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TECHNICAL PAPER

Influence of grain size on deformational behavior in microextrusion process

S. Nanthakumar[1] · **D. Rajenthirakumar**[2]

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Abstract

Miniaturization drives the need for developing appropriate technology for microproducts of extremely small geometric features with high tolerances. In this work, the authors have investigated the material behavior and size effect in microextrusion of pure copper and aluminum with different grain sizes. A forward microextrusion assembly has been developed in the first phase of work to investigate the grain size effects. The experimental results are then compared to finite element simulation to quantify force displacement response. It has been found that the simulated deformation load is comparable with experimental results. The influence of size effect in both copper and aluminum showed that the extrusion load and average microhardness of 38 μm and 34 μm are higher when compared to 204 μm and 124 μm. In the second phase of work, an attempt has been made to fabricate the copper microgear ($m = 0.416$ mm) by the developed extrusion setup. The findings of this work are essential for further development of micro-formed parts and will facilitate in introducing microextrusion for mass production of industrial components.

Keywords Size effect · Material behavior · Microgear · Microhardness

1 Introduction

Several microextrusion processes have been developed and studied since 1990, when microforming was evolved. A good example of a well-established microscale manufacturing process with low raw material wastage is microextrusion. Micro extrusion is receiving a lot of attention recently, because it is a fast process and ideally suited for mass production. Some of the applications from microextrusion include miniature screws, IC chips, contact springs, connector pins for electronics, microgears and microshafts. In case of microextrusion and microforming techniques, an in-depth analysis and research are still to be done which will help in implementing these technologies widely across the globe for numerous applications and to achieve the goal for mass production. The design and development of microparts are usually based on the experience and know-how obtained via trial-and-error. Understanding the material behavior and deformation behavior, relevant properties in microforming process are critical in predicting the quality of the microparts. A comprehensive work on force displacement response for microextrusion with materials of different grain sizes was carried out by Rajenthirakumar and Sridhar [1].

Knowledge of grain size is critical in determining the appropriate load for deformation and flow stress for forming. The authors investigated the size and distribution of grains of pure copper and aluminum and found that the strength of materials increased with the reduction of grain size. Chan [2] in his work has made a detailed investigation about the behavior of copper with different grain sizes in terms of experimental and numerical simulation method. Further the study concluded that conventional material deformation behavior is not applicable for the analysis of microforming processes. In order to study the deformation behavior of different grain sizes, microstructure and microhardness analyses were carried out and it has been found that the

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✉ S. Nanthakumar
kumarmechpsg@gmail.com

✉ D. Rajenthirakumar
rajentkumar@gmail.com

[1] Department of Mechanical Engineering, PSG Institute of Technology and Applied Research, Coimbatore, Tamil Nadu, India

[2] Department of Mechanical Engineering, PSG College of Technology, Coimbatore, Tamil Nadu, India

deformation parameters were mainly influenced by the size and location of specific grain as inhomogeneous deformation arises in the case of coarse grains [3]. Also the results showed that the pins fabricated with coarse-grained material had a higher hardness value compared to fine grain material. This result contradicts with the well-known Hall–petch relationship. Another main factor to be considered during the study of deformation behavior is friction.

Three different extrusion dies were coated with diamond-like carbon with silicon (DLC-Si), chromium nitride (CrN), and titanium nitride (TiN)used in the microextrusion experiments. These coatings worked satisfactorily in reducing the friction and extrusion force [4, 5]. Apart from coating of dies, lubricants could also be used during the extrusion process to increase life time and decrease the forming load. Moreover, coating inside the die orifice is the biggest challenge as the dimensions are in microscale. Successful lubrication of die could increase the final part dimension significantly. But, however, coating of dies is preferred compared to lubricants as weaker lubrication effect increases pressure on tool and reverse forming [6]. Many authors have tried products with different features with the aid of microextrusion process. One such important feature is microgear. A microgear is an important component widely used in microelectro mechanical systems (MEMS). Various methods are involved in manufacturing of microgears such as micromachining, powder injection molding, casting, microforming; microinjection molding and MEMS-based lithography technologies. Appropriate microforming techniques should be developed for the manufacturing of microgears. Dong et al. [7] successfully extruded the high strength aluminum alloy microgear and tested for various parameters such as extrusion velocity, extrusion temperature, microhardness, microstructure and lubrication conditions on the formability.

Prediction of grain size is important in order to design the process by adjustment of parameters such as punch speed. Also nonlubricated gear has the tendency to bend, which is not in the case of lubricated extruded gear. The development of micromachines for microextrusion has attracted a lot of interest from researchers. A typical model machine for backward extrusion was developed in Gunma University, Japan [8, 9].

The key issues encountered by researchers across the globe on micromanufacturing and microforming are studied to length, and there is a need to establish defined standards with the consideration of size effects [10, 11]. Much works are still be done in developing machineries especially designed for microforming and micromanufacturing. Similarly Wang [12] reported that the fine extrusion device approach provides precise sizes in a higher level than those obtained from conventional extrusion. The device has the punch which is not identical to the die, meaning that the products of any shape can be obtained. Major issues which have been investigated are related to the understanding of material deformation, material property characterization and process modeling and analysis, etc., which emphasis on the size effects. Both mechanical and metallurgical aspects should be considered for microforming as it will help in designing proper microforming systems [13, 14]. The above studies and research focus on extrusion at room temperature. Another field of study involves extrusion at elevated temperatures. This means the temperature of the specimen is raised to an optimum temperature for achieving good formability. The effect of temperature on mechanical properties in AZ80 magnesium alloy was studied by Azimi and Mirjavadi [15]. A suitable simulation software (Deform-3D) was used to simulate the process, and then material flow pattern behavior was studied by increasing the process temperature to 350 and 450 °C. The results showed extraordinary grain refinement, and it gave rise to the increase in strength compared to the as received material. During plastic deformation, material's formability is not only related to inherent properties, but also strongly dependent on environment temperature. In order to achieve the precise dimension and good formability, a material has to undergo a minimum inhomogeneous deformation [16]. To reduce the above-mentioned effect, forming at elevated temperature will have a benefit of reduced forming load and better formability. This is mainly due to thermally activated recovery processes and additional slip systems, as already known from conventional scale. For example magnesium bars had a better formability at the extrusion temperature of between 250 and 300 °C while a forming failure occurred at the extrusion temperature of 150 °C due to severe work hardening induced by incomplete recrystallization [17]. Pure titanium with refined grain (ECAP) exhibits better microforming properties compared to coarse grain. Good formability was observed when the deformation temperature raised to 300 °C [18]. Formability of stainless/carbon steel bimetal medium-thick composite was investigated in terms of experimental trials and simulations [19].

