Original Article

Institution of MECHANICAL ENGINEERS

Journal of MECHANICAL ENGINEERING SCIENCE

Proc IMechE Part C:
J Mechanical Engineering Science
0(0) 1–12

DOI: 10.1177/0954406219899114
journals.sagepub.com/home/pic
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Influence of temperature on deformation behavior of copper during microextrusion process

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Abstract

Micro scale deformational behavior of metals is improved upon increasing the room temperature. Further, the drawbacks of micro forming caused by size effects are reduced significantly. In the current work, investigation on the material behavior of copper at elevated temperature ranging from room temperature to 200 °C is conducted. On the experimental part, a novel micro extrusion die set assembly has been developed along with temperature assistance, where the specimen is heated within the die assembly to study deformation behavior. When the forming temperature is raised, an enlargement of the forming limits is achieved along with a significant reduction in extrusion force. Further, the flow of material inside the die orifice was more uniform, and the micro pin showed a good replication of the die dimensions with homogeneous material deformation. During the increase of extrusion temperature and lubrication conditions (diamond-like carbon coating), the micro pin is more complete with higher dimensional accuracy and surface finish. The investigation on the influence of temperature showed that there is a reduction in microhardness of samples compared to the hardness of samples extruded at room temperature. However, there is a significant reduction of scattering due to homogenizing effect.

Keywords

Copper, size effect, material behavior, forming temperature

Date received: 12 October 2019; accepted: 14 December 2019

Introduction

An economical, reliable, and environmental friendly technology is indispensible for the manufacturing of metallic micro parts ranging from mobile phones to medical products. Metal forming technology is best suited for mass production of metallic micro parts due to its virtues of low cost and high productivity. Some examples include IC chips, connector pins, miniature screws, micro gears, facial implants, clavicle implant, knee plate, and miniaturized tools for minimal invasive surgery. One of the key challenges faced by industrialists is size effects when a macro scale forming process is scaled down to micro scale forming process. It is well understood that in order to facilitate more extensive use of micro forming, better understanding about the mechanism behind size effects is desirable, as it results in the inaccuracy of final product due to the increase in the scatter of the process parameters.[1,2] This is due to the fact that only few grains directly participate in the forming process. Further, each grain characterized by its individual size, orientation, position, and randomly distributed characteristics lead to inhomogeneous material behavior.[3,4] One possibility to counteract the abovementioned effect is performing extrusion at elevated temperature, as size effects occur significantly at room temperature. However, they tend to decrease when the forming temperature is raised. So, in order to compensate the influence of size effect, the forming temperature is increased during micro extrusion process.[5] Chang et al.[6] investigated the effect of temperature on forming by heating the workpiece to an appropriate temperature and found an increase in formability due to the activation of more slip systems. Further, these results are validated by the works of Eichenhuellar et al.[7] Here, the authors investigated the micro forming process at elevated temperature (above room temperature and below recrystallization temperature) and

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observed a homogeneous deformation in the extrusion process due to the dislocation movement which is thermally activated only at elevated temperature. Moreover, it was found that the forming temperature significantly affects the material deformation behavior compared with other factors such as pin diameter, lubrication condition, grain size, and punch velocity. To further understand the forming behavior and inhomogeneous material character at elevated temperature, extrusion with CuZn15 and stainless steel was performed.[8–10] In all the cases, it was found that the average hardness of the specimen formed at room temperature has 60% higher hardness compared with the specimen formed at elevated temperature . However, the scatter of single hardness spots decreases at elevated temperature. Another similar result which was observed was that the increase of temperature reduces the flow stress significantly with an enlargement of the forming limits. However, there are some limitations in conducting elevated temperature forming process as temperature should be controlled in a certain range to avoid excessive grain growth and metal oxidation.[11] In order to understand the physical nature and deformation mechanism behind the thermo-mechanical interactions, analytical and numerical methods have been developed. Finite element simulation study was also carried out to study the microstructure evolution using conventional recrystallization theory models.[12] It was reported that a larger extrusion ratio, faster extrusion speed, friction coefficient, and a refiner initial grain helped to obtain a smaller grain size with more homogeneous grain distribution. The relationship between extrusion temperature and micro structure for magnesium alloys has been widely reported.[13] Mg-3Zn-02Ca-0.5Y alloy had a good formability with an optimal mechanical properties with fine grained micro structure obtained at the extrusion temperature of 250 °C. Further, 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 material as received. Investigation of heat resistant magnesium alloys with excellent mechanical properties could be found in the works of Tang et al.[14] It was found that addition of Sn element can effectively refine grain, form high melting point, high hardness, and good thermal stability. Also pure titanium with refined grain equal channel angular pressing (ECAP) exhibits better micro forming properties compared to coarse grain. Good formability was observed when the deformation temperature rose to 300 °C.[15] Investigation of laser-heating methods for stamping cylindrical micro parts with a diameter of 4 mm was carried out, and it was found that the process could be used to reduce the stamping force requirements and increase the achievable aspect ratios of stamped parts.[16]

Although there are number of works which are available on various aspects of micro forming, there is still a lack of adequate research that addresses micro forming at elevated temperature. Moreover, the influence of temperature on friction, hardness, and surface finish is still to be explored. In the current work, the influence of temperature on deformational behavior of copper during micro extrusion process is investigated in a temperature range starting from room temperature to 200 °C. Micro extrusion tests with heating assistance were conducted using cylindrical specimens made by pure copper. The effect of temperature on deformation force, friction, micro-hardness, and surface finish was investigated to understand the deformation behavior. The benefit of forming at elevated temperature is that it includes the reduction of applied force and improves material formability with an expectation of homogenizing effect. Further, all materials demonstrate superior ductility while being formed, regardless of its mechanical characteristics at room temperature.

