Based on the experimental observations, the process of sheet compressing through its thickness to a die cavity has two main forming stages. The first stage is upsetting of the material between the surfaces of the punch and die. The second stage relates to material extrusion into the die cavity. In the first stage, some material enters die cavity; however, this amount in comparison to the amount of second stage, is not significant. As a result, the main height of the micro gear forms in the second stage.

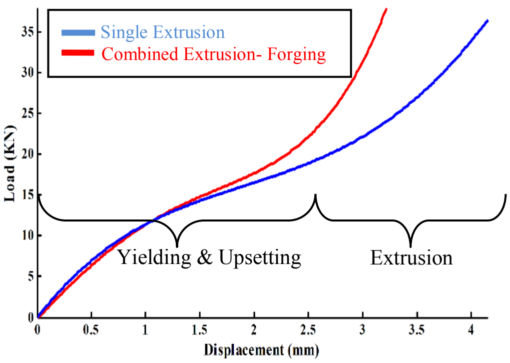


Fig. 9. Load-displacement curve of the micro gears

As illustrated in Fig. 11, both cases of single extrusion and combined extrusion-forging have similar trend. The curves are almost identical till the 1.7 mm stroke. For the single extrusion curve, the first stage of the forming, yielding and upsetting, was done approximately to the 2.5 mm stroke. After this point, the slope of the curve grows gradually which means that the flowing speed of the material into the die cavity is increasing. Since the material entry into the die cavity becomes harder, therefore, the slope of the forming load increases in the second stage.

For combined extrusion-forging, after the stroke of 1.7mm, the load-displacement curve deviates from that of the single extrusion curve gradually. This is because the curvature of micro gear top surface reaches to the hard stopper sooner than the rest of material. Hereafter, the forging process also was performed in the forming zone and the material was forced to fill the die corners and bottom of the teeth. Hence, the load increases sharply. In fact, the material that is forced to come into the die cavity by extrusion process fills the die features through the forging process.

3.2 Micro-hardness tests

In comparison to blanking process, the processes examined in this research do not need a punch like gear teeth and precision clearance. Because of using punch with bigger diameter, the punch has better strength. Also, since the parts are produced by deformation, they would have better mechanical properties than the blanked ones where the process is merely cutting the edges. In order to measure the micro-hardness of the gear tooth, the distance between the center of the tooth to the edge was divided into equal sections and micro-hardness at each position was measured after grinding and polishing of the micro gears. The micro-hardness versus position curves are shown in Fig. 11.