Based on a detailed study of various researches it has come to light that only very few researchers have tried microextruding of gears and those scientific data were not sufficient for real time implementation. Further there is a large gap in the researches conducted and the actual industrial requirements. Hence, there is a necessity to develop a microforming process for manufacturing microgears with ferrous and non-ferrous metals.

The main objective of this paper is to investigate the material behavior and size effects of copper and aluminum using microextrusion process. As an application of microextrusion, copper microgear extrusion is also investigated. In addition to the experimental work, a finite element (FE) simulation was carried out to predict the force displacement response and the results were compared with experimental trials.

2 Experimental setup

In order to study the size effect on material behavior in microextrusion process, a novel experimental setup has been developed and tests were carried out with pure copper and aluminum billets. Based on the requirement of the testing setup, the die and the punch pin are designed and dimensioned accordingly. Figure 1 shows this testing platform which is equipped with a load cell (10 kN) and an LVDT (0–100 mm) to measure the extrusion force and the corresponding ram displacement. Table 1 gives the other important specifications of the machine. Five tests were performed using the die to check the repeatability of the process, and the average value was taken. The first phase of the experiments was conducted at room temperature without lubrication, and in the second phase, the dies are coated with diamond-like carbon with silicon to reduce the effect of friction [4]. It is a nanocomposite coating that has unique properties of natural diamond, low friction, high hardness and high corrosion resistance. The coating is done using plasma-assisted chemical vapor deposition method, with a layer thickness of 3 µm and the average surface roughness value of 0.66 µm.

The experiments have been classified into two phases. The first phase comprises of microextrusion of aluminum and copper stepped pin, and the second phase comprises of microextrusion of copper gear.

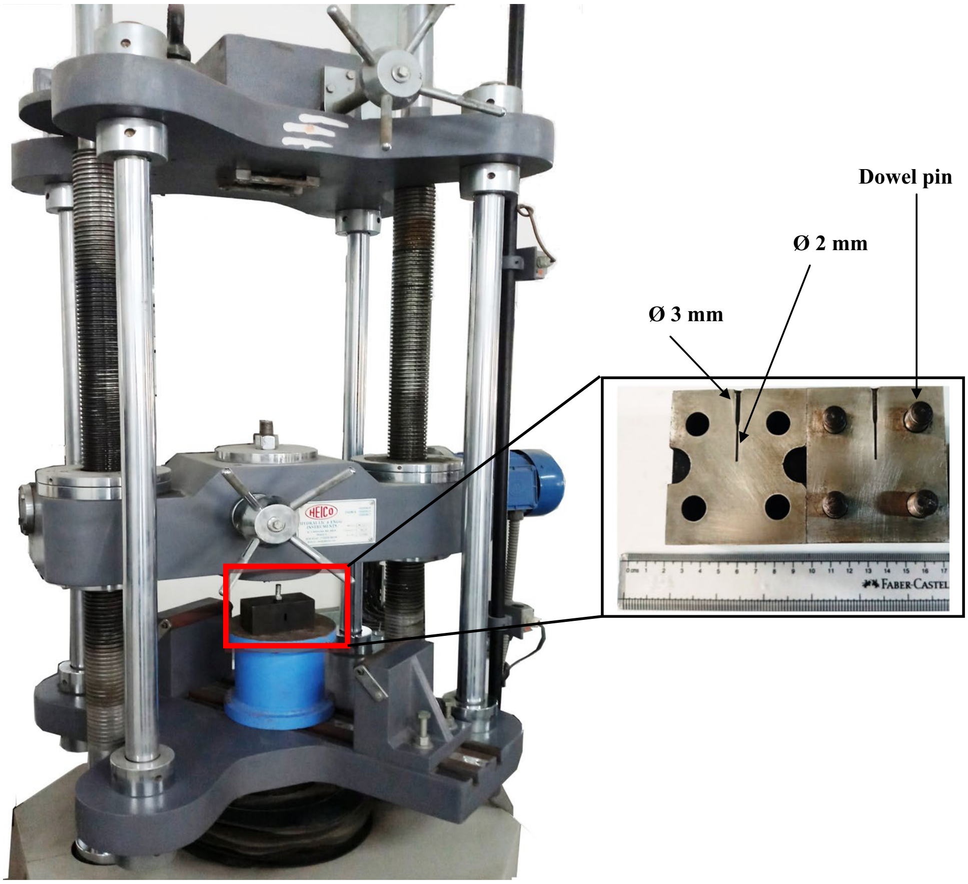


Fig. 1 Microextrusion testing platform

Table 1 Microextrusion machine specifications

Sl. no.	Parameters	Value
1	Load range	0–10 kN
2	Load measuring accuracy	± 2% to 100% of load cell used
3	Maximum crosshead stroke	1000 mm (without grips and load cell)
4	Clearance between columns	450 mm
5	Crosshead displacement measurement	0.01 mm
6	Power supply	230 V AC, 50 Hz single phase
7	Make/model type	FIE universal testing series Unitek 9400

