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ORIGINAL ARTICLE

Analysis of size effect on flow-induced defect in micro-scaled forming process

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Abstract In microforming process, flow-induced defects caused by the irrational material flow in forming process have a significant effect on the quality of micro-formed part. In design of micropart and microforming process, this type of defects needs to be analyzed and the formation mechanism identified, such that the defects can be predicted and avoided via the rational design of micro-formed parts and microforming process. To address this issue, the size effect affected flow, and deformation behaviors need to be investigated. To explore how the size effects affect the flow-induced defects, experimental studies on the influence of a few significant parameters including geometry and grain sizes on the degree of flow-induced defects in microforming process of pure copper were conducted in this research. The flow-induced defects in microforming of a designed part are investigated, and the microstructure and flow pattern in micro-scaled extrusion of the parts with complicated shape are also studied. Based on the experimental results, the formation of folding defects is mainly affected by geometry size. The folding defect-free deformation occurs in the cases with coarse grains such that the parts with coarse grains do not have flow-induced defects, but some grains are broken and become potential insecurity factor. Furthermore, the relationship between grain and geometry sizes under which the flow-induced defects and grain broken can be successfully and simultaneously avoided is identified.

Keywords Size effect · Flow-induced defect · Microstructure · Microforming

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1 Introduction

In the past two decades, the increasing demand on micro-scaled metal-formed parts provides a great driving force for researchers and practitioners to conduct extensive research and development of microforming processes. It provides a solution to mass production of microparts to meet the huge demanding from industries for its high production, near net shape, and good product quality [1, 2]. In microforming arena, the high demanding quality and the reliability of microparts require the in-depth investigation of material deformation behavior and the qualities of micro-formed parts. When the size of workpiece is scaled down to at least two dimensions less than 1 mm, the so-called size effects exist, which make the traditional macro-scaled deformation behavior [3–5] different with the one in micro-scaled [6–10]. The flow stress, anisotropy, ductility, and the forming limit depend on the workpiece size, microstructure, and grain size. These size–effect-affected deformation behaviors need to be considered in the design of micro-formed part and forming process [11–15]. It is thus necessary to investigate the size effects and the size–effect-affected deformation behaviors. Recently, Fu and Chan [16] reviewed the state-of-the-art microforming technologies including size–effect-affected deformation behaviors and various microforming processes developed. In general, two kinds of size effects, namely geometry and grain size effects need to be considered. Both size effects have been extensively studied by using different micro-scaled plastic deformation processes such as the compression of different size-scaled specimens [17]. It is found that the flow stress of materials decreases with specimen size, and the deformation becomes inhomogeneous when there are only a few grains in the deformation zone of the micro-scaled workpieces [18].

In metal-forming industries, product quality is one of the most critical issues, and the designed forming process must be able to produce quality parts with desirable geometries and that are defect-free [19]. From the flow-induced defect prediction and avoidance perspective, a number of previous researches have been conducted to explore defect formation mechanism and avoidance methods in macro-scale forming processes. To reduce the number of forming operations and design complexity, Arentoft et al. [20] created a Defect-Matrix to describe the various forging defects and classified the possible root-causes of the defects. Lee et al. [21] concluded that the dead metal zone is the root-cause of lapping formation in the combined cold extrusion of a piston-pin and then proposed new processes to prevent the flow-induced defect by removing the dead metal zone. Chan et al. [22] investigated the root-cause of folding defect, which is one type of flow-induced defect in forming of axially symmetrical flanged components. By using finite element (FE) simulation, the variation of material flow behavior with the change of part geometry parameters was studied, and a practical defect avoidance approach was proposed. Wang et al. [23] proposed a feature-based method to identify the best forming process for defect-free deformation of nonaxisymmetric components using meso-forming process and developed a defect-free multi-stage forming process. With the help of FE simulation, Petrov et al. [24] investigated the formation of lap of the isothermal enclosed die forging of an aluminum part with a deep central cavity and irregular shape, and obtained the relationship between the lap length and geometrical parameter of die. Fu and Luo [25] simulated the isothermal forging of a aluminum wheel and revealed that an abnormal flow pattern was the root cause of macro-defects by the rigid-viscoplastic finite-element method, and proposed that the improvement in die design and lubrication condition was the effective measure to avoid this kind of defect.