Design of experimental setup

In order to study the effect of temperature on deformational behavior in micro extrusion process, a novel die set assembly has been designed and developed to carry out the tests with pure copper. Based on the requirement of the testing setup, the die and the punch pin are designed and dimensioned accordingly. Five tests were performed using the die to check the repeatability of the process and the average value was taken. The experiments were conducted in three phases. In the first phase, the trials were conducted without any lubrication; in the second phase, servo 68 lubricants were used as lubricant; and in the third phase, the dies were coated with diamond-like carbon (DLC) with silicon to reduce the effect of friction.[17,18] It is a nano composite 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 0.65 μm. Figure 1 shows the details of die set assembly which includes upper plate, lower plate, and segmented die (split type). Table 1 gives the details of material and manufacturing operations used for die assembly components. One of the most important and critical component of the die set assembly is the extrusion die. The die cavity is machined using electrode sparkling technique. The die surface is polished to ensure similar surface roughness values (1 μm). In order to facilitate easy removal of the extruded product, segmented die (split type) is used. In the previous works, ejectors were used to remove the extruded product from the die assembly which might considerably damage the extruded product. To overcome the above problem, segmented die pattern is used.

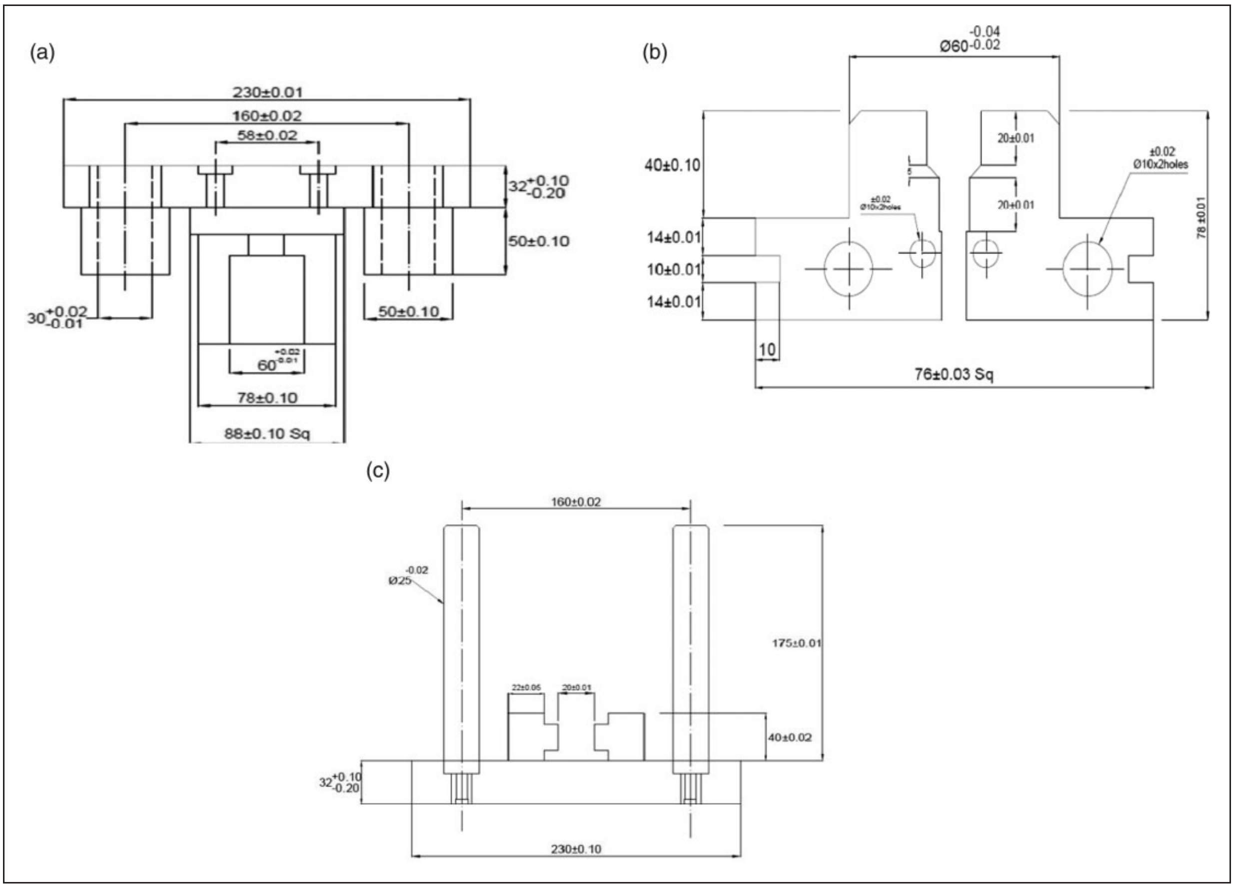

Figure 1. Details of microextrusion die assembly: (a) upper plate, (b) split die, and (c) lower plate.

Table 1. Details of die set assembly.

S. no.	Parts	Materials	Manufacturing operations
1	Upper plate	AISI 1140 carbon steel	Rough turning, milling, and grinding
2	Lower plate	AISI 1140 carbon steel	Rough turning, milling, and grinding
3	Pillar shaft	AISI 1140 carbon steel	Turning, milling and cylindrical grinding
4	Die	HCHCr/WPSDIN 1.23711/AISI D2 (cold work steel)	Drilling (electrode sparkling technique), Wire cut EDM and oil quenching
5	Punch holder	AISI 1140 carbon steel	Turning, milling and grinding
6	Punch pin	HCHCr/WPSDIN 1.23711/AISI D2 (cold work steel)	Turning with carbide tip followed by oil quenching

In this method, the dies are split and the extruded product is removed without any damage. The material is extruded at a punch speed of 0.01 mm/s.