Table 2 Material composition

Material	Composition
Pure copper	99.95%Cu, density = 8.96 g/cm^3
Pure aluminum	99.0 Al, density = 2.6989 g/cm^3

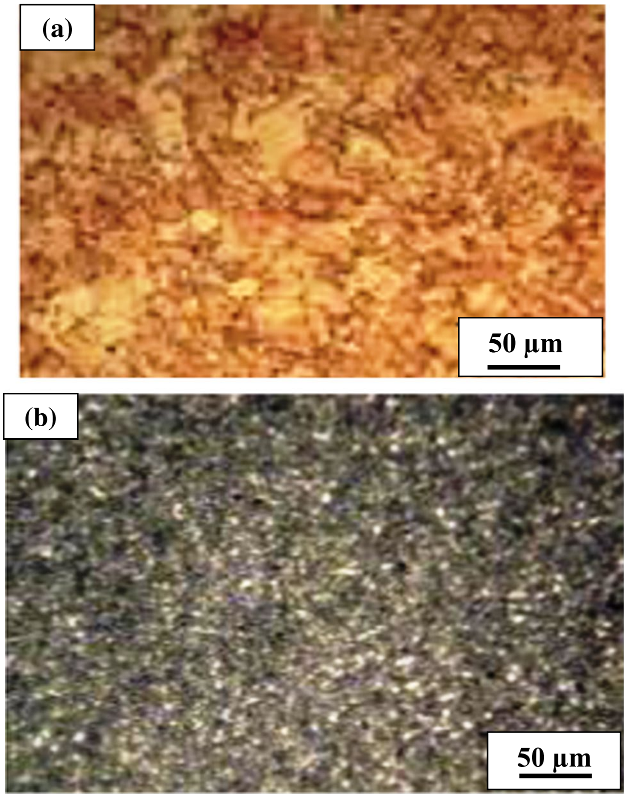


Fig. 2 Microstructure of **a** copper and **b** aluminum before heat treatment

2.1 Material preparation

Pure copper and aluminum are used as testing materials in this study as they have wide applications in various fields such as heat exchangers, coil makers, wrist watches, watch pins, connector pins and electrical pins. The material composition of copper and aluminum is specified in Table 2. The billets received with a diameter of 6 mm to a length of 50 mm are then reduced using a microturning lathe to 3 mm and length of 20 mm. The original microstructure of copper and aluminum was examined and is shown in Fig. 2. The initial grain size of copper (without heat treatment) is 38 µm, and for aluminum it is 34 µm. The billets are annealed at different temperatures and working times to obtain modified grain sizes which are mentioned in Table 3. The microstructures of copper and aluminum after heat treatment are shown in Figs. 3 and 4.

Table 3 Details of heat treatment

Specimen name	Material	Annealing conditions (°C)	Obtained grain size (µm)
Cu38	Pure copper	As received	38
Cu90		400 °C	90
Cu204		650 °C	204
AA34	Pure aluminum	As received	34
AA74		200 °C	74
AA124		350 °C	124

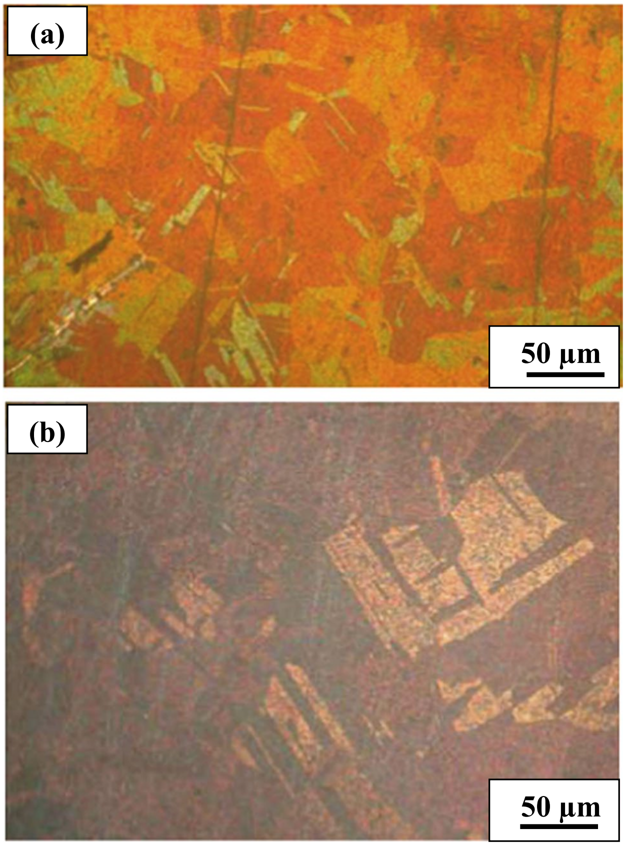


Fig. 3 Microstructure of annealed copper **a** 90 µm, **b** 204 µm

2.2 Experiments: microstepped pin

The experimental setup consists of following components: the microextrusion dies (Split type), punch, billet (work piece) and microextrusion testing platform (Fig. 1). The die cavities are machined by microelectrical discharge machining. The die has the base diameter of 3 mm, an extruded diameter of 2 mm, and the total extrusion length is 20 mm. In order to facilitate the removal of the micropin after the extrusion process, segmented die (split type) is used. The die surface is polished to ensure similar surface roughness