Based on the above-summarized prior researches, it can be seen that the study of flow-induced defects was mainly focused on macro-forming. In microforming, however, for this type of defect, there is still lack of in-depth understanding, and further investigation is thus needed. With the decrease of workpiece size, the individual factors such as part size, grain size and shape, grain orientation, and the interfacial conditions between workpiece and tooling show a significant effect on the formation of flow-induced defects, microstructure of the formed parts, and the load in plastic deformation process. For flow-induced defect, it is the most critical issue. To have a good understanding of this phenomenon, Rosochowski et al. [26] conducted backward extrusion of miniature cups by using the traditional coarse grain, ultra-fine grained metals and nanometals and concluded that ultra fine-grain structure facilitates the more uniform flow of material and results in a more uniform structure, better shape representation, and enhanced properties of the micro-formed parts. Through micro-extrusion with different grain sizes, Parasiz et al. [27] analyzed the curving tendency of the extruded pins, which showed that, as the grain size approaches the specimen feature size, the

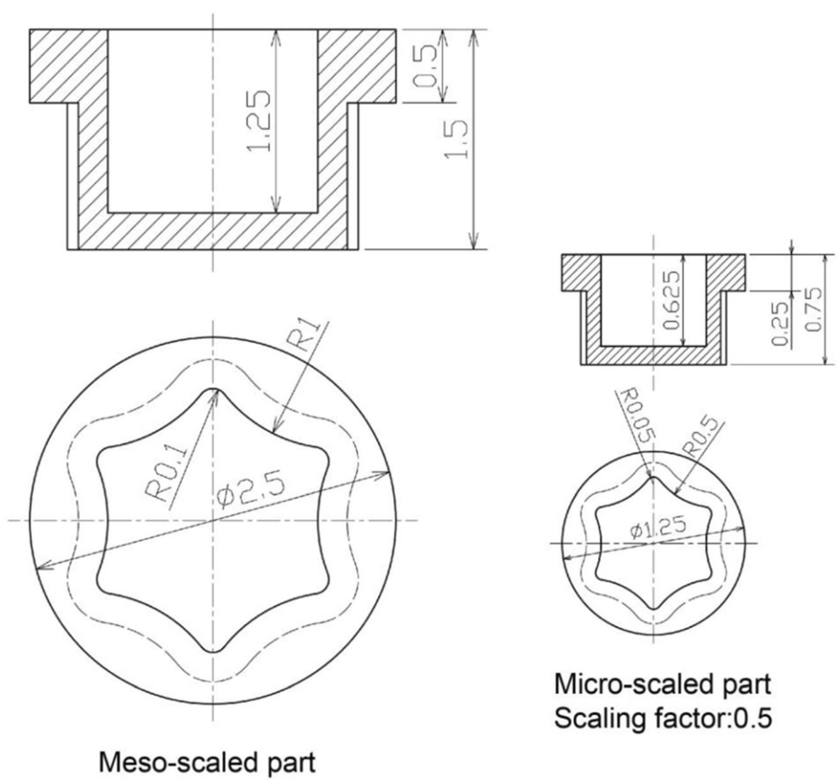

Fig. 1 Two different scale parts

Table 1 Heat treatment parameters

Annealing conditions	Case1	Case 2	Case 3	Case 4
	As-received	450 °C, 2 h	600 °C, 2 h	750 °C, 3 h
Grain size	10 μm	20 μm	30 μm	50 μm

deformation characteristics of the extruded pins are significantly affected by the size and location of specific grains, leading to a nonuniform plastic deformation.

The objective of this study is to conduct an in-depth study on the formation of flow-induced defects and microstructure of the micro-formed parts by micro-cold extrusion process. This is the continuous research on the flow-induced defect in meso-scaled forming process [23]. Whether the size effect affects the flow-induced defect and what size effect (grain or geometry size effect) is the main factor have not yet been explored and identified. Furthermore, how the flow-induced defect changes with the grain and geometry sizes is also needed to be explored. All of the above-mentioned issues have a significant influence on flow-induced defect. In this research, two different scale nonaxisymmetrical metal-forming parts with 2D axisymmetrical features shown in Fig. 1 were studied by micro-cold extrusion process in order to explore the geometry size effect. As for grain size effect, the heat treatment of the two scale parts was conducted to get three different grain sizes for each part. The formation mechanisms of the flow-induced defects in the two parts were investigated via experiment.