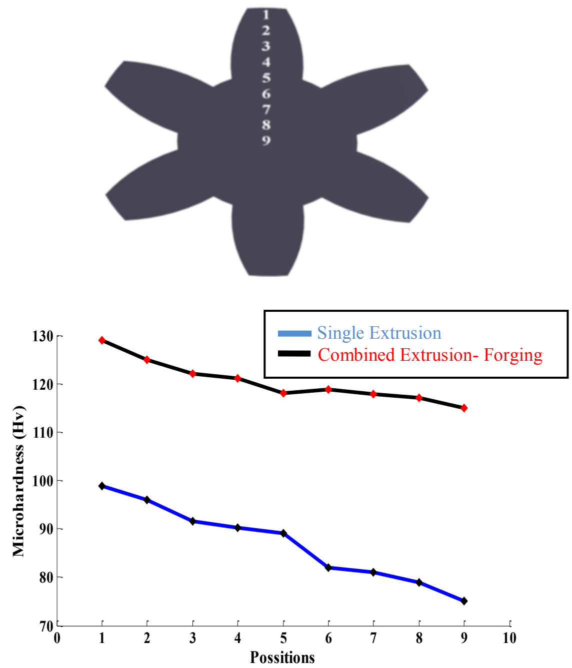


Fig. 10. Micro-hardness – position curve on the cross section of micro gears

For both the extrusion processes, the maximum and minimum hardness was at the tooth edge and at the tooth center. According to the curve, at the tooth edge, the material was under high deformation forces and large strain which makes a large strain hardening, and subsequently, higher micro-hardness. In fact, the grains of material, especially those at the sides, experienced high frictional force caused by contact between the material and the cavity wall. So, the boundary materials were subjected to intense shear stresses over the interior materials. Hard edge teeth could be a promising property for micro gear. By continuing the path and leaving the tooth edge area, a significant decrease was occurred in micro-hardness, especially for single extrusion process, which reveals how much the deformation of grains on this position can be different from the edges area. Micro hardness for combined extrusion-forging was more uniform than the single extrusion. This is because of the influence of the forging process. The center of the formed part has the least micro-hardness that would be predictable due to the less deformation of the center region of the part in the extrusion processes. Totally, micro-hardness of the combined extrusion-forging was higher than the single extrusion at each position. This was due to severe plastic deformation and higher load for the combined extrusion-forging process.

3.3 Ejection method based on torsion operation

According to the concept of progressive microforming, after forming of micro gear it needs a blanking stage to eject the parts from sheet. So, in this case the main question would be how the extra material among the teeth and the bottom of the micro gear can be eliminated. In this study, after forming, the micro gears were ejected from the die cavity with both of the conventional method and the new approach based on the Torsion operation. In this approach, after the forming operation, by keeping constant of insert holder and insert, the blanking die was twisted through its symmetry axis and the micro gear was departed simply from the blank. The Torsion operation was done with hand power. Fig. 12 shows the topography of the tooth surface after the Torsion test.

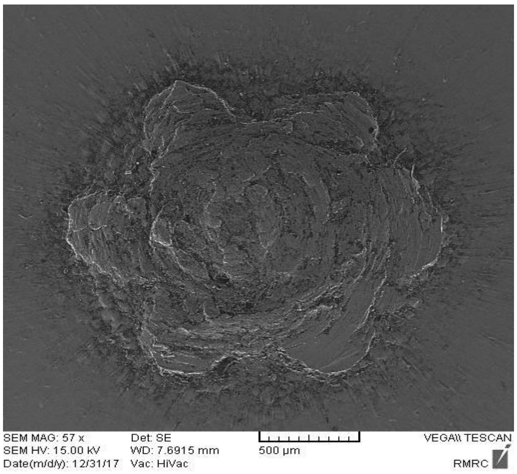


Fig. 11. Topography of blank surface after torsion operation

As it can be seen from Fig. 13, some material remained on the blank which affected the bottom surface geometry of micro gear. The formed micro gear which was still in die cavity can be pushed out by the next extrusion operation.

By means of the presented approach, the mass production of micro gears can be achieved by using sheet metal. Generally, the whole forming and ejecting operations can be done without moving the part. In fact, one stage could be specified for forming, after that, by a torsion operation the formed micro part can be departed, finally by extruding another part to the cavity this formed part pushed out.

It should be pointed out that this study concentrated on the presentation, feasibility and partial analysis of a new method for forming of micro gears. So, the investigation and optimization of parameters such as the relation between tip of extrusion punch diameter, pitch circle diameter and the sheet thickness, friction due to surface roughness of insert and roughness of inner side of cavity, effect of material, constraining condition and blanked part diameter, speed of the test and especially effect of elevated temperature on the test, etc. would be the issues of next researches.

4 Conclusions

- The implementation of using directly sheet metal for producing micro gears was successful. The micro gears were formed completely and filled the die cavity in both the extrusion processes.
- The pure copper sheet with the thickness of 2.75mm can produce a 5mm height micro gear with 6 teeth, module 250µm under the conditions of room temperature, dry condition of lubricant, ram speed of 3mm/min, lateral constraining of blank and 4.15mm stroke.
- The load-displacement curve of the micro gear has two main stages; yielding and upsetting as the first stage and extrusion as the second one. The main height of micro gear was formed in the second stage.
- In both of extrusion processes, the maximum of micro hardness was at the teeth and the minimum was at the center of micro gear. Comparing the hardness of initial material to the micro-hardness of the formed gear shows a promising mechanical property.
- Generally, the whole forming operation and ejecting can be done in one stage. One stage can be specified for forming, after that, by a torsion operation the formed micro part can be departed. Finally, by extruding another part to the cavity this formed part pushed out. However, the topography of cut surface must be studied more.

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