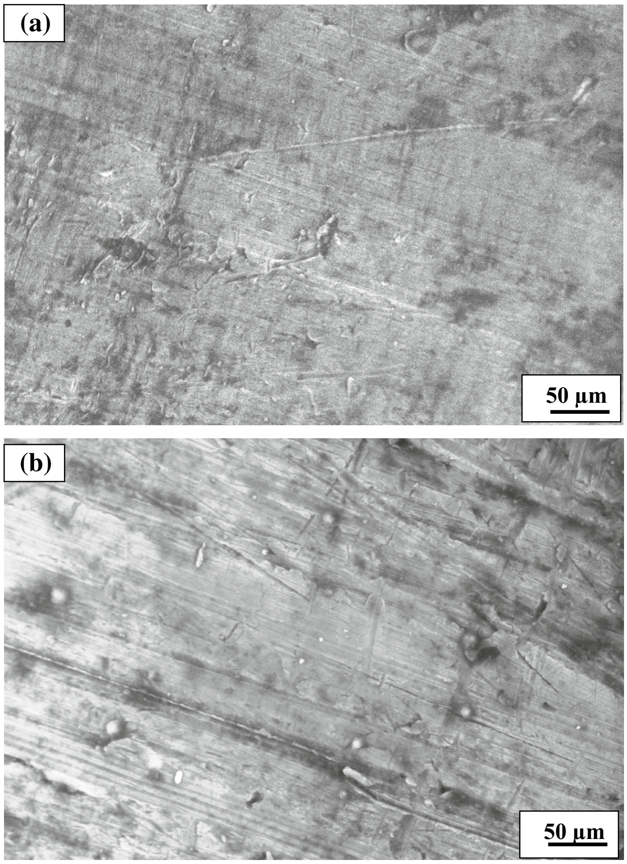


Fig. 4 **a**, **b** Stereomicroscope micrographs of the aluminum at different annealed temperatures

values (1 µm). The material is extruded at a punch speed of 0.01 mm/s. The billet of copper or aluminum is inserted into the die initially and it is placed over the working table of the testing platform. The punch pin should be placed along the axis of the billet. Required force is applied through the punch pin which pushes the billet inside the die geometry. The die is tightly clamped by a '*C*' clamp which is a type of clamping device typically used to hold a wood or metal work piece. Once the process gets completed, the product is removed by disassembling the segmented die.

2.3 Experiments: microgear

The second phase of experimental involves in extrusion of microgear. Figure 5 refers to the microgear die and geometry of gear specimen. The gear profile has the following dimensions, outer diameter 3 mm; inner diameter 2 mm; 6 numbers of teeth. For accurate positioning of split dies, dowel pins are inserted. The material chosen for the die is P20 die steel due to its high hardness. A solid circular rod is machined to 50 mm diameter and 12 mm thickness to obtain the circular microforming die. Then the bar stock is cut into two halves symmetrically to generate the gear profile by wire cut electro discharge machining.

3 Results and discussion

The microextrusion of stepped pin and copper microgear is performed successfully using segmented die. The results of force displacement response, microhardness and surface finish are discussed in the subsequent sections.

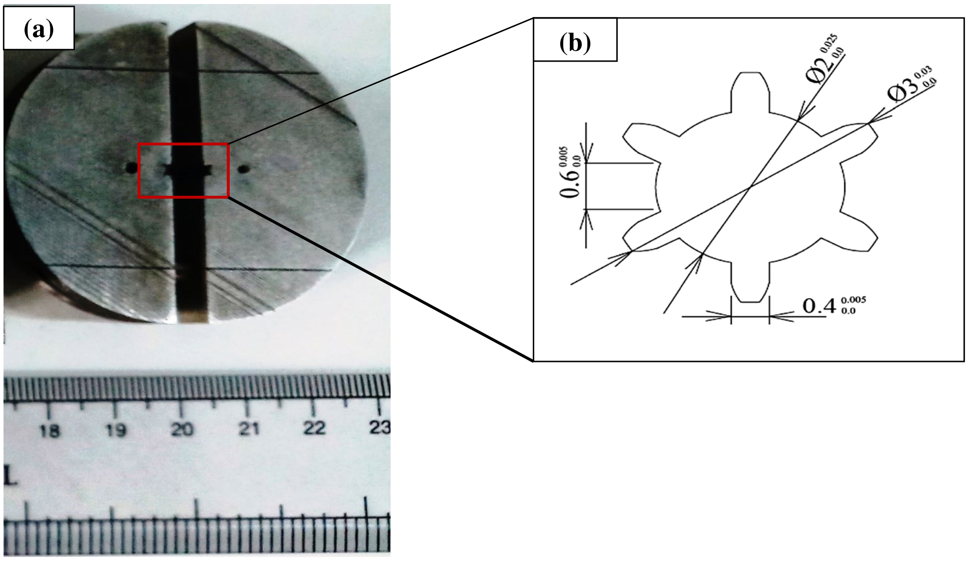


Fig. 5 **a** Microgear extrusion die. **b** Geometry of gear specimen

3.1 Force displacement response

3.1.1 Microstepped pin

In order to predict the force displacement response of forward microextrusion of pure copper and aluminum, a finite element simulation run was carried out using a commercial CAE system, AFDEX (metal forming simulator). The forming tools are modeled as analytical rigid bodies, while the forming material is modeled as an elastic–plastic body. The die which is modeled is fed in the software, and the basic parameters are given as input. From the simulation run, the maximum deformation force for aluminum and copper billets is 1348 N and 7280 N, respectively. To verify the results, experimental trials are conducted multiple times with pure aluminum and copper billets. The force displacement curve for aluminum and copper after reaching a steady state is shown Figs. 6 and 7. The maximum load for aluminum is 1310 N and in case of copper is 6841 N. It is found that the simulated deformation loads are comparable with experimental results. The percentage of deviation between experimental and simulation for copper (38 µm) and aluminum (34 µm) was determined and found well within the limit of 12% and 16%, respectively. It can be seen that the

Fig. 6 Force versus displacement of aluminum (simulation versus experimental)