2 Experiments

2.1 Microstructure of the testing material

Pure copper is widely used in electrical and electronics industries for its excellent electrical conductivity, reasonable mechanical properties, good manufacturability, and plastic formability. Two kinds of pure copper billets with the diameter of 1.8 and 0.9 mm were used. To explore the influence of grain size effect, each type of billet with different grain sizes were obtained via annealing treatment. The annealing conditions and the obtained grain sizes are presented in Table 1. After the annealing heat treatment, the microstructures of the billet are shown in Fig. 2. The average grain size increases with annealing temperature and holding time. For the as-received materials with different dimensions (Case 1), the average grain size

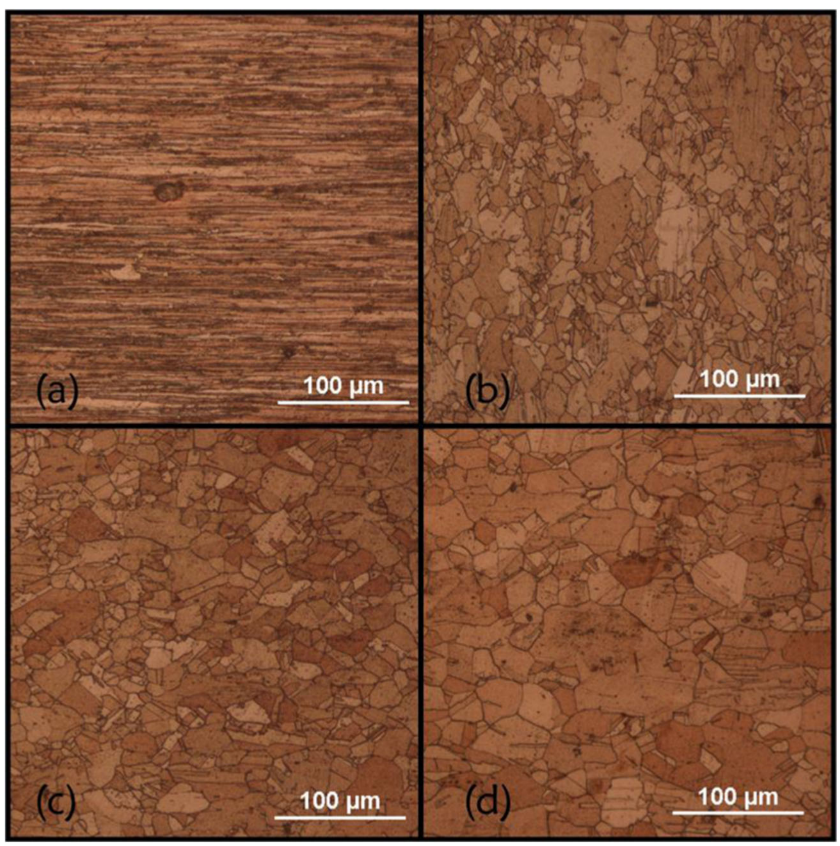

Fig. 2 Microstructures of the pure copper. **a** As-received, **b** 450 °C annealing, c 600 °C annealing, **d** 750 °C annealing

is about 10 μm. For the Case 2 as shown in Table 1, the average grain size is about 20 μm, which is almost twice the average grain size in Case 1. For Case 3, the average grain size is around 30 μm. In the last case, viz., Case 4, the average grain size is 50 μm, which is much larger than that of other cases.

2.2 Micro-cylindrical compression test

The mechanical properties of the annealed treatment metal billet were determined by the micro-compression test conducted in a MTS material testing machine with a load cell of 30 KN. A micro-compression tooling set was employed as the experimental platform. The specimens were lubricated with machine oil in order to minimize the frictional effect. For each category of metal billet, three tests were conducted to minimize testing error. The crosshead velocity of the testing machine was set to be 0.02 and 0.01 mm/s for meso- and micro-scaled billets, respectively. All the specimens were compressed by 60 % of the corresponding specimen height at room temperature. The dynamic loading and displacement data were recorded via a built-in data acquisition system. The true stress–strain curves for the two kinds of billets with different grain sizes were obtained.

