Grain size effect on the assembly quality of micro-scaled barrel formed by microforming

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Abstract

In this research, a method employing micro-extrusion was designed to produce the micro-scaled barrel-shaped parts with complex geometrical features to study the feasibility of the proposed microforming method and its grain size (GS) effect on the formability of the complicated internal features in terms of deformation behavior, material evolution, accuracy of dimensions and final components quality. The results reveal that the deformation behavior is highly affected by GS and becomes unpredictable with increased GS. In addition, assembly parameters including feature dimension, tolerance and coaxiality also vary with GS, and the variation of GS needs to be accommodated by different assembly types, viz., clearance fit or transition fit. From the microstructural evolution aspect, it was identified there are two dead zones and four shear bands, and the formation of these deformation zones is barely affected by the variation in GS. Though bulges, cracks, and fracture induced voids were observed on the surface of the final components, tailoring the microstructure of the working material with finer grains can significantly avoid these defects. This study advances the understanding of

forming microparts by extrusion processes and provides guidance for microforming of similar microparts.

Keywords: Microformed part; size effect; extrusion; microstructural evolution; dimensions; assembly accuracy.

Highlights:

1. An extrusion microforming system was developed to fabricate micro-scaled barrel-shaped components with complex features.
2. Grain size effect during the process was comprehensively investigated.
3. The assembly types of the part produced by microforming are highly related to the grain size.

1. Introduction

Pogo-pin, which is assembled by the plunger, barrel and bulk, is a precision electronic hardware component and is widely used in aviation, aerospace, communications, and electronics because of the advantages of small size, high precision, and light quality. However, pogo-pin is a kind of micropart traditionally manufactured by micromachining with at least two dimensions less than 1 mm, which requires a few time-consuming machining operations to obtain the needed geometries and quality [1]. A more efficient and cost-effective manufacturing approach is thus needed. Microforming is a micro-manufacturing technique aimed to realize the fabrication of micro-scaled parts via plastic deformation of materials and is a promising process for mass-production of microparts with large-scaled needs due to its many distinct benefits such as high material utilization, low cost, high productivity and good efficiency [2]. However, the micro-scaled deformation behaviors of materials can no longer be fully predicted by macro-scaled theories such as material flow behaviors [3], yield strength [4], springback performances [5], inhomogeneous deformation behaviors [6], formation of undesirable geometry [7], etc., which are partly induced by the so-called size effect [8]. It is worth noting that grain size (GS) is one of the main factors that lead to unpredictable material behaviors [9-11]. Although the microforming systems aiming at fabricating the plunger and bulk of the pogo-pin have been developed [1, 12], the forming of the complex features of the barrel of the pogo-pin is difficult to be well controlled in terms of formability, accuracy of dimensions and assembly performance due to size effect; thus, it is still a challenge to realize the fabrication of this component through microforming by successfully addressing these issues.

Extrusion forming operation is widely used in microforming and has been extensively investigated and developed in prior applications. Various conditions such as lubrication, die material and die size were considered in microextrusion process to investigate size effect during the process [13, 14]. Moreover, scale size and GS induced size effect in extrusion process were also comprehensively investigated in terms of the material deformation behaviors [15, 16], formation quality of the material [17, 18], the microstructural evolution of the material [19, 20], etc. Jiang et al. [18] verified that extrusion is a feasible method for making accurate internal features in microforming by fabricating the internal gear by extrusion.

The feasibility of the processing methods for fabricating the parts with complex features and the deformation behaviors induced by size effect during the process have not been systematically studied. Meanwhile, GS induced variable assembly properties need to be investigated to meet the needs of different assembly types in the industry. In this research, the barrel-shaped part with two adjoining hole features was accepted as the case study component. The microforming system based on extrusion technique was developed. The effect of GS on deformation behavior, the evolution of microstructures, the accuracy of dimensions and surface quality was investigated. It should be worth mentioning that GS effect on the component dimensions related to assembly including tolerances and coaxiality was extensively investigated, which was not systematically studied in previous research.

2. Materials and methods

T2 pure copper sheet (purity > 99.90 wt.%) was selected here as the test material. Three annealing conditions including 500°C for 2h, 600°C for 3h and 750°C for 2h were adopted to obtain various GSs, and Equation. (1) was adopted to describe the flow stress of the specimens, where y is yield stress, n is the strain exponent, and c is the strength coefficient.

$$\bar{\sigma} = c\bar{\varepsilon}^{n} + \mathrm{y} \tag{1}$$

A metallographic microscope was adopted to characterize the microstructures of the specimens. Room temperature tensile tests of the specimens were conducted on an MTS mechanical test system at a strain rate of 0.001 s−1. The corresponding microstructures are shown in Figures. 1(a-c), and the room temperature plastic strain-flow stress curves and their corresponding fitted curves obtained by Equation. (1) are shown in Figure. 1d.

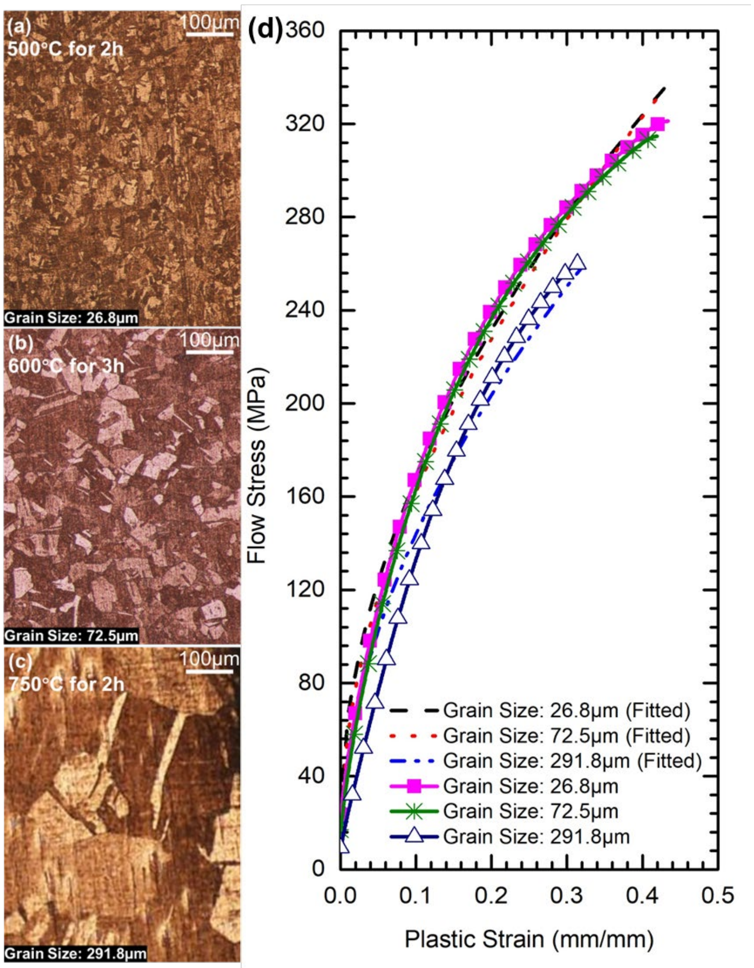

Figure. 1. Microstructures of pure copper annealed in various conditions: (a) 500°C for 2h, (b) 600°C for 3h, and (c) 750°C for 2h; (d) properties of materials with various grain sizes (GSs).