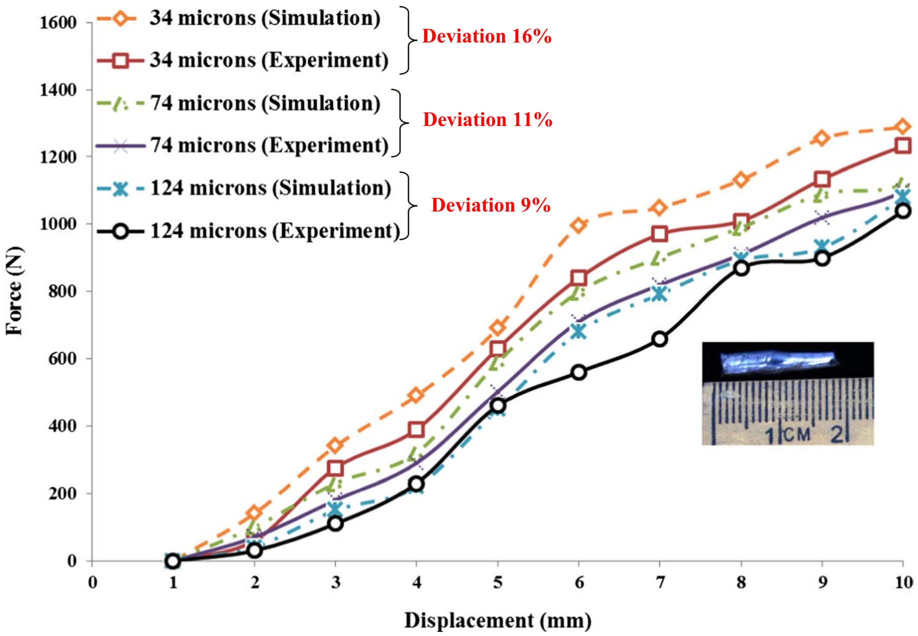
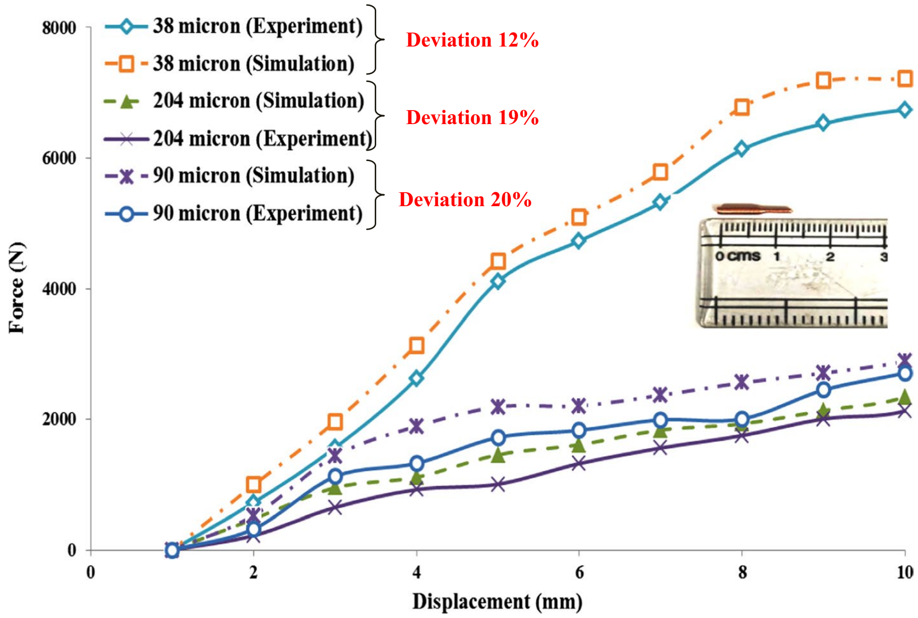


Fig. 7 Force versus displacement of copper (simulation and experimental)



force–displacement curve has a steeper slope for the original copper with extremely fine grains. In case of fine grain structure means a large number of grain boundaries which requires a high deformation load for extrusion. Because these grain boundaries acts as a barrier for slip transfer as it produces hindrance to the dislocation movement and thus resulting in pile-up dislocations which increases the strength and thereby increases the ductility. A similar trend is observed in the work of Rajenthirakumar and Sridhar [1]. Copper with extremely fine grains requires a large deformation load compared to coarse grain. This is attributed to the strengthening effect of the grains. The average value of maximum load for copper is 8996 N which is 24% higher compared to the present study and for aluminum the maximum load is 1752 N (25% higher). One of the reasons for the reduction of deformation load is the effect of interfacial friction between die and work piece. In the current, study the authors have used a special type of coating (diamond-like carbon with silicon) to reduce the effects of friction [4, 5]. But in the previous work, liquid lubricants (servo way 68) were used during the extrusion process.

Knowledge of grain size is very important to estimate the deformation load. Various authors have researched at length, to study the effect of grain size and also its effects on deformation load. In the current study, the grain size of aluminum and copper is varied by heat treatment process as mentioned earlier. The results were similar to the works of chan et al. [2] and Parasiz et al. [3]. The average value of maximum force for aluminum is 1280 N for 74 µm samples and 1210 N for 124 µm. In case of copper it is 3001 N for 90 µm samples, and 2721 N for 204 µm samples. The percentage of deviation between experimental and simulation for copper (90 µm & 204 µm) was determined and found well within the limit of 19% and 20%, and incase of aluminum (74 µm & 124 µm) it was 11% and 9%, respectively. With respect to the forming force, it is noticed that the deformation force with coarse grain (90 µm, 204 µm) is generally lower than the one with fine grain (38 µm) for copper. In case of aluminum, the deformation force with coarse grain (74 µm, 124 µm) is also lesser than fine grain (34 µm). Figures 8 and 9 represent the extruded copper and aluminum samples. Due to presence of more grains and less interstitial positions, fine-grained structure provides more resistance for deformation. Whereas in coarse-grained structure, there will be less resisting areas due to less grains and more interstitial positions. Since there are only a few grains present in the work piece and even distribution of different grains no longer exists, the anisotropic properties of each grain become significant to the deformation behavior and lead to the inhomogeneous deformation [10, 11]. From the above, it is found that the relatively coarse grain structure leads to non-uniform material flow and lack of repeatability during extrusion process. In order to avoid the above effect, extrusion at elevated temperature can be conducted which will lead to homogeneous deformation and better forming. This is due to the dislocation movement of grains which are thermally activated at elevated temperature. But, however, at higher temperature the property of the materials might change dramatically. In this regard further research activities are needed which will lead to better results and understanding.