The true stress–strain curves for the two kinds of metal billets with different annealing conditions and dimensions are shown in Fig. 3. It is found that the flow stress decreases with the increase of grain size for the same billet. The flow stress of the materials with different grain sizes is different significantly for the meso-billet. This indicates that the grain size effect obviously affects the flow stress of these materials. This is also in tandem with the Hall-Petch equation. In addition, the stress–strain curves have good repeatability and consistency for the same metal billet. However, for the micro-billet, the flow stress of the billet heat treated at the temperature of 600 °C is slightly larger than that of the billet treated at the temperature of 750 °C and in the large strain region, the flow stress of the billet treated at the temperature of 600 °C even smaller than that heat treated at the temperature of 750 °C, which could be caused by the friction effect. For the small volume to grain size ratio, the single grain plays an important role in the entire deformation process. The flow stress scatter is thus caused by the friction between random grain and tooling surface.

According to Fig. 3, flow stress varies with grain size; the grain size effect thus exists in the microforming process. These two types of billets with different grain sizes could be used to conduct microforming process. The formed parts with flow-induced defects are influenced by grain and geometry sizes.

2.3 Microforming experiments

The micro-cold extrusion experiments were conducted to investigate the influence of size effect on the formation of

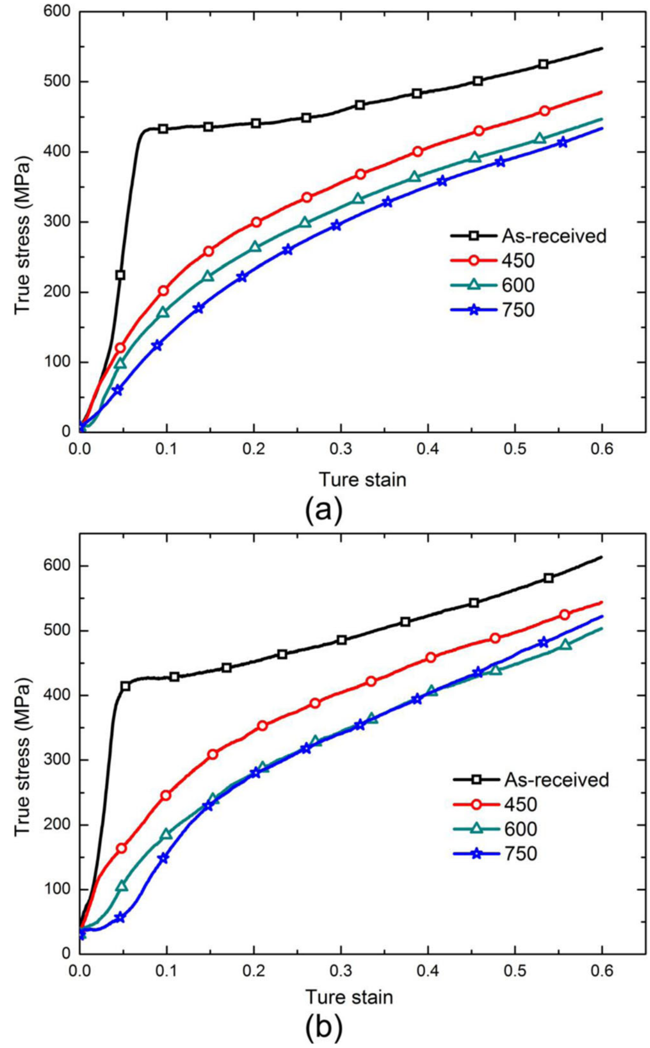

Fig. 3 True stress–strain curves of the two kinds of metal billets with different grain sizes. **a** Dimension=Ø1.8×1.3 mm, **b** Dimension=Ø0.9×0.65 mm

flow-induced defects. All the microforming experiments were done in a MTS test machine with a load cell of 30 KN. The tooling set is shown in Fig. 4. In order to avoid the influence of strain rate, the velocity of the cross-head of the test machine was set to be 0.01 mm/s. Based on the volume constant principle in plastic deformation process, the cylinder billets with the dimensions of Ø1.8×1.3 and Ø0.9×0.65 mm were prepared. The parts were deformed by one-stroke process. The tooling and billet contact region was lubricated by a machine oil. The punch stroke was 1.05 and 0.525 mm, respectively.