The dimensional schematic of the target part is shown in Figure.2, and the tolerances of the diameters of the two holes are both +100 μm. In tandem with previous research, extrusion technique was proved to be an effective method for processing micro-scaled parts. Therefore, extrusion technique was chosen as the candidate here, and the forming system based on extrusion was developed. Figure. 3 and Table. 1 show the details of the forming system and its corresponding dimensions, respectively. During the first operation, a cylinder with a diameter of D_{11} is cut from the workpiece and the resulting hole is used for the location of the punch in the next operation. In the second operation, a ring is cut from the sheets by blanking operation. Then, the ring is formed into the barrel-shaped part by a punch with the desirable features in the third operation. The punches with the diameter of D_{22} and D_{33} are designed for the location of the specimen. A 50kN MTS machine was selected to conduct the extrusion process, and the effect of strain rate was neglected due to a slow punching rate of 0.01 s^{-1}. Machine oil was selected to keep the surfaces of the workpieces and equipment lubricated before each operation to reduce friction. The microstructural evolution and surface qualities of the components were identified by the metallographic microscope and scanning electronic microscope (SEM). FE simulations were conducted by DEFORM to numerically study the material deformation and formation mechanism of undesirable geometries.

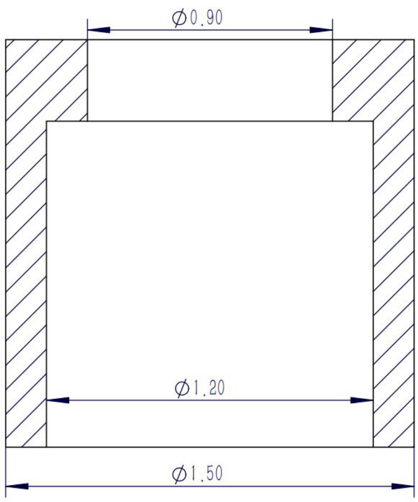

Figure. 2. Dimensional schematic of the target part (Unit: mm).

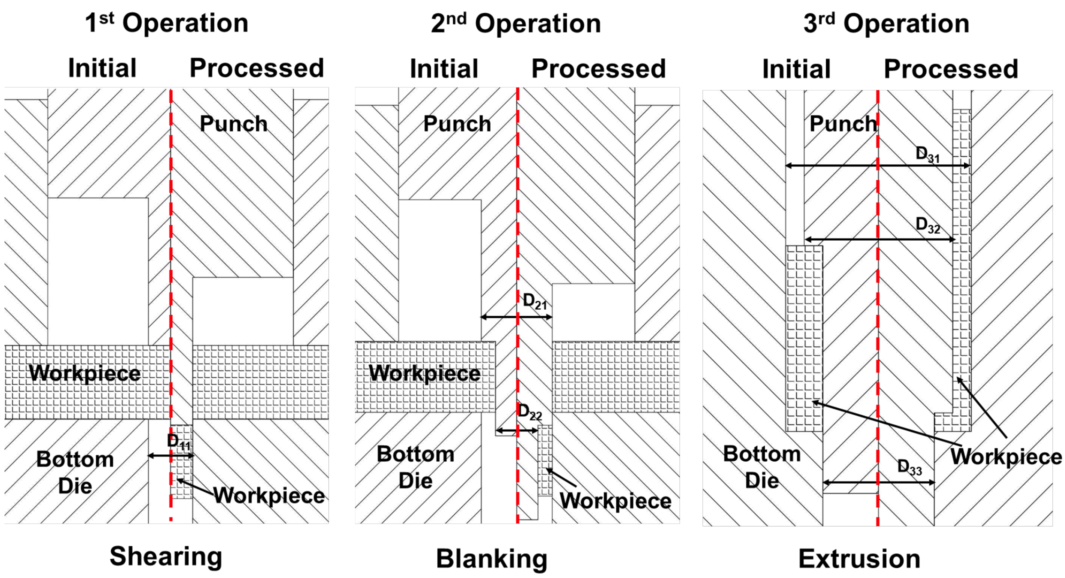

Figure. 3. Improved three-stage forming system based on extrusion.

Table. 1 Dimensions of the forming system.

Feature	D_{11}	D_{21}	D_{22}	D_{31}	D_{32}	D_{33}
Size (mm)	0.9	1.5	0.9	1.5	1.2	0.9

3. Results and discussion

3.1 Deformation behaviors

To understand the deformation behavior, load-stroke curves during each operation obtained by physical experiments are plotted in Figure. 4. For the first and second operations, shearing is the main deformation type and there are three stages to the operations as shown in Figures. 4(b,c), which are similar to the results in previous research [12, 21]. The deformation loads in both operations increase when GS decreases. It is known that the grain boundary acts as a barrier to dislocation motion [22]. The grain boundaries greatly become denser with the refinement of the GS and thus outcome in a stronger constraint to the deformation, leading to a higher load of deformation. As shown in Figure. 4d, the load of deformation in the experiment is increased with stroke and also decreased with the increase of GS during the third operation. Unlike the first and second operations, the deviations of load between various GSs decrease at the later stage as the punch moves. That is because the value of the load is influenced not only by material deformation but also by friction between the component and tools. The wall of the sample grows along the height direction during the third operation, which leads to the expanded contact surface between the parts and tools. Thus, the friction may increase with the movement of the punch and make more contributions to the load, which causes reduced deviations. Figure. 5 show the comparison of both fine-grained and coarse-grained stroke-load curves in the third operation obtained by both physical experiment and simulation. In the first and second operations, only the ring-shaped workpiece is blanked from the sheet, which means that both operations have little influence on the formation of the final part. Thus, simulating the first and second operations is meaningless and time-consuming. All the target features are realized through the third operation, and most of the internal microstructural evolutions also occur in the third operation. Thus, it is indispensable to simulate the third operation. The third operation of the process exhibits a concentrated deformation area primarily located at the edge of the punch, which means that the initial two operations of blanking have a negligible impact on the material deformation behavior during the third operation. Thus, the third operation was simulated directly, ensuring efficient and effective prediction in this research. The results show that both fine-grained and coarse-grained curves obtained by simulations and experiments show similar trends, which means that the simulations have the ability to predict the deformation behavior of the material during the process.