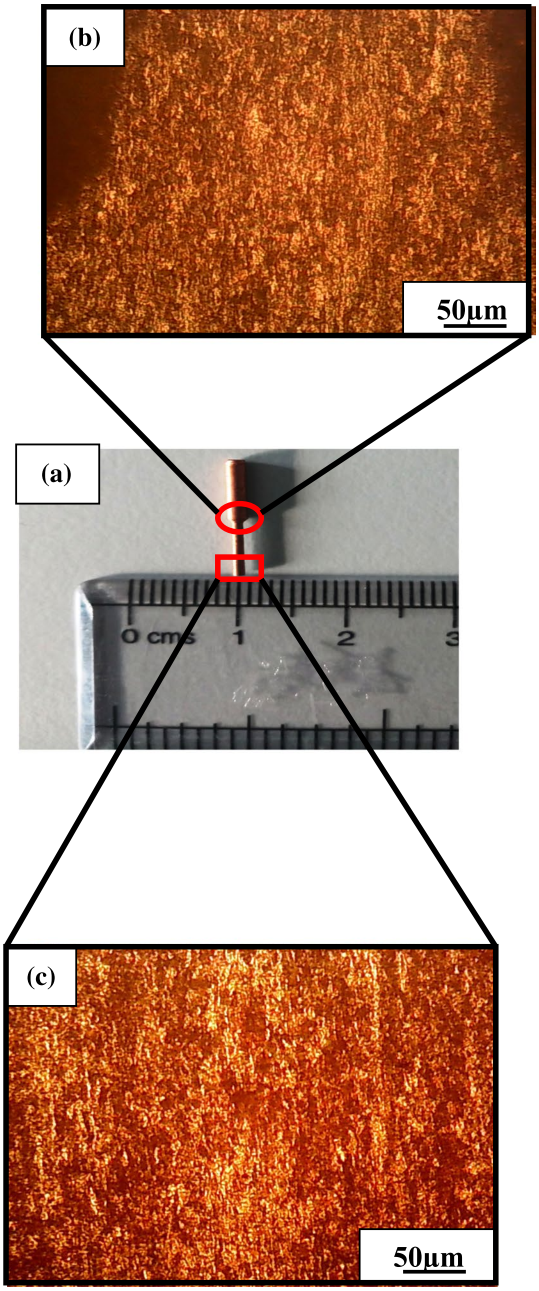


Fig. 8 **a** Microextruded copper stepped pin. **b**, **c** Microstructure of extruded stepped pin

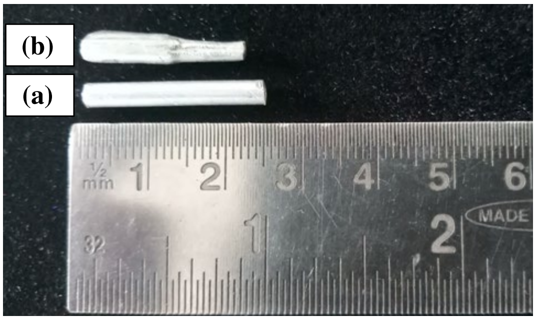


Fig. 9 **a** Aluminum billet. **b** Aluminum microstepped pin

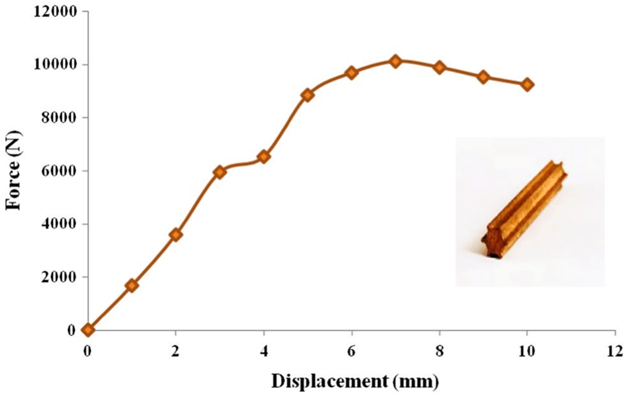


Fig. 10 Force versus displacement (copper microgear)

3.1.2 Microgear

As one among the few applications of microextrusion is that the developed components which could be used in most of devices are microgears. In this work that has been taken and successfully extruded. The force–displacement curves for copper microgear during the extrusion are shown in Fig. 10. The load gently increased in the beginning during the upsetting stage and then sharply increased during the combined indentation unsteady extrusion stage and, finally, saturated during the steady extrusion stage. It could be noted that shear deformation in the material occurred near the surface compared to pure deformation at the center. The maximum force in case of copper is 10,100 N. The extruded gear shaft shows good replication of the die dimension with high surface quality. Figure 11 represents extruded copper microgear and the stereomicroscope micrographs. The microstructure depicts that the grains are more smother owing to the direct implication of better grain refinement. A similar pattern of results could be observed in the works of Dong et al. [7]. Formability of 7075 aluminum alloy was investigated and found that better lubrication conditions and optimum elevated temperatures caused a reduction in the necessary extrusion pressure and improved the gear surface quality. Further study specific to the area of extruding microgear at elevated temperature could be carried out.