The load-stroke curves of the meso-scale part with different grain sizes have a similar trend in deformation process, as shown in Fig. 5. In the first two stages, the deformation load increases with the decrease of annealing temperature. As for the third stage, the all deformation loads of the workpieces with different grain sizes have a significant increase due to friction. Similarly, the load–stroke curves of the micro-part also have the similar trend. In the third stage, however, the

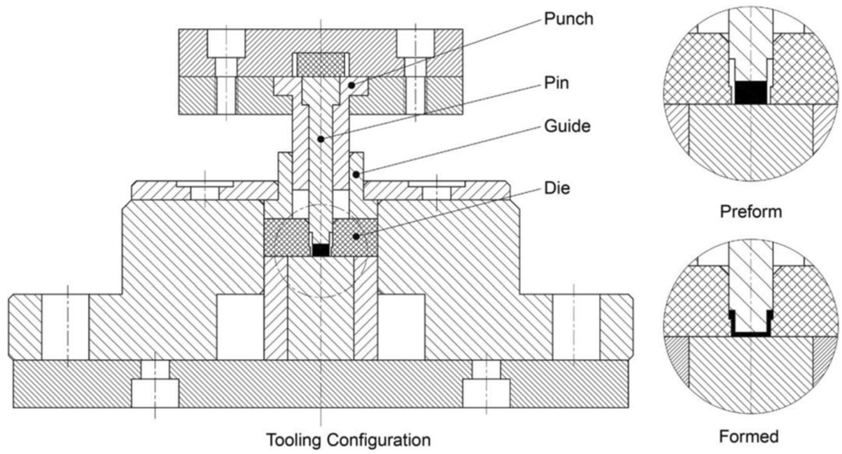

Fig. 4 Experimental tooling set

load–stroke curves of the micro-part for different materials are randomly scattered due to the severe friction.

The formed parts are shown in Fig. 6, and there are two flow-induced defects, viz., folding and inner defects, as shown in Figs. 7 and 8. In this case, the first defect is an uneasily discovered folding defect appearing in the inner star surface. The detailed analysis is presented in the next section.

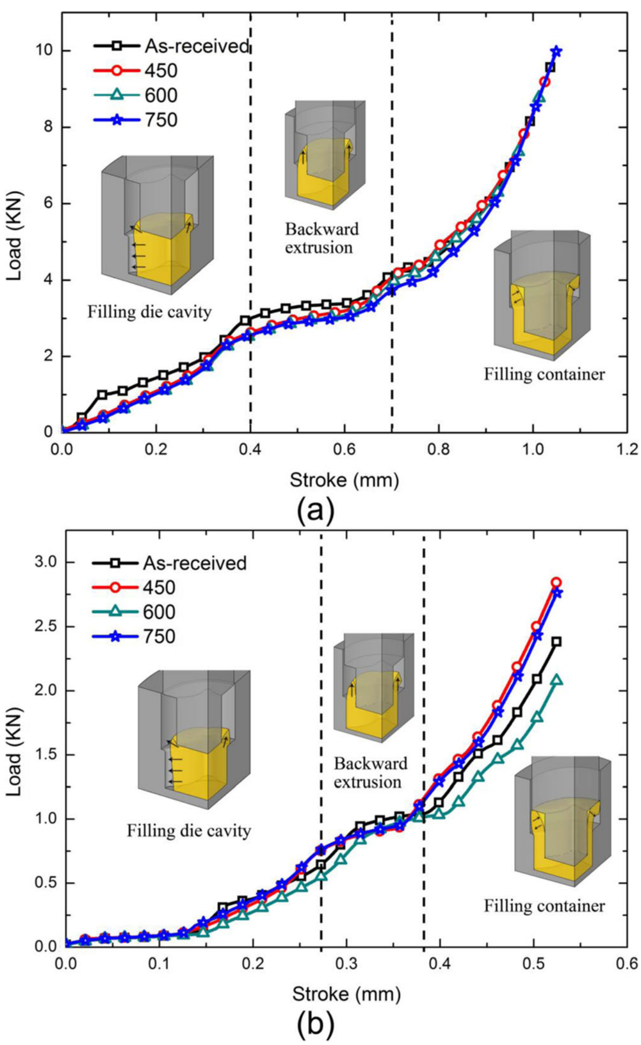

Fig. 5 Load–stroke curve. **a** Meso-scaled part, **b** micro-scaled part

3 Results and analysis

From Fig. 5, it is found that the entire forming process can be divided into three stages. In the first stage, billet undergoes deformation in both the radial and axial directions simultaneously until the radial die cavity is completely filled. The second stage is the backward extrusion until the punch shoulder contacts the deforming workpiece. In this stage, the deformation load slightly rises. The last stage is the combined forward and backward extrusion until the entire die cavity is totally filled up. At this stage, the deformation load sharply increases since the unfilled place in the cavity is very small, and thus, the final filling needs a great pressure compared with the preceding two stages.