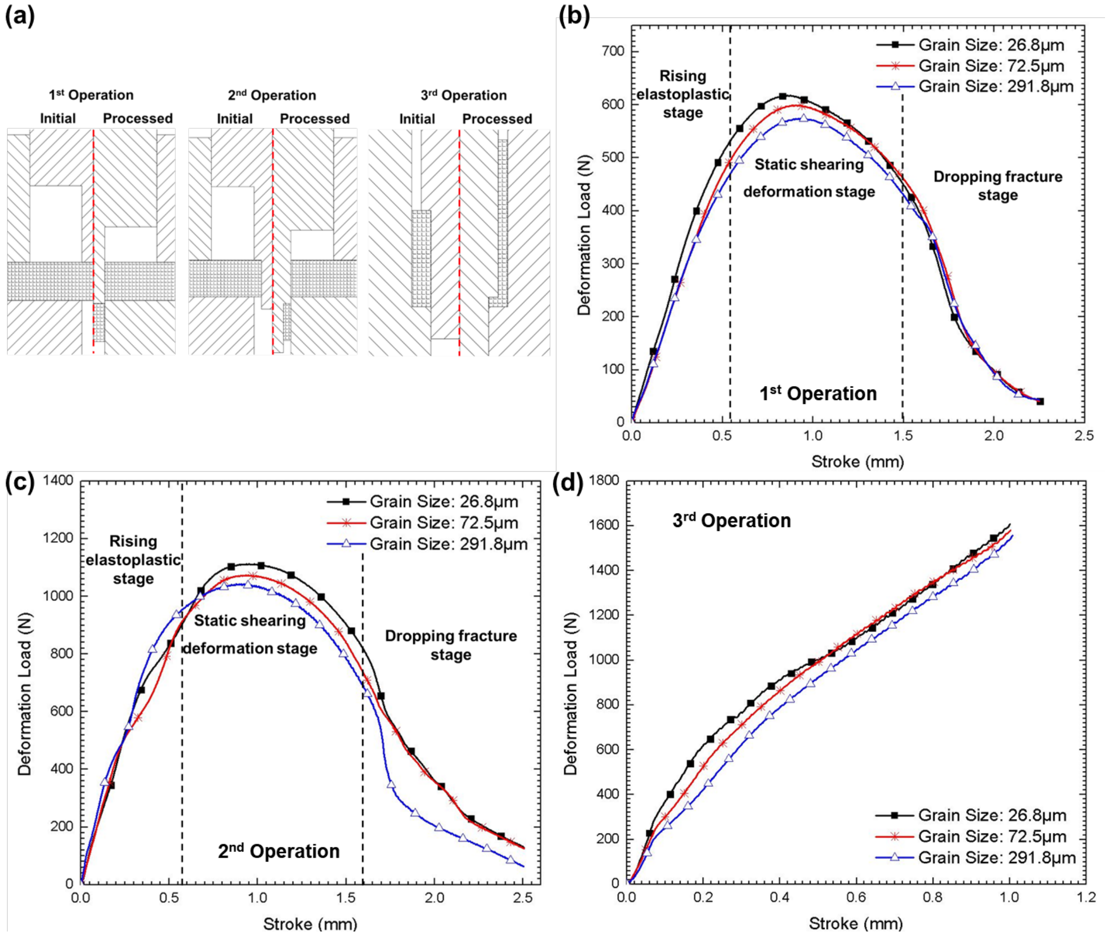

Figure. 4. (a) Schematic diagram of each operation, and load-stroke curves in (b) the first operation, (c) the second operation, (d)the third operation.

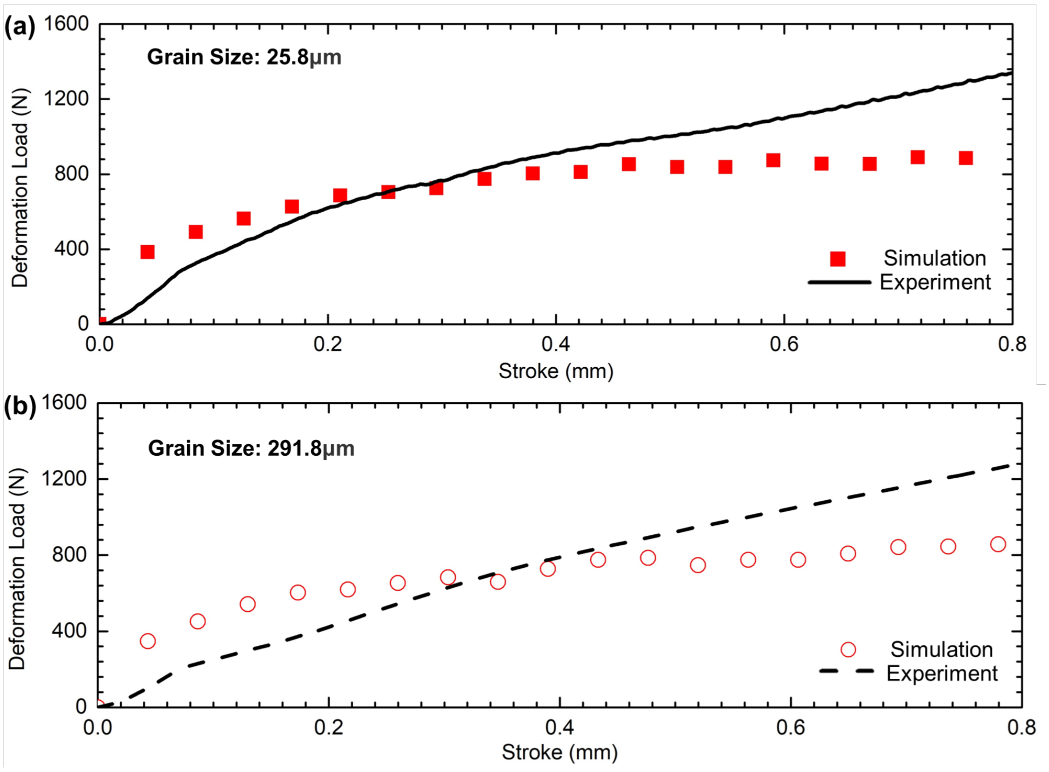

Figure. 5. Comparison of stroke load curves obtained by simulations and experiments with various GSs: (a) 25.8μm and (b) 291.8μm.