3.2 Measurement of microhardness

3.2.1 Microstepped pin

In order to compare the deformation of fine and coarse grain size materials, a series of microhardness measurements were taken on various radial locations in order to assess its work hardening after extrusion. The measurements are taken using the microhardness tester (Mitutoyo-load range 10 g–2 kg). Samples have to be prepared for microhardness test in order to provide a specimen small enough to fit into the tester (Fig. 12). For the microhardness test procedure, ASTM E-384 is followed and the values are averaged. From Fig. 13 it could be found that the hardness increased significantly along the radial location of the microstepped pin because the material, which is deformed first through the reduction, will have lower hardness values than material deformed later due to fewer restrictions during deformation. Further, fine-grained billets have relatively higher hardness than coarse-grained billets after the extrusion process. This is consistent with Hall–petch relation which states that the strength of the coarse grain size material should be lower than those of finer grain size material. Jindal et al. demonstrated that the hardness of CuZn30 brass depends on the grain size and follows Hall–petch relationship [20]. This attribute is due to fine-grained structure which provides more resisting areas due to the presence of more grains and less interstitial positions, whereas, for a coarse-grained structure, there will be less resisting areas due to less number of grains and more interstitial positions present inside it. Thus, the deformation of individual grains is not as constrained by neighboring grains as in polycrystalline tensile deformation. Further the grains undergo slip and rotation in a complex manner during extrusion that is determined by the extrusion forces and by also the deformation of adjacent grains [21].

Parasiz et al. [3] find the hardness distribution along the length of the pins fabricated was more uniform compared to pins fabricated from coarse-grained material. Further deformation of fine-grained material showed a consistent pattern along the length of the pin. Where as in coarse-grained structure large individual deformed grains were observed and showed a very less consistent pattern along the length. The inconsistent deformation pattern of grains through the length of the pin indicates the occurrence of more inhomogeneous deformation and higher influence of individual grains in the coarse-grained material.

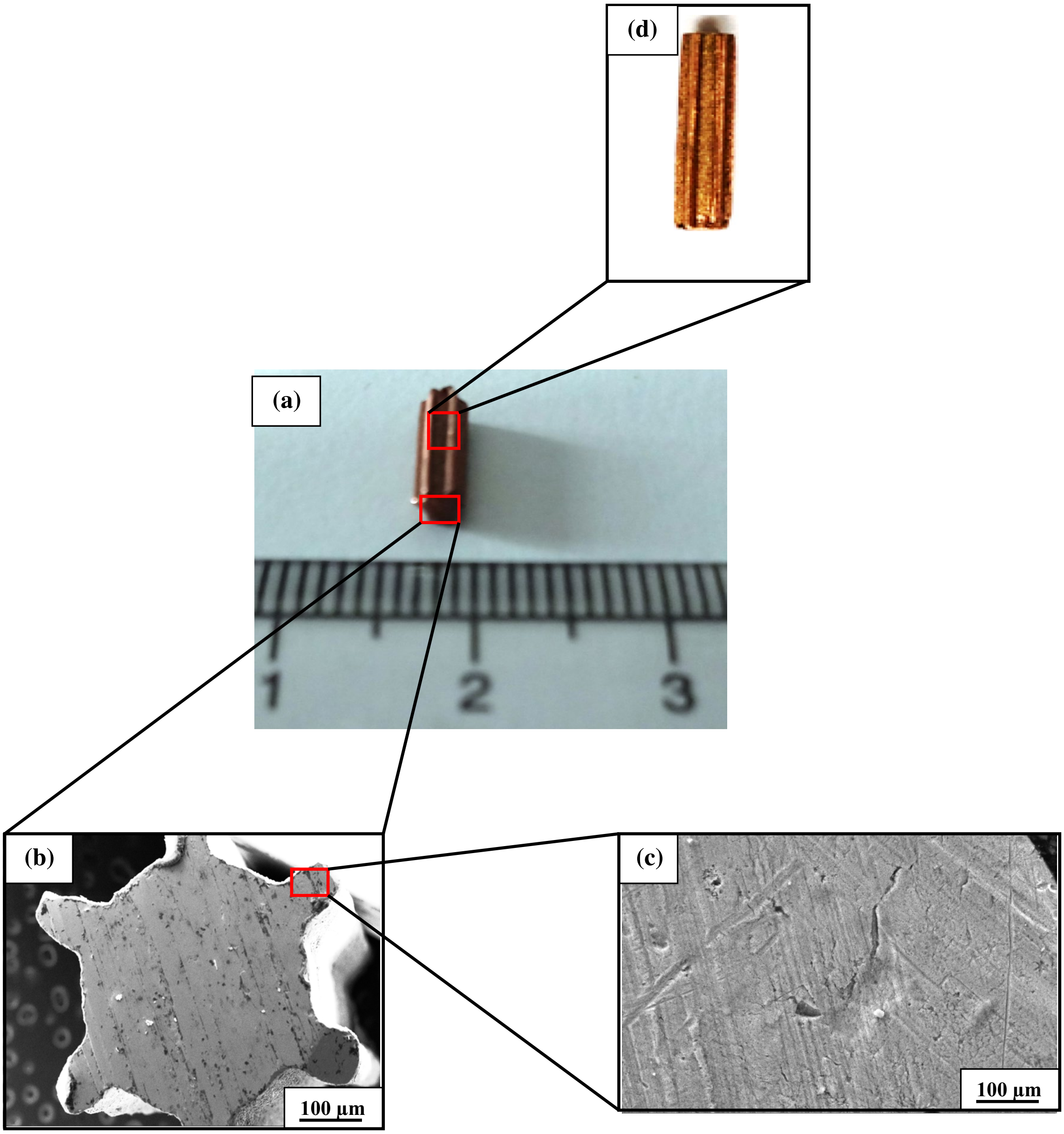


Fig. 11 **a** Microextruded copper gear. **b**, **c** Stereomicroscope micrographs of the microgear columns extruded from pure copper. **d** Top view of copper microgear