Design of elevated temperature experimental setup

In the current study, the forming temperature is raised from room temperature to 100 and 200 °C. The recrystalization temperature of copper is 270 °C. So the micro forming of copper at elevated temperature should be conducted within the recrystallization temperature. So in this regard, a temperature range of 100 to 200 °C is chosen.[2] In order to raise the temperature of the die set assembly, suitable temperature assistance is interfaced. As in macro forming processes, the billet cannot be heated up outside the die assembly due to high ratio of surface to volume results in high heat dissipation, which cools the billet before beginning the experiment. In the current work, the die set assembly is fabricated such that the billet is heated within the die assembly so that the billet itself gets the desired temperature purely by conduction and the extrusion process takes place subsequently. This prevents the loss of heat in the micro part during extrusion. Further minimum time was required to attain the desired temperature and also sufficient uniform temperature distribution was achieved within the die assembly. The initial source of temperature rise is heating the die. Thus, the die must be machined in order to interlope the heater inside to reach higher temperatures. The die is drilled to a diameter 14 mm on either side which is slightly undersize relative to the nominal diameter of the heater. The heater is assembled inside the die, and proper care is taken to ensure that there is no air gap between the die and heater. Similarly, for temperature measurement, hole to the diameter of thermocouple is drilled and inserted. Both the heater and thermocouple is connected to the controller unit for optimum temperature control. Required temperature can be set in the controller. A relay is an electromagnetic switch that is used to turn on and turn off a circuit by a low power signal, or where several circuits must be controlled by one signal. The relay switch is mainly connected between the main supply and the temperature controller. Thus, when the temperature has reached the desired value, the relay switch cuts-off the supply between the temperature controller and the main supply to avoid over heating of the die. Figure 2 shows the comparison between the measured temperature and pre-set temperature. It can be noted that at the pre-set temperature of 50, 100, 150 and 200 °C, the measured values (using infrared thermometer) were 53, 102, 154, and 203 °C, respectively, indicating that the temperature is well controlled using the heating assistance setup. Table 2 gives the list of components required for elevated temperature setup. Figure 3 shows the testing platform which is equipped with a load cell (10 kN) and an linear variable differential transducer (LVDT) (0–100 mm) to measure the extrusion force and the corresponding ram displacement. Table 3 gives the other important specifications of the machine.

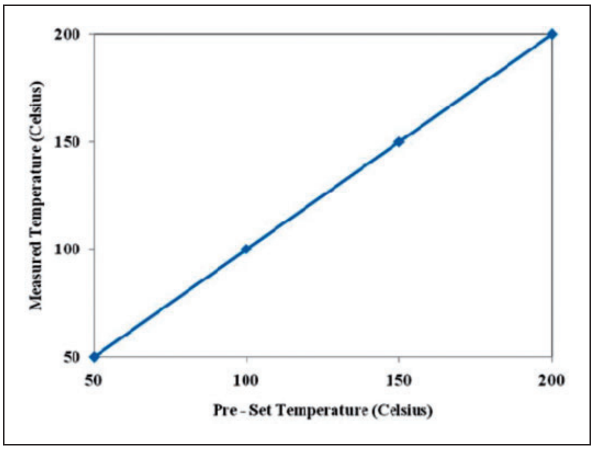

Figure 2. Comparison between pre-set and measured temperature.

Material and processing

Pure copper (99.95%Cu) is used as testing materials in this study, as it is frequently used for micro parts in various microelectronic devices due to its low density, good conductivity, and favorable combinations of mechanical and electrical properties. Copper also finds an important place in the field of micro electro mechanical systems. So understanding the different aspects of formability is essential in order to advance the use of copper in these fields. The billets received with a diameter of 6 mm to a length of 40 mm are then reduced using a micro turning lathe to 2 mm and length of 20 mm with the highest possible accuracy to minimize the geometrical effects. The heat treated copper specimens were etched in a solution of 5 g $FeCl_3$, 50 ml HCl, and 100 ml H_2O for 20–30 s. The microstructure of the tested specimen was observed through optical microscope. The microstructure of copper at different annealing conditions is shown Figure 4.

Experimental procedure

First the prepared copper billet is placed inside the segmented die. Then the segmented die is assembled and inserted through the die provision at the lower flange. The punch pin along with the punch holder is assembled in the upper plate. Now the upper plate along with the punch holder and punch pin is

Table 2. Details of elevated temperature extrusion setup.

S. no.	Item	Function	Specifications
1	Cartridge heater	To heat the die	Diameter 12.7 mm
2	Thermocouple	Used to measure temperature	Type K Thermocouple (Nickel-Chromium)
3	Controller unit	Used for automatic temperature control	Input: thermocouple power supply:80–270 V AC
4	Relay switch	It is an electro-mechanical switch used to cut-off the supply between the temperature controller and the main supply, when the temperature is reached to the desired value	Solid state relay Input: 3–32 V DC Output: 24–480 V AC
5	Display unit	Used to provide set point and also to view the temperature obtained in a digital format	7 segment LED single display Configurations: 3 digits
6	LED	Used to emit light when current flows through it	Red, 3 mm diffused LED

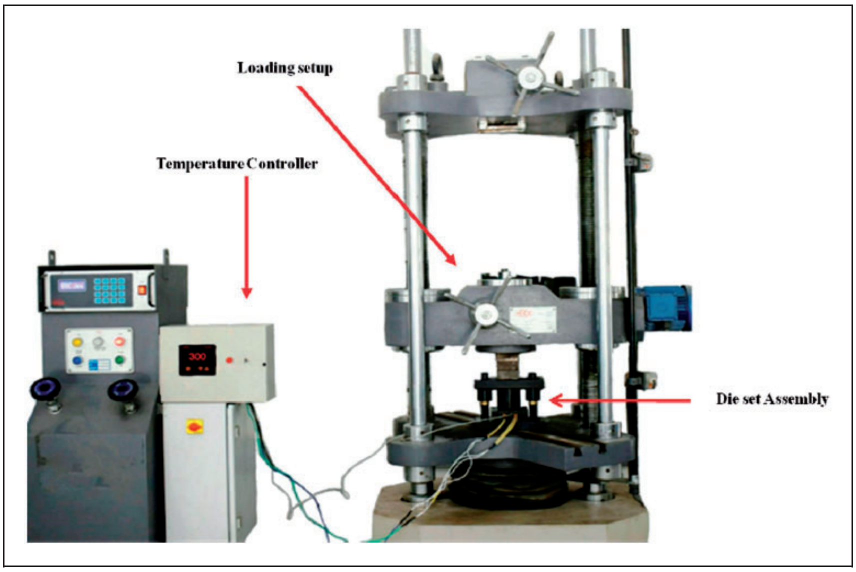

Figure 3. Micro extrusion testing platform.