3.2 Microstructural evolution

To predict the material flow and promote the final performance of the components effectively, the microstructural evolution of the deformed samples was investigated and analyzed systematically. The microstructure of the component can be split into two categories including shear bands and dead zones (DZs). The DZs are defined as the areas which are not or less deformed [23]. The local area of the DZs and shear bands were characterized by the enlarged view, as shown in Figure. 6a. The results show that the deformation and material flow behaviors of final components with various GSs are similar. For all the components, the grains in Zone A and Y are barely deformed, and grains in other areas show obvious flow trends. Thus, the formation of various deformation zones is seldom affected by GSs in this research. Take the fine-grained sample as an example, Zones A and Y are identified as DZs, and others are recognized as shear bands through the combination of experimental and FE simulation results as shown in Figures. 6(b, c). Based on the metallographic microstructure, the distribution map of strain and material flow velocity, it can be seen that the grains in Zone A and Y are almost undeformed. Grains in Zone B are seriously distorted following the direction tangent to the corner of the punch and flow towards the shear band Z. Though the simulation result shows that the strain in Zone C is not significant, grains there are distorted. The gap between the bottom die and punch, which cannot be avoided in physical experiments, was not considered in simulations. Meanwhile, the distribution map of strain also shows relatively large strains around the gap region. The grains flow not only horizontally but also into the gap and are deformed severely around the gap area due to the continuous compression of the punch. The extreme shearing deformation induced by blanking and extrusion causes the shear bands X and Z, respectively.

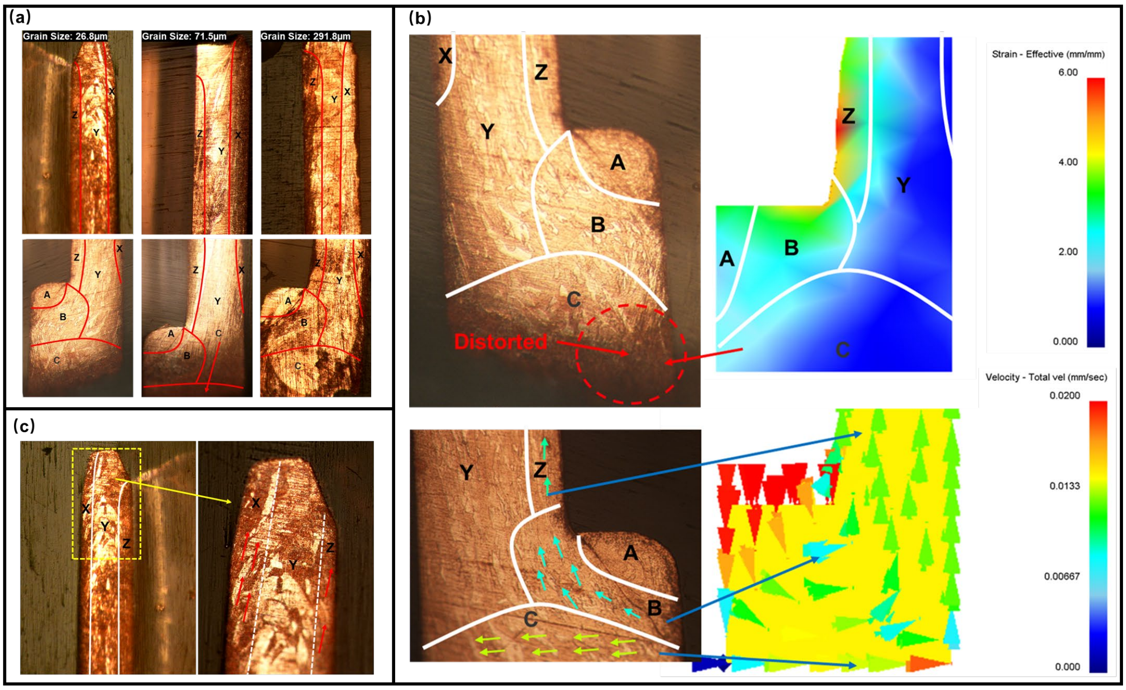

Figure. 6. (a) Microstructural evolutions of components with various GSs; microstructural evolution of the components annealed at 500°C for 2 h: (b) metallographic microstructures, distribution map of strain and flow velocity in top hole area, (c) metallographic microstructures and strain distribution in earing area.

3.3 Accuracy of assembly dimensions

To be assembled with the current bulk and plunger, the dimensional accuracy of the barrel-shaped components was investigated. Several assembly parameters including feature dimensions, tolerances and coaxiality with various GSs were studied here. The dimensions of the components were observed by a metallographic microscope. All dimensions were measured multiple times and extreme values were removed. The average value of the measured data is considered as the obtained size, and the corresponding tolerance is obtained by sampling range. Figures. 7(a,b) show the schematic of the dimensions of the target part and their corresponding values, respectively. The top diameter barely varies with GS. The similar top diameters are benefited from the barely deformed DZs A, and also the severely elongated Zone B and C which are less influenced by GS. However, it was worth noting that the tolerance of the diameter of the top hole of the coarse-grained samples is much larger than the samples with fine grains. The excessive tolerance value of the top hole diameter in the coarse-grained component can be analyzed from two perspectives. Firstly, the surface grain can be considered as a single crystal material which is less restricted than the internal grain due to the surface layer model theory [24]. For coarse-grained workpieces, the ratio of internal grains at the top-hole area is much smaller, which leads to fewer constraints on deformation. Meanwhile, the behaviors of individual grains are more significant during the deformation, which makes the anisotropy of the material more obvious. Thus, the coarse-grained component is more easily deformed inhomogeneously, and the diameter of holes falls into a larger range of values. In contrast, the diameters and tolerances of the bottom holes are all increased with GS. During the formation of the bottom hole, the workpiece continuously fills the gap between the bottom die and punch and flows in the height direction with the punch moving; thus, the bottom diameter is related to the filling rate of materials in this study. The filling rate for components is mainly controlled by the initial GS and it is increased with the decreased GS in extrusion process [18]. In addition, fine-grained sheets have more arbitrarily aligned slip planes for dislocations of grains compared with coarse-grained workpieces; thus, they have better material flowability to insert the gap between the punch and bottom die. Therefore, the dimensions of the finergrained bottom hole are more accurate and can meet the requirements of assembly. The GS induced variable dimensions were further quantitatively analyzed as shown in Figure. 7c. Dimensionless scale ratio, which is the ratio of the initial designed thickness of the ring in the third operation to the GS, was involved in visual analysis and comparison of the GS effect on the dimensional deviations. The accuracy can be described by Equation (2).

$$Accuracy = \frac{Obtained\ size - Designed\ size}{Designed\ size} \times 100\% \quad (2)$$