In micro-deformation process, the material flow behavior is further influenced by the size effect. For this component, the intersecting portion between different features most likely leads to irrational metal flow and thus forms the flow-induced defects. From Figs. 7 and 8, it can be concluded that the folding defects are mainly located in the upper portions, namely inner hole and flange. So, in the subsequent analysis, these two portions in the different section views are analyzed and compared. The formed components are nonaxisymmetric. In order to thoroughly investigate the size effects on folding defect, these components were cut along the two symmetry planes as shown in Fig. 9. There are two sections, viz., S–S and O–O, which are used to observe the formation of folding defect.

3.1 Geometry size effect on folding defect

In order to investigate the influence of geometry size on folding defect, there are two different groups for each grain size. Figures 10 and 11 show the comparison of folding defect

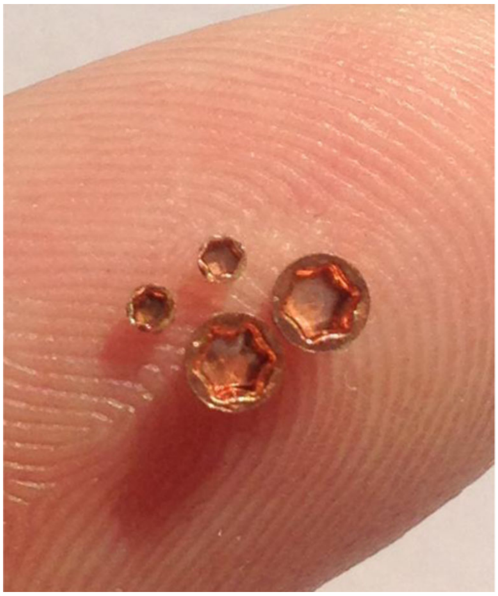

Fig. 6 Formed parts: meso-scaled and micro-scaled parts

formation between the meso- and micro-scaled parts with different grain sizes in S–S and O–O sections, respectively. Columns 1 and 2 represent the meso-scaled parts and Column 3 represents the micro-scaled part sizes, respectively. Rows 1 to 4 indicate different grain sizes including 10, 20, 30, and 50 μm.

Generally, no matter what grain size the material has, the meso-scaled part always has folding defects in both inner hole and flange portion while the micro-scaled part does not have any folding defect. Regarding the Row 1 in S–S section, the as-received material has small folding lines due to the specific orientation of grains as shown in Fig. 2a. This specific orientation of grains affects material flow pattern in microforming process and thus leads to the formation of the slightly folding defect in the upper surface of the flange in the micro-scaled part.

In the O–O section of the meso-scaled part, there is always a folding defect in the inner hole, but there is no defect in the inner hole and the flanged portion in the micro-scaled part.