3.2.2 Microgear

Microhardness values of microextruded gears are plotted in Fig. 14. The hardness differs depending on the position across the specimen. It could be noticed that the hardness value at the tooth area is higher when compared to the central area. This is due to the fact that tooth area must have experienced the most severe deformation during microextrusion which results in the smallest grain size while the center area that must have experienced the least deformation has the largest grain size. This indicates that extrusion at room temperature produces smaller grain size, which is related to low grain growth rate at a low temperature [22]. As demonstrated [4] it is worthwhile to remember that the hardness in the surface region of the brass micropins extruded at room temperature is larger than in the central region. Similar results could be found in the works of Dong et al. [7] where the larger strain in the tooth region has higher microhardness while smaller strain in the central region has lower hardness. Further due to high friction coefficient between the billet and die, the microhardness of the gears under nonlubricated extrusion condition was lower compared to that of gears under lubricated extrusion condition. Also the hardness of the gear reduces when the

Fig. 12 Copper samples prepared for microhardness testing

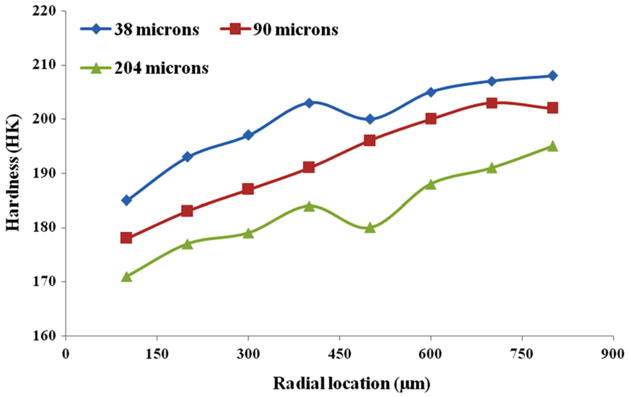


Fig. 13 Average microhardness values of different grain sizes of copper (after extrusion)

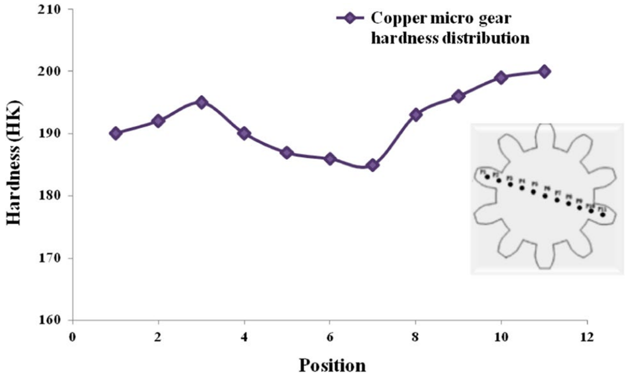


Fig. 14 Average microhardness distribution of copper microgear (after extrusion)

extrusion temperature increases. This is due to the fact that during hot working, dynamic recovery and dynamic recrystallization reduces the dislocation density which further reduces the strength and hardness of gear and simultaneously increases ductility [23].

3.3 Surface finish measurements

3.3.1 Microstepped pin

Surface roughness measurement is carried out using a portable surface roughness tester with the sampling length of 0.8 mm with a velocity of 0.5 mm/s. Measurements were taken for all extruded samples of copper and aluminum. As a means of comparison one set of uncoated die was also used in the experiment. Table 4 gives the surface roughness values which are consistent across grain sizes. The results indicate that the die coated with diamond-like carbon with silicon has a better surface finish when compared with uncoated die. This trend is in agreement with the results reported by Krishnan et al. [4].

3.3.2 Microgear

Surface roughness measurement for the microgears has been measured, and the average value is 1.649 µm (R_a). It should be noted that the trials have been conducted with any lubrication. Better lubrication could have improved the gear surface quality. This was observed in the case of microgear extrusion of 7075 aluminum alloy [7]. Another interesting phenomenon noticed was nonlubricated gears showed the tendency to curve while lubrication extruded ones did not. This might be due to the presence of only four grains across the diameter of the initial work piece, and therefore, any inhomogeneous deformation could cause this bending behavior. This pattern of behavior was not observed in the current work.

4 Conclusions

In this work, experimental investigation on microextrusion is presented. On the experimental side, microextrusion setup and split die type extrusion die has been designed and tests were conducted successfully to study the deformation characteristics. A simulation run has been carried out using AFDEX software to find out the force displacement response, and the results are compared with experimental trials.

The following concluding remarks are drawn:

- For both copper and aluminum specimens, the smaller grain consumes high deformation force due to the presence of high grains count compared with larger grain specimens.

Table 4 Details of surface roughness measurement

Specimen name	Material	Grain size (μm)	Average surface roughness (R_a) without coating (μm)	Average surface roughness with (R_a) coating (μm)
Cu38	Pure copper	38	0.528	0.468
Cu90		90	0.566	0.487
Cu204		204	0.572	0.515
AA34	Pure aluminum	34	0.630	0.624
AA74		74	0.651	0.641
AA124		124	0.677	0.669

- In case of coarse grains the anisotropic properties of each grain become significant to the deformation behavior and lead to the inhomogeneous deformation.
- Fine-grained billets have relatively higher hardness than coarse-grained billets after the extrusion process. This is consistent with Hall–petch relation which states that the strength of the coarse grain size material should be lower than those of finer grain size material.
- Strength of material increases due to decrease in grain size.
- Dies coated with diamond-like carbon with silicon has a better surface finish when compared with uncoated dies.
- The copper microgear of modulus 0.416 mm, 6 numbers of teeth and outer diameter of 3 mm has been successfully extruded.
- In microgear, it could be noticed that the hardness value at the tooth area is higher when compared to the central area.

The conventional knowledge on material deformation behavior is not applicable in the analysis of microforming process. This research will further facilitate the development of new microforming technology in the areas of microelectro mechanical systems, which will help in introducing microextrusion for mass production.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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