The results show that both values of accuracy are decreased with the increase in ratio. When the scale ratio changed from about 0.51 to 5.59, the accuracy of the two diameters changed from around 1.97% to 1.08% and from around 2.72% to 0.98%, respectively. Table 2 shows the rate of both kinds of accuracy from the coarse-grained group to the fine-grained group, which is defined as the slope of the line between two scale ratios. The slopes between various GSs and for different dimensions are defined as BS_1, BS_2, TS_1 and TS_2, respectively, as shown in Figure. 7c. It was revealed that the coarse-grained rates are more dramatic. For coarse-grained components, there are only 2-3 grains in the thickness direction, as shown in Figure. 6a, GS induced undesirable dimensions are more obvious due to the less restriction to deformation and significant individual deformation behavior as mentioned above. In contrast, the difference between the various scale ratios is not significant for fine-grained workpieces. The relationship between GS and dimensions of the component is not always consistent. While reducing GS can improve the mechanical properties, it may not necessarily result in a significant change in the dimensions of the fine-grained components. Thus, it may not be necessary to pursue smaller GSs during processing, as it may lead to processing difficulties and result in only marginal improvements in part quality. However, if the scale ratio exceeds a certain limit, it can lead to dimensional instability or undesirable size, which can be noticeable and non-recommended.

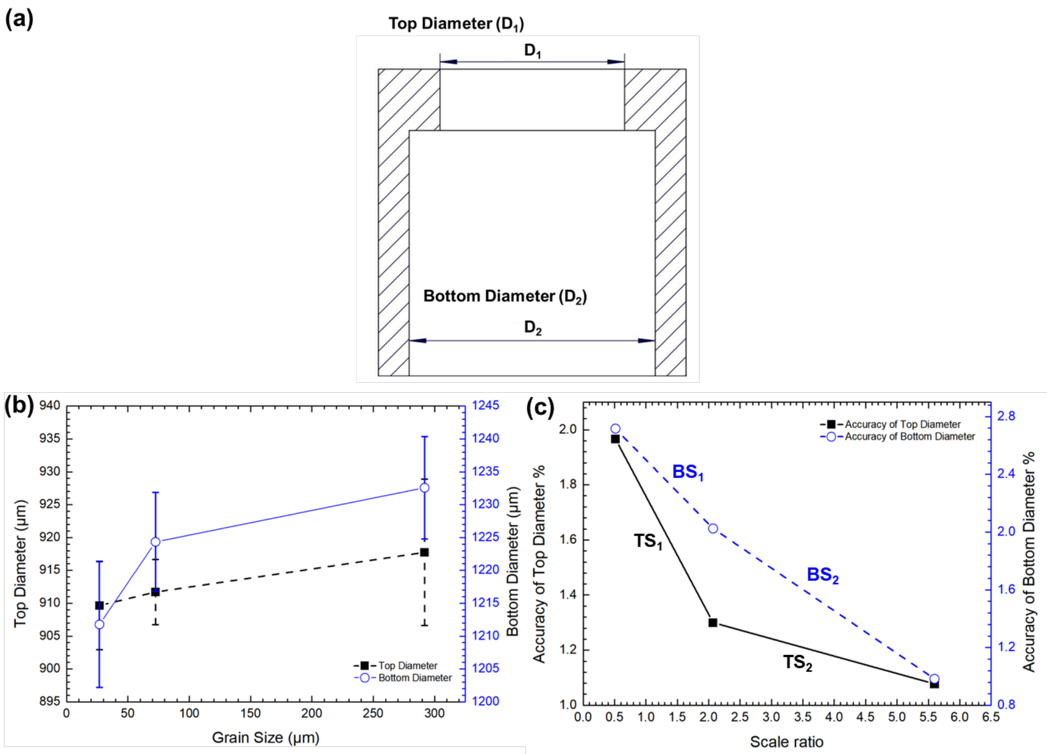

Figure. 7. (a) Diagrammatic representation of the measured diameter, (b) diameter of the top hole (D_1) and diameter of the bottom hole (D_2), and (c) accuracy of both holes with various scale ratios.

Table 2 Rate of the accuracy of the diameter of both holes

	TS_1	TS_2	BS_1	BS_2
Rate	4.29e-3	0.63e-3	4.45e-3	2.95e-3

The desirable diameters range of the fabricated plunger and bulk parts for being assembled with the barrel are shown in Figure. 8 [1, 12]. Diameters of the top and bottom holes with various GSs and the corresponding tolerances are shown in Table. 3, and they are also indicated in Figure. 8 to confirm the type of assembly. For the top hole, the diameters of the final components with three kinds of GSs can realize clearance fit (CF) for the plunger part, and the size of the gap between the barrel and plunger is increased with GS. The assembly of the bottom hole and the plunger has a similar situation. On the one hand, suitable clearance ensures the movement of the plunger in practical applications. On the other hand, excessive clearance may have a negative effect on the conductivity of the pogo-pin. Thus, the fine-grained component, which can realize accurate clearance fit, is a better choice for assembly. As to the bottom hole and bulk, the coarse-grained dimension realizes CF and others realize transition fit (TF) with the bulk. The bulk is designed to be fixed with the barrel; thus, the bottom hole of the fine-grained barrel is more desirable. In short, the fine-grained dimensions meet the requirements of being assembled with the current plunger and bulk parts. It is worth noting that variations in GS may lead to various assembly types in microforming. Thus, to meet the needs of different assembly situations, GS of the workpiece should be considered before the process.

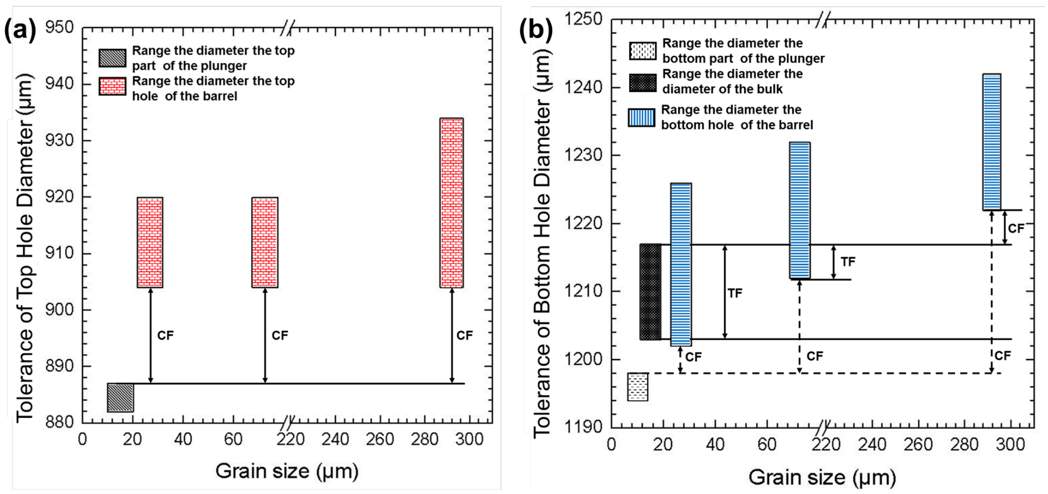

Figure. 8. Assembly conditions: (a) conditions of the top hole, (b) conditions of the bottom hole.