Table 3. Micro extrusion machine specifications.

S. 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

assembled through the guide piller shaft. The die assembly is placed over the testing platform. The temperature is set in the temperature controller and heating process is started. Once the desired temperature is achieved, the force is applied through the upper punch of the hydraulic press which pushes the upper plate. This will in turn push the punch pin which drives the billet through the die orifice and it is reduced gradually along the travel path. Punch force was recorded at every 1 mm movement of punch travel. The application of force was continued till it reaches the steady state and up to the maximum extrusion length. Once the process is over, the machine is stopped and the segmented die is separated from the lower plate. Then the die is disassembled and the extruded product is removed.

Results and discussion

The micro extrusion of stepped pin is performed successfully using segmented die. The results of effect of temperature in deformation force, friction, microhardness, and surface finish are discussed in the subsequent sections.

Effect of temperature in deformation force

The force–displacement curve (with DLC coating) of copper after reaching a steady state is shown in Figure 5. The maximum deformation force for copper at room temperature (28 °C) is 7451 N, while at elevated temperature of 100 °C and 200 °C, it is 5440 N and 5091 N, respectively. As it can be seen, the punch force is significantly affected by deformation temperature. When the temperature of the die assembly is raised, specimen inside gets heated up. As a result, the grain size of the specimen increases along with the enlargement of grain boundaries. In case of large grain boundaries, there are fewer chances to stop the dislocation at the grain boundaries.[19] Further, increasing of grain size increases the pile up at the boundary which reduces the required stress necessary to move the dislocation across the grain boundary. This makes the metal softer and the force required for deformation decreases significantly. This phenomenon makes the total extrusion force lesser when extruding at the temperature range of 100 and 200 °C. Further, there is a reduction in extrusion force of about 27% and 32% when compared to forming at

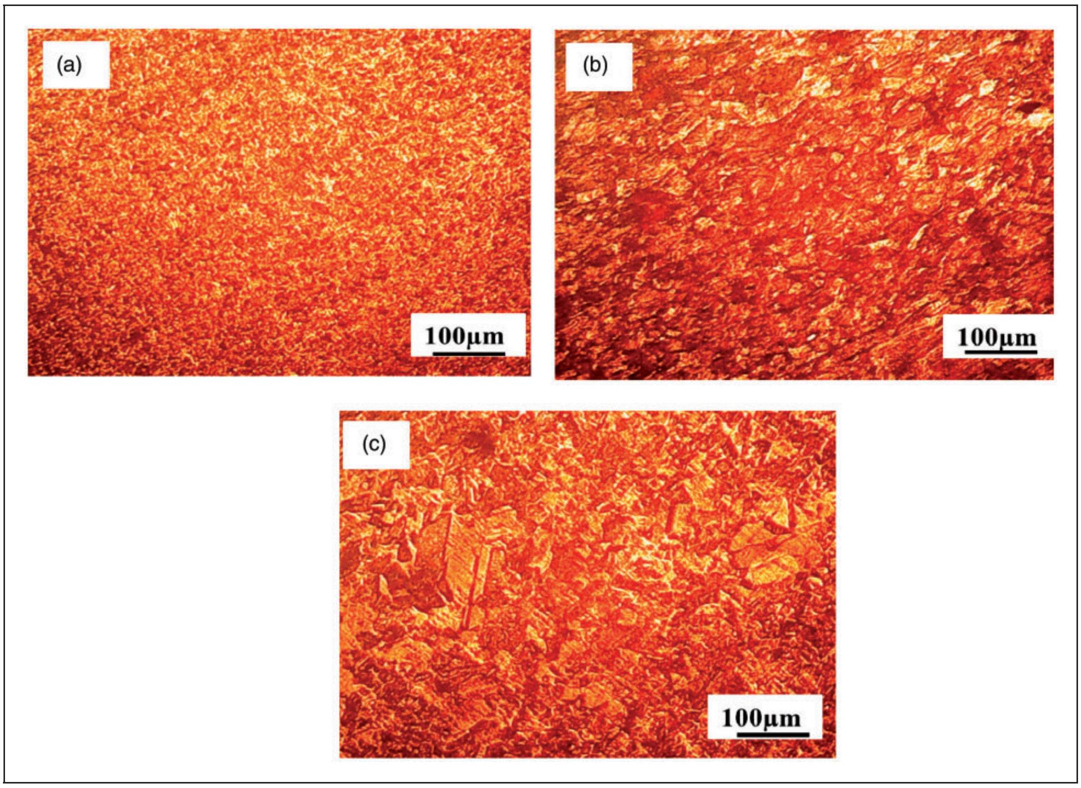

Figure 4. Microstructure of annealed copper: (a) as received, (b) 100 °C, and (c) 200 °C.

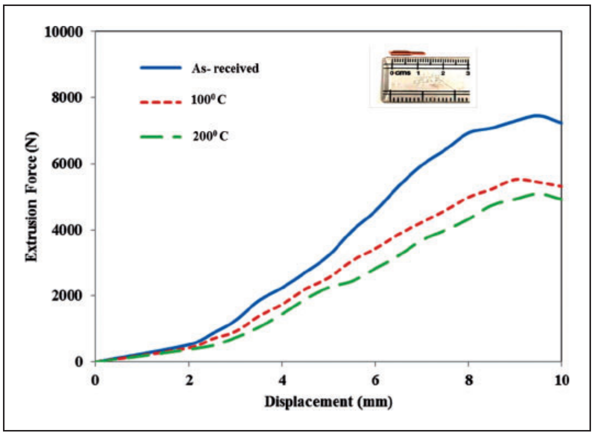

Figure 5. Force vs. displacement of copper at different extrusion temperature (with DLC coating).