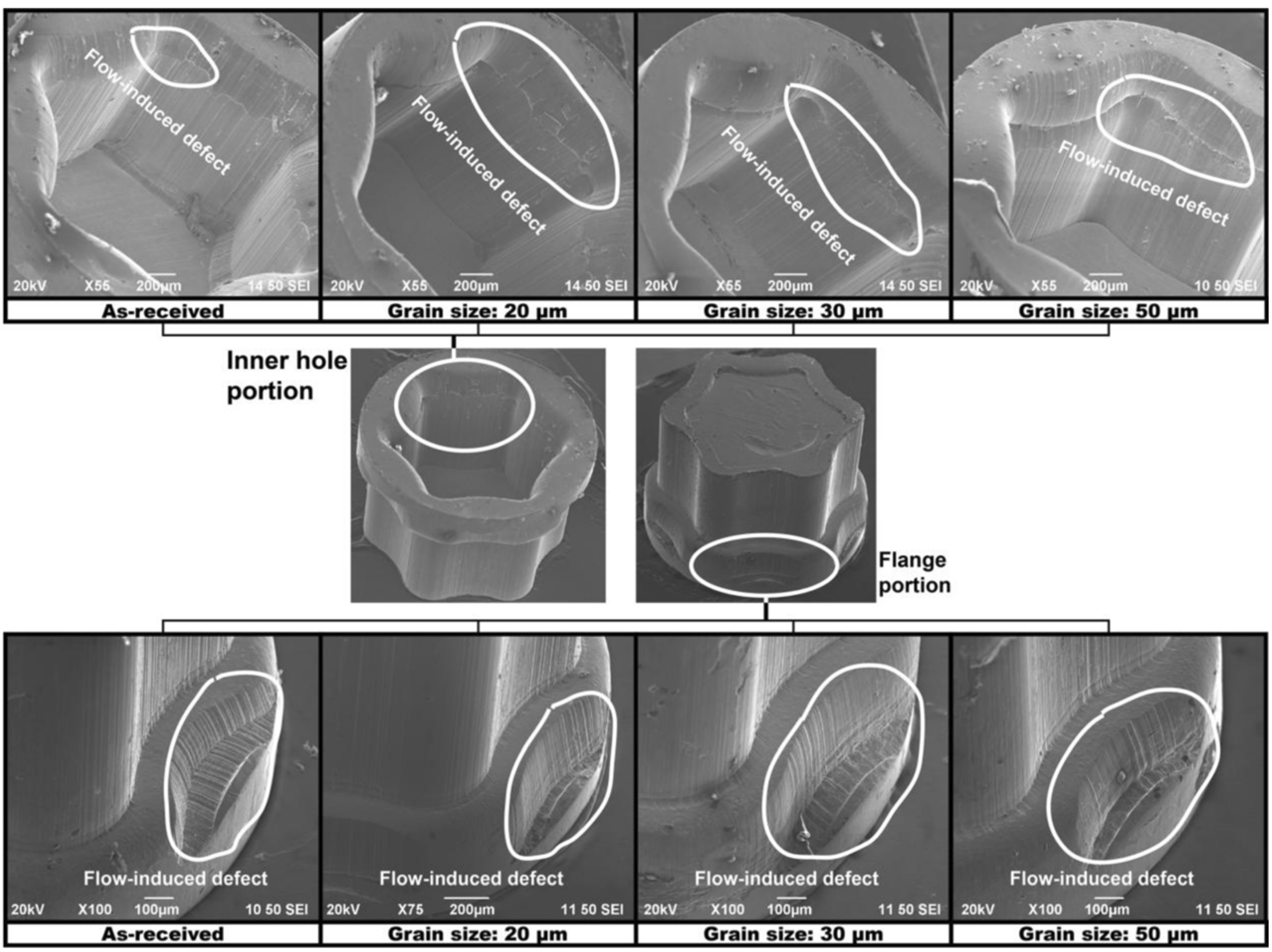

Fig. 7 SEM photograph of the meso-scaled part

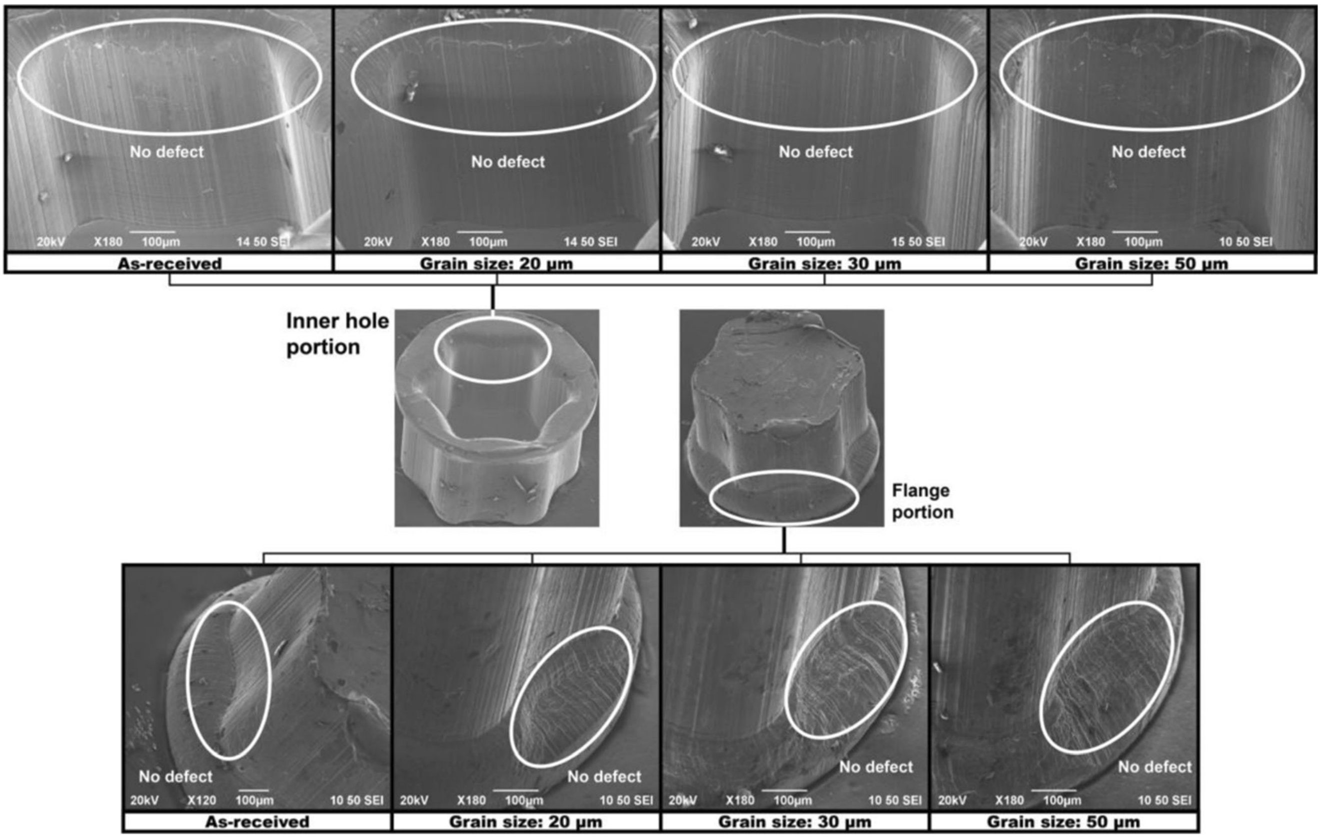

Fig. 8 SEM photograph of the micro-scaled part

Comparing the meso- and micro-scaled parts in the different sections and positions for the same grain size, it can be concluded that the geometry size has a significant role in the formation of folding defect, and the smaller geometry size is easily to form defect-free parts.

3.2 Grain size effect on folding defect

For the same geometry size components, the grain size effect on the formation of folding defect is also shown in Figs. 10 and 11. For the meso-scaled part, there are severely folding defects in the inner hole and the flanged portion in all the parts. The grain