Table. 3 Dimensions of the top and bottom holes

Grain Size (μm)	28.6	72.5	291.5
Top diameter (mm)	$0.9097^{+0.0103}_{-0.0056}$	$0.9117^{+0.0083}_{-0.0077}$	$0.9177^{+0.0163}_{-0.0137}$
Bottom diameter (mm)	$1.2118^{+0.0142}_{-0.0098}$	$1.2243^{+0.0077}_{-0.0123}$	$1.2326^{+0.0094}_{-0.0106}$

Coaxiality is a position tolerance, which is one of the important parameters for assembly. If the deviation of the coaxiality exceeds the allowable range, the hole (barrel) and shaft (plunger and bulk) will not be fitted. The top hole is located by the punch in the third operation, and it was verified that the diameter of the top hole barely varies with GS; thus, the top hole is selected as the benchmark, and the bottom hole is adopted as the tested section. The equation to describe coaxiality (C_o) is shown in Equation. 3, and D_c is the distance between the center of the circle of the two holes as shown in Figure. 9a.

$$C_o = 2 \times |D_c| \tag{3}$$

The values of coaxiality with various GSs were evaluated at various times and averaged in order to obtain reasonable results. As shown in Fig. 8b, the value of the coaxiality increases with GS from 0.118 mm to 0.207 mm and 0.316 mm, respectively. The coaxiality required by industrial production should be less than 0.12 mm, so according to the results of this research, only fine-grained samples can meet the requirements.

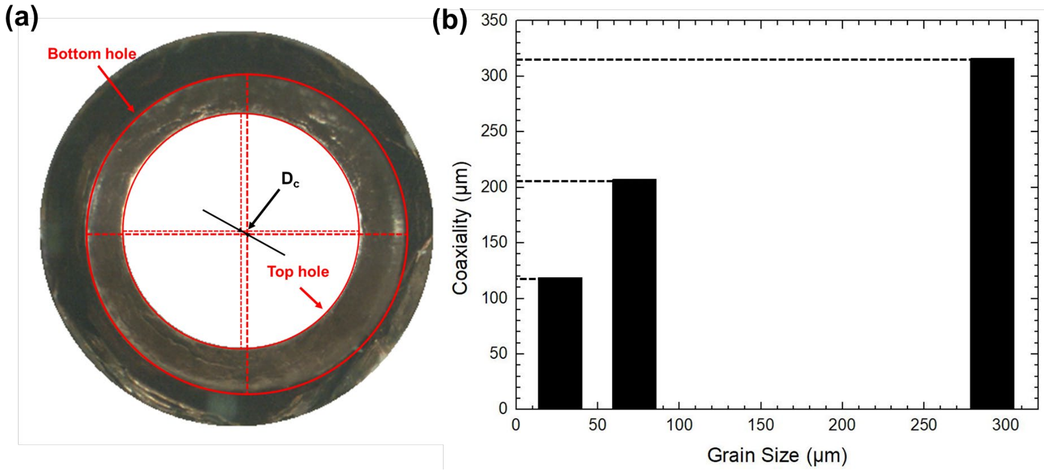

Figure. 9. (a) Diagrammatic representation of the coaxiality, (b) coaxiality of the bottom hole.

To sum up, the assembly parameters of the fine-grained barrel meet the requirements of assembly. As shown in Figure. 10, the barrel-shaped part was successfully assembled with the existing plunger and bulk after deburring each component [1, 12].

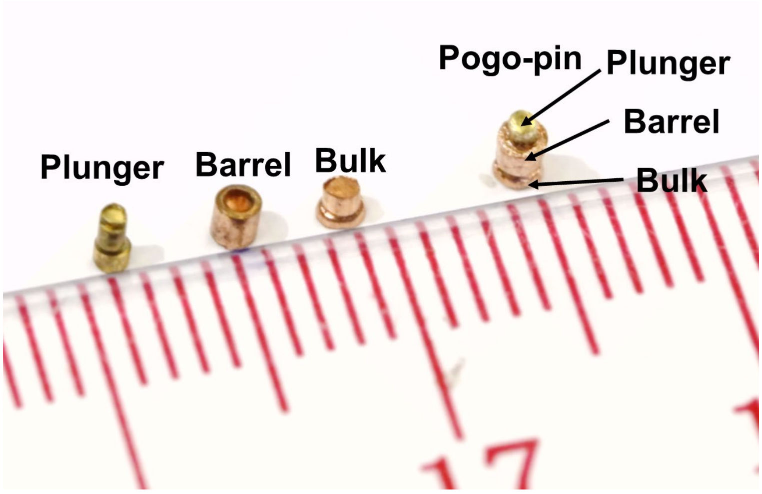

Figure. 10. Assembled pogo-pin and corresponding parts.

3.4 Final quality and related defects

The surface quality of the final components was further investigated in terms of bottom earing, top hole, internal and external walls. Figure. 11 shows the surface quality of the earing of all kinds of components. It shows that the uneven areas whose shapes are like wrinkles appear on the coarse-grained bottom earing. These uneven surfaces on the bottom earing are induced by the inhomogeneous distribution of stress during the extrusion operation. In addition, bulges and fracture surfaces with microvoids are identified near the inner earing and outer earing, respectively. Though the size of the voids is decreased with the increased GS, the number of the voids barely changes significantly, which is not found in previous research [12, 25]. The formation of bulges on the inner earing may be related to some external factors. For example, lubricants, dust, etc., can involve in the gap between the workpiece and the tool, which leads to uneven material deformation in the transverse direction. The unusual fracture surfaces at the outer earing are caused by the combination of different operations. Firstly, the blanking operation leads to some microvoids at the grain boundaries or inclusions [25]. After that, extrusion makes these microvoids further deformed and elongated, which makes their shapes and sizes unpredictable. Figures. 12 shows that there are also bulges on both the external and internal surfaces of the top hole, but the bulges of fine-grained parts are not obvious. The external-top-hole bulges are led by the gap between the punch and the bottom die which provides the path for the material to flow outside. However, the formation mechanism of the internal bulges is different. In fact, the top hole formed by punching cannot exactly fit with the punch because of the inhomogeneous material flow in the micro-scaled parts, and the gap between the hole and the tool is increased with GS. Thus, the specimen is deformed not only in the transverse direction but also in the longitudinal direction leading to the formation of bulges. Besides, cracks on the top hole are captured as shown in Figure. 12b. They appear when the accumulation of stresses reaches the limit of the materials [26]. The overall quality of the walls is desirable, and only a few slight bulges and uneven surfaces are found on the walls as shown in Figure. 13, which may be associated with the gap between tools and the workpiece.