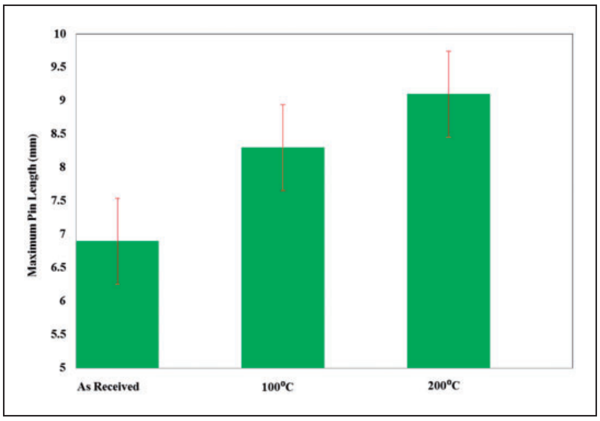

Figure 6. The effect of temperature on the final part dimension (for the pin diameter of 1 mm reduced from the initial diameter of 2 mm).

room temperature. Similarly, a significant improvement in material flow and formability has been observed in micro forming of CuZn15 and X4CrNi18-10.[7] Also, the forming temperature significantly affects the material deformation behavior compared with other factors such as pin diameter, lubrication condition, and grain size. As reported earlier, at elevated temperatures (400 and 800 °C), the metal gets softer so that less deformation force is required to make the billet flow inside the die orifice and extrude to the required dimension.[20,21] Figure 6 represents the maximum pin length obtained from different forming conditions. The maximum pin length of 9.1 mm was achieved during forming at 200 °C. Minimum length of 6.9 mm was observed when forming at room temperature. One possible explanation for the minimum length is a high resistance in the flow of material inside the die orifice which results in reduced length and poor replication with respect to die dimensions. But when the extrusion temperature is raised the flow of material inside the die orifice was more uniform and the micro stepped pin showed a good replication of the die dimensions. Another important aspect of forming at elevated temperature is homogeneous deformation. Forming at room temperature results in inhomogeneous material behavior. The effect of this leads to increased scatter which further results in unpredictable mechanical properties and random forming behavior. As a result, it makes the process design impossible. Figure 7 depicts the coefficient of variation (ratio of standard deviation to mean flow stress) quantifying the scatter. Initially, the percentage of scatter was more at room temperature and as the temperature increases, there was a reduction in scattering. By comparing the scattering between the room temperature and 200 °C at a longitudinal strain $\acute{\epsilon} = 0.8$, a reduction of approximately 73% was achieved. Similarly, for 100 °C, the reduction was about 7%. The results are in agreement with the previous works.[8] With the elevation of forming temperature and grain refinement, it is possible to minimize size effects and reduce inhomogeneous material flow significantly.[2]This explains the ease of formability of the process at elevated temperature where more homogeneous material behavior is achieved compared to the forming processes at macro scale. Figure 8 represents the stereomicroscope (SEM) micrograph of copper samples at different forming conditions. From the figure, it could be noted that there is only a negligible amount of surface oxidation phenomenon happened at the temperature range of 100 °C and 200 °C. Jiang et al. in their work observed a massive oxide layer formation in warm forming of copper samples at a temperature range of more than 650 K. In order to avoid oxidation, the authors carried out warm forming at a temperature range of less than 650 K.

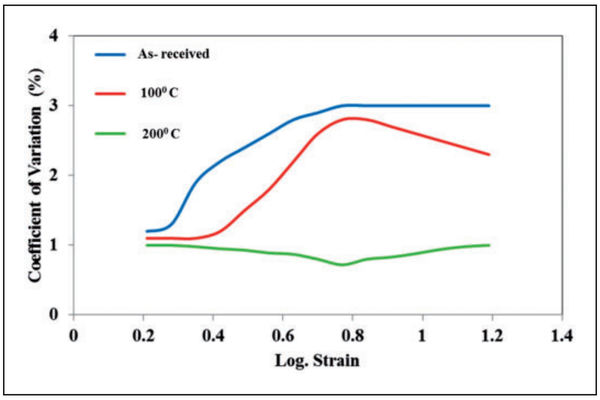

Figure 7. Coefficient of variation vs. longitudinal strain for copper at different forming temperatures.

Effect of friction at micro scale deformation

Due to the high ratio of the free surface to volume of micro parts and surface topography of the specimen being held constant, friction has more effect in the micro metal forming process compared to traditional macro forming process. Figure 9 represents the micro stepped pin of various length obtained from different forming conditions. The variation in the length of the pin at different conditions is due to unbalanced material flow inside the die orifice. Comparison of pin length and extrusion force does permit in evaluating the better friction conditions for micro forming. In this regard, the experiments were conducted in three different phases. In the first phase, the dies were uncoated and in the second phase, servo 68 lubricants were used, whereas in the third phase, the dies were coated with DLC. DLC coating has been increasingly gaining more attention as it eliminates size effects of