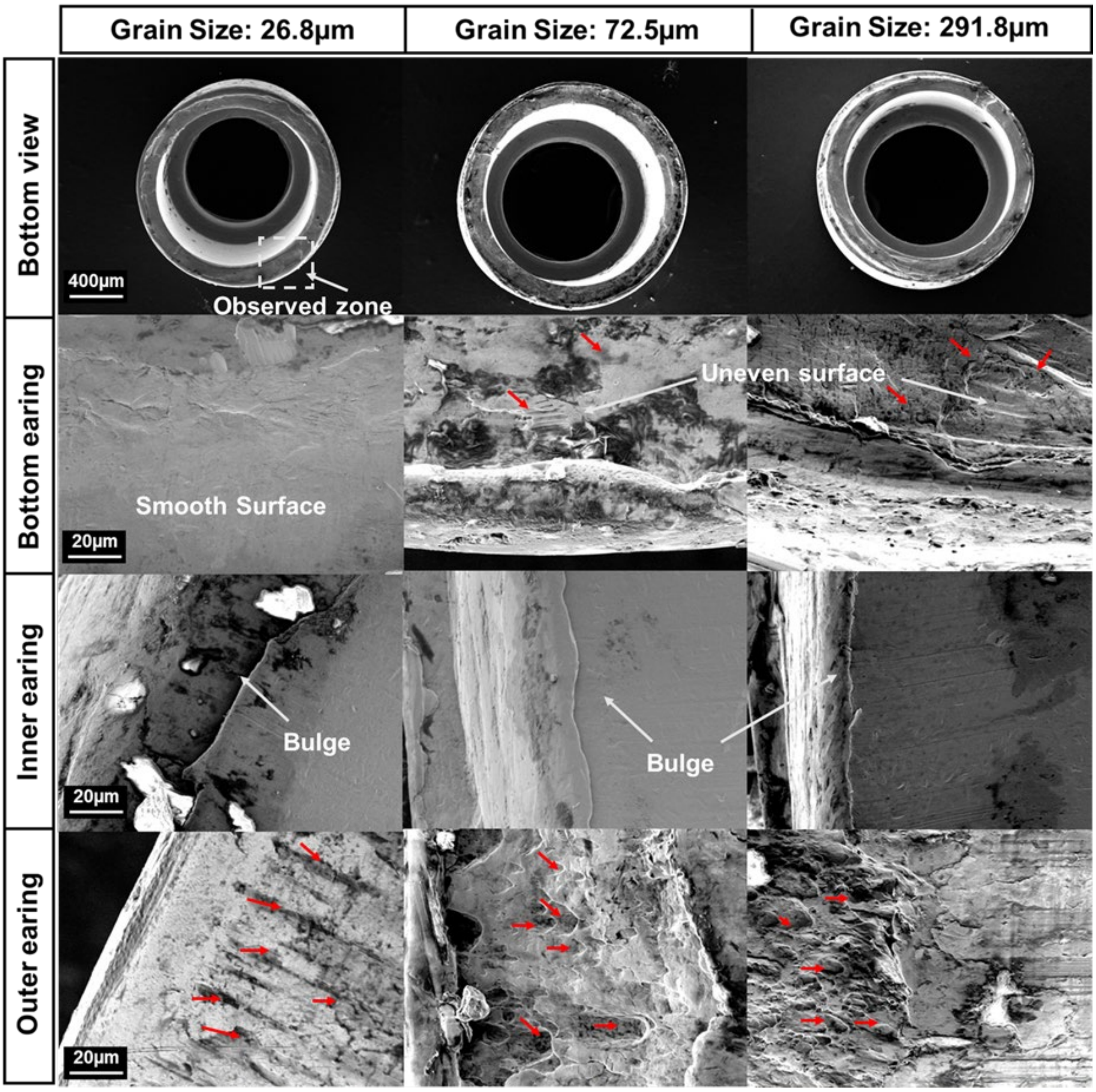

Figure. 11. SEM images of earings.