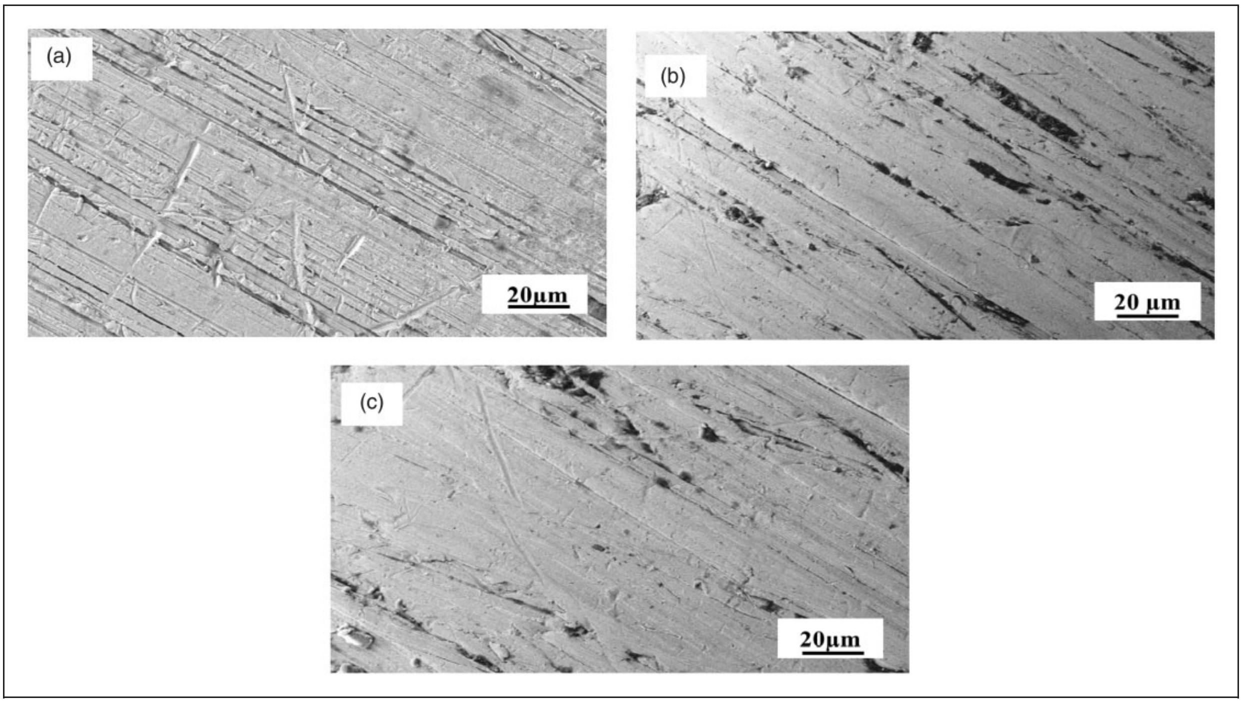

Figure 8. SEM micrograph of copper samples at different forming conditions: (a) as received, (b) 100 °C, and (c) 200 °C.

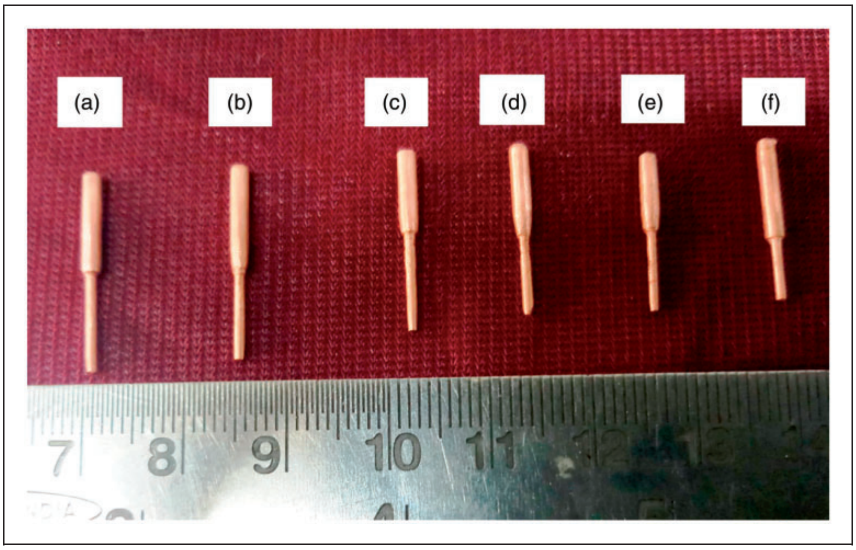

Figure 9. Copper micro stepped pin of various lengths obtained from different forming conditions: (a and b) 200 °C, (c and d) 100 °C, and (e and f) as received.

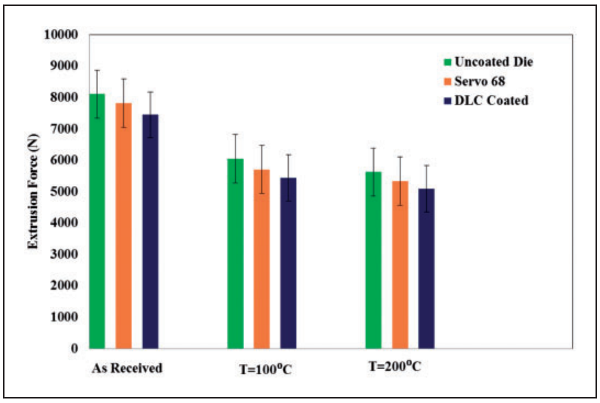

Figure 10. Effect of friction on extrusion force at different forming conditions. DLC: diamond-like carbon.

Table 4. Details of micro stepped pin lengths obtained from different friction conditions, at the forming temperature of 28 °C.

	Uncoated die	Servo 68	DLC-coated die
Maximum pin length (mm)	5.8	6.8	6.9
Minimum pin length (mm)	5.1	6.2	6.4
Mean pin length (mm)	5.5	6.4	6.7
Standard deviation	0.27	0.23	0.19
Mean maximum extrusion force (N)	8112	7823	7451

DLC: diamond-like carbon.

friction in micro forming and also protects the die with respect to wear resistance. Figure 10 represents the different extrusion force obtained from different friction conditions. The minimum extrusion force (7451 N) required for deformation is found in the case of DLC-coated die. In case of servo 68 lubricant, the deformation force is lesser when compared to uncoated but not lower than DLC. A similar trend is observed when the forming temperature is raised from 100 °C and 200 °C. About 9% reduction in extrusion force is observed between uncoated and DLC-coated dies in all three cases of friction conditions. A reduction of punch load by 15% using DLC coating was also reported in previous cases.[22] Further, as demonstrated in literature,[17,18] it is worthwhile to remember that DLC coating had reduced load of 25% with respect to uncoated die. One possible explanation was that higher the temperature, better the lubrication, which has resulted in a considerable reduction of friction. With increasing extrusion temperature and better lubrication conditions, the micro stepped pin was more complete with higher dimensional accuracy.[23–25] In order to carry out a detailed investigation on friction at cold forming, the forming force and pin length were compared for different friction conditions (see Table 4). Three replicates were carried out at different conditions. Three replicates are found sufficient to assess the repeatability of the experiments. As expected, minimum force (7451 N), maximum pin length (6.9 mm), and maximum average pin length (6.7 mm) was noted in the case of DLC-coated dies. A longer pin length indicated a lower level of friction between the die and work piece. In case of uncoated die maximum force (8112 N), minimum pin length (5.1 mm), and average pin length (5.5 mm) were noted. The results seemed to be consistent and repeatability of the process was pretty good. When the forming temperature was raised to 100 °C, an overall reduction in forming force was noted in all three cases of friction conditions as reported in Table 5. In addition, there is a rise in the pin length when the forming temperature is raised.