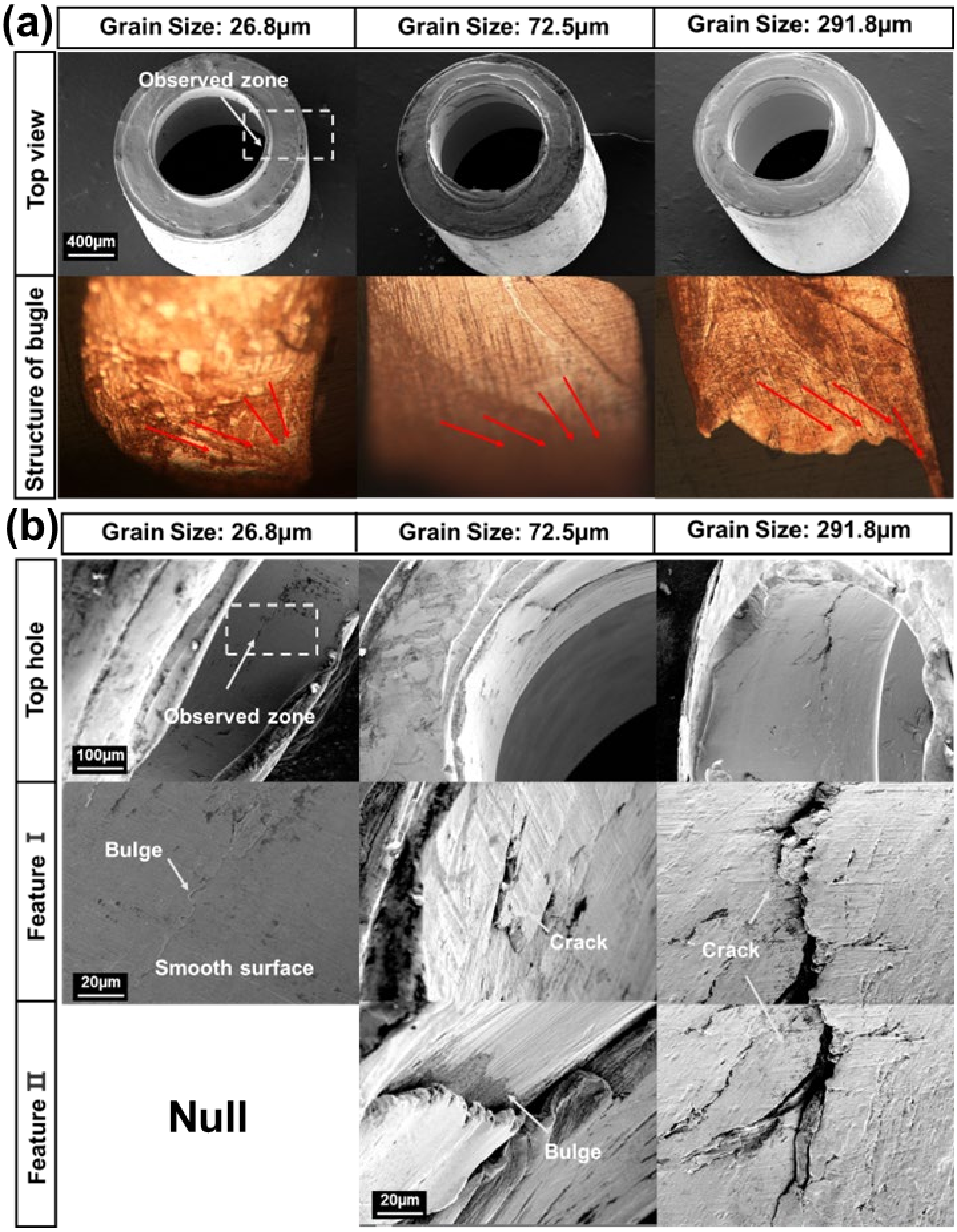

Figure. 12. SEM images: (a) external surfaces of the top holes and (b) internal surfaces of the top holes.

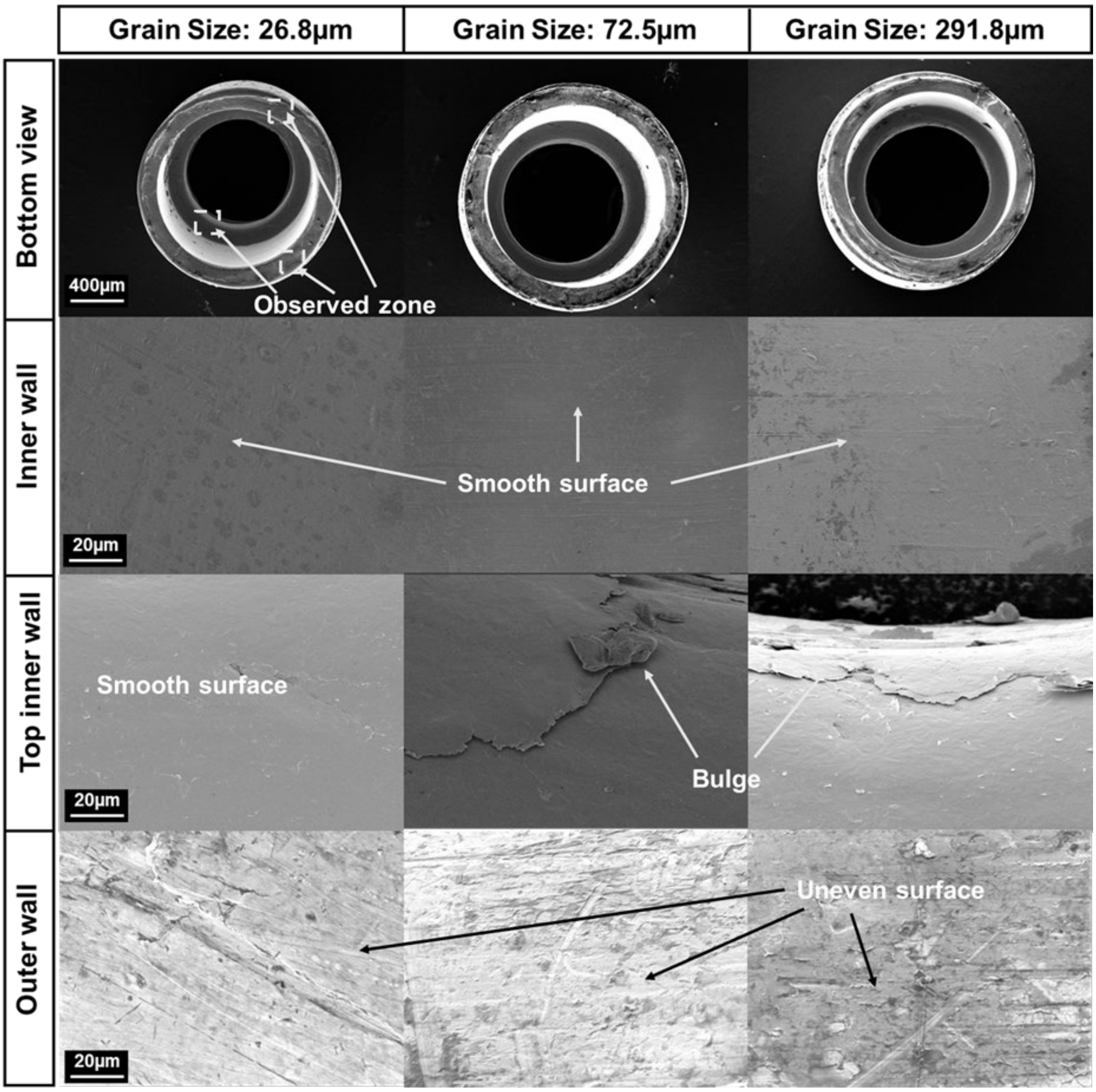

Figure. 13. SEM images of walls.

4. Conclusions

In this research, a microforming system based on extrusion technique was developed to fabricate barrel-shaped parts which can be assembled with current bulk and plunger components. The effect of GS on the deformation behaviors, material evolution, assembly accuracy and surface defects during the extrusion process was investigated systematically. It can be drawn the following conclusions:

1. The microforming system based on extrusion provides the possibility to fabricate micro-scaled barrel-shaped parts with accurate assembly dimensions, which is an efficient and economic method in the industry.
2. During the whole extrusion process, the deformation load increases with the decrease of GS. Meanwhile, increasing friction leads to the continuous reduction of differences between various GSs with the movement of the punch in the extrusion operation.
3. DZs and shear bands were identified due to the various material flow and deformation behaviors, and they are barely affected by GS.
4. Assembly parameters including hole diameters, corresponding tolerances and coaxility vary with GS, and various GSs lead to different types of assembly with current bulk and plunger. Fine-grained workpieces lead to the closer designed sizes and the most desirable assembly situation. Besides, the overall quality of the final fine-grained components is desirable.

In short, finer GS of the workpiece leads to better formation quality such as accurate geometry and high surface quality, and various GSs can induce different assembly types. Therefore, in order to fabricate desirable parts for industrial applications, it is crucial to develop an advanced microforming system and also put more effort into tailoring the microstructure of the materials.

Disclosure statement

No potential conflict of interest was reported by the authors.

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