Table 5. Details of micro stepped pin lengths obtained from different friction conditions, at the forming temperature of 100 °C.

	Uncoated die	Servo 68	DLC-coated die
Maximum pin length (mm)	6.7	7.1	8.3
Minimum pin length (mm)	5.9	7.6	7.9
Mean pin length (mm)	6.3	7.3	8.1
Standard deviation	0.29	0.19	0.15
Mean maximum extrusion force (N)	6048	5712	5440

DLC: diamond-like carbon.

Table 6. Details of micro stepped pin lengths obtained from different friction conditions, at the forming temperature of 200 °C.

	Uncoated die	Servo 68	DLC-coated die
Maximum pin length (mm)	7.1	8.4	9.1
Minimum pin length (mm)	6.7	8	8.8
Mean pin length (mm)	6.9	8.2	8.9
Standard deviation	0.16	0.15	0.13
Mean maximum extrusion force (N)	5628	5346	5091

DLC: diamond-like carbon.

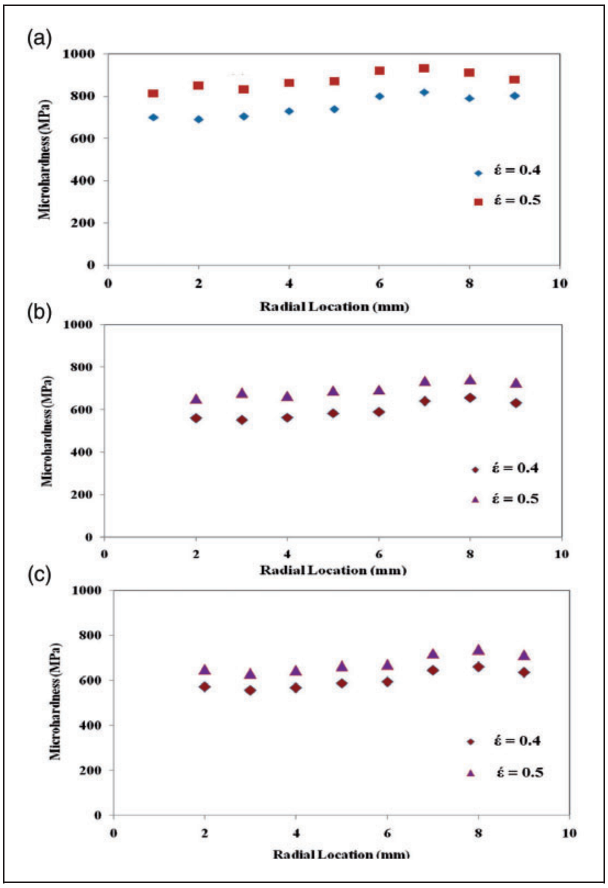

Figure 11. (a) Microhardness distribution at room temperature and microhardness distribution at warm forming temperature 100 °C (b) and 200 °C (c).

Maximum pin length (8.1 mm) was also observed. Table 6 represents the conditions of forming at 200 °C. Maximum pin length (9.1 mm) was achieved with the average pin length of 8.9 mm. So it can be concluded that at room temperature, there is a high resistance in the flow of material inside the die orifice which results in the poor replication with respect to die dimensions. Further, due to the absence of lubricant and surface coating, friction increases significantly which results in the lowest pin length. In case of liquid lubricant being used, it could not be retained inside the die orifice as it was easily squeezed out from the die wall surface. But when the extrusion temperature is raised along with proper lubrication condition (DLC coated), the flow of material inside the die orifice was more uniform with minimum resistance resulting in the largest pin length.

Microhardness evaluations

As part of the study on mechanical properties, microhardness tests on the extruded samples were done. Microhardness measurements were taken at various axial locations on deformed micro stepped pin after the extrusion process. For the microhardness test procedure, ASTM E-384 was followed, and due to smaller diameter of samples, they could be used directly for microhardness measurement. The specimen was mounted in epoxy resin and polished to half of the diameter to avoid surface effect in microhardness testing. The measurements were done using the microhardness tester (Mitutoyo – load range 10 g to 2 kg). Indentation was carried out with a load of 50 g for 10 s during the test. Comparing Figure 11(a) and (c) of universal microhardness of cold and warm forming specimens, a decreasing hardness was noticed along with a reduction of hardness scatter in both the strain rate ($\dot{\epsilon} = 0.4$ and $\dot{\epsilon} = 0.5$). In case of hardness measurement for the forming conditions at 100 °C and 200 °C, the reduction with respect to room temperature was 20% and 22%, respectively. The results are quite similar with the previous work,[7] where a reduction of 50% average hardness gradient was achieved by elevating the temperature from 200 °C to 300 °C using CuZn15. Similarly, a reduction of 60% of coefficient of variance at a strain $\dot{\epsilon} = 1.0$ was noted.[8] Tables 7 and 8 represent the average microhardness and coefficient of variation of the samples extruded at different forming conditions at two different strain rates ($\dot{\epsilon} = 0.4$ and 0.5). At lower strain rate, the coefficient of variation was maximum (6.8% and 4.8%) at 28 °C and minimum (6.2% and 4.4%) at

Table 7. Microhardness of the extruded product at different forming conditions ($\epsilon = 0.4$).

Forming temperature (°C)	Microhardness of extruded products – Locations (mm) 1	2	3	4	5	6	7	8	9	Coefficient of variation (%)
28	701	690	705	730	738	800	820	790	810	6.80
100	686	666	691	705	712	770	772	792	773	6.41
200	571	555	567	587	594	630	643	660	635	6.25

Table 8. Microhardness of the extruded product at different forming conditions ($\epsilon = 0.5$).

Forming temperature (°C)	Microhardness of extruded products – Locations (mm) 1	2	3	4	5	6	7	8	9	Coefficient of variation (%)
28	815	840	831	843	859	920	930	910	870	4.81
100	754	735	740	774	781	805	821	831	820	4.64
200	650	630	635	645	651	655	702	717	665	4.49

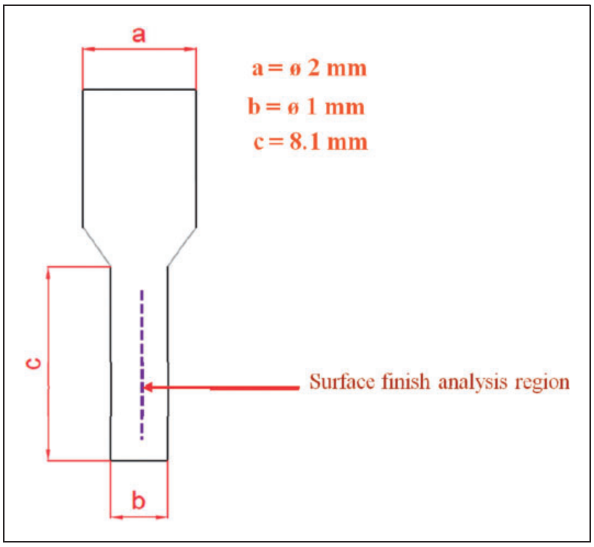

Figure 12. Surface finish measurement of micro stepped pin.

200 °C. Further as expected, the coefficient of variation was found decreasing when the forming temperature was raised.[26,27] Thus, it could be concluded that with the rise of temperature, more uniform hardness can be achieved.

Surface finish measurements

Surface finish 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 carried out along the length of all extruded samples of copper. The center line average value surface roughness value (R_a) was measured for three replicates. For each samples, the measurements were taken at 4–5 points (Figure 12). Tables 9, 10, and 11 give the surface roughness values of copper extrudates at different forming conditions. The combined data of all measurements was used to make inference about the average quality attribute. From the table, it could be noted that surface finish of copper samples extruded at room temperature (28 °C) and without coating has a poor finish (0.541 µm) when compared with samples extruded from DLC with the forming temperature of 200 °C (0.460 µm). As expected, lubricated die (Servo 68 and DLC) always produces better surface quality, i.e., low roughness value. The increase of surface roughness of extrudates is due to increase in plastic deformation. At elevated temperature (200 °C), about 17% raise in surface finish value was noted between the samples extruded from uncoated die to DLC-coated die. Further, extrudates with maximum forming length resulted in a better surface finish compared with extrudates of minimum forming length. Higher

Table 9. Details of surface roughness measurement (uncoated).

Specimen name	Forming temperature (°C)	Pin length (mm)	Average surface roughness (R_a) (µm)
Cu 28	28	5.8	0.527
		5.1	0.541
Cu 100	100	6.7	0.517
		5.9	0.529
Cu 200	200	7.1	0.508
		6.7	0.516

Table 10. Details of surface roughness measurement (servo 68 lubricant).

Specimen name	Forming temperature (°C)	Pin length (mm)	Average surface roughness (R_a) (μm)
Cu 28	28	6.8	0.493
		6.2	0.499
Cu 100	100	7.6	0.471
		7.1	0.475
Cu 200	200	8.4	0.453
		8	0.459

Table 11. Details of surface roughness measurement (DLC coated).

Specimen name	Forming temperature (°C)	Pin length (mm)	Average surface roughness (R_a) (μm)
Cu 28	28	6.9	0.452
		6.4	0.460
Cu 100	100	8.3	0.440
		7.9	0.447
Cu 200	200	9.1	0.426
		8.8	0.429

the temperature with better lubrication conditions, the improvement in the surface finish was significantly better.

Conclusions

The present work focuses on the material behavior of copper at elevated temperature using micro extrusion process. On the experimental part, a novel micro extrusion die set assembly has been developed along with temperature assistance where the specimen was heated within the die assembly and experiments were conducted successfully to study the deformation characteristics.

The conclusions drawn from the study are summarized:

- Due to the rise of temperature during forming, there is a reduction in the extrusion force of about 27% and 32% when compared to forming at room temperature.
- The maximum pin length of 9.1 mm was achieved during forming at 200 °C and minimum length of 6.9 mm was observed when forming at room temperature.
- The percentage of scatter was more at room temperature, and as the temperature increased, there was a reduction in scattering. Comparing the scattering between the room temperature and 200 °C at a longitudinal strain $\acute{\epsilon} = 0.8$, a reduction of approximately 73% was achieved.
- The maximum extrusion force at room temperature was observed in uncoated die (8112 N) and then minimum force was at DLC-coated die (7451 N).
- About 9% reduction in extrusion force was observed between uncoated and DLC-coated dies in all three cases of friction conditions.
- Minimum pin length of 5.1 mm was extruded with the average length of 5.5 mm during forming at room temperature in case of uncoated die.
- Maximum pin length of 9.1 mm was extruded with the average length of 8.9 mm during forming at 200 °C with DLC-coated die.
- In case of microhardness measurement for the forming conditions at 100 °C and 200 °C, the reduction in hardness with respect to room temperature is 20% and 22%, respectively.
- The surface finish of samples extruded at room temperature and without coating has a poor finish when compared with samples extruded from DLC with the forming temperature of 200 °C.

Summarizing the benefits of forming at elevated temperature, the drawbacks of micro forming caused by size effects is reduced. Thus, this work will facilitate a dedicated and more extensive use of micro forming technology especially for hard to work alloys and polymers to boost the forming limits and will definitely pave the way for future research and development in the area of elevated temperature micro extrusion process. Moreover, the experimental results obtained will be useful for benchmarking of theoretical models.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The authors wish to thank the Science and Engineering Research Board, Government of India (EMR/2015/000370) and Management of PSG College of Technology, Coimbatore and PSG Institute of Technology and Applied Research, Coimbatore, for their funding and support provided to carry out this research work.

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