size is quite small compared with the geometry size. The deformation region thus contains quite lots of grains, and the individual grains with different properties can be randomly and evenly distributed and do not affect the material flow behavior and result in the isotropic deformation behavior. Therefore, the grain sizes do not have an obvious effect on the formation of folding defect.

As for the micro-scaled parts, Figs. 10 and 11 Column 3 show that the flow lines of the formed specimens gradually disappear with the increase of grain size. The complicated deformation region only contains several grains, and the individual grain and its boundary have a significant effect

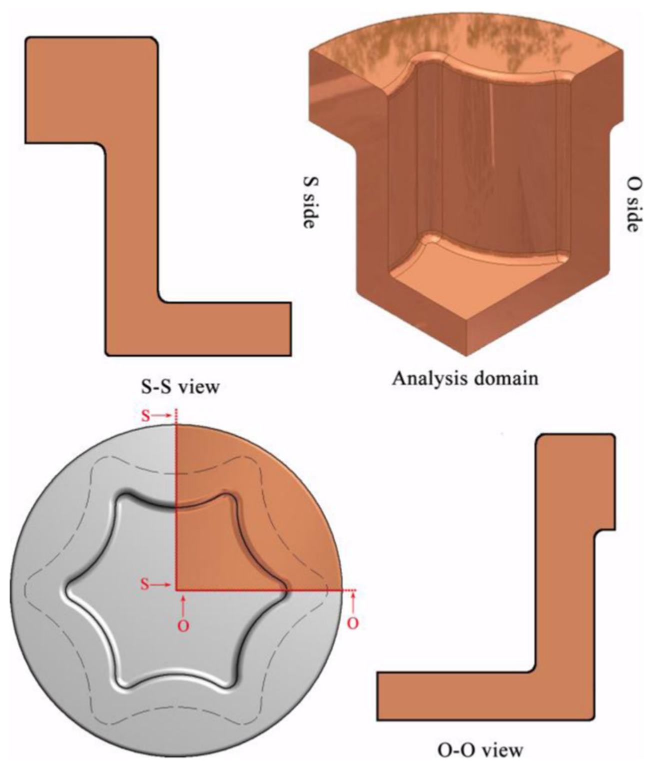

Fig. 9 Cross-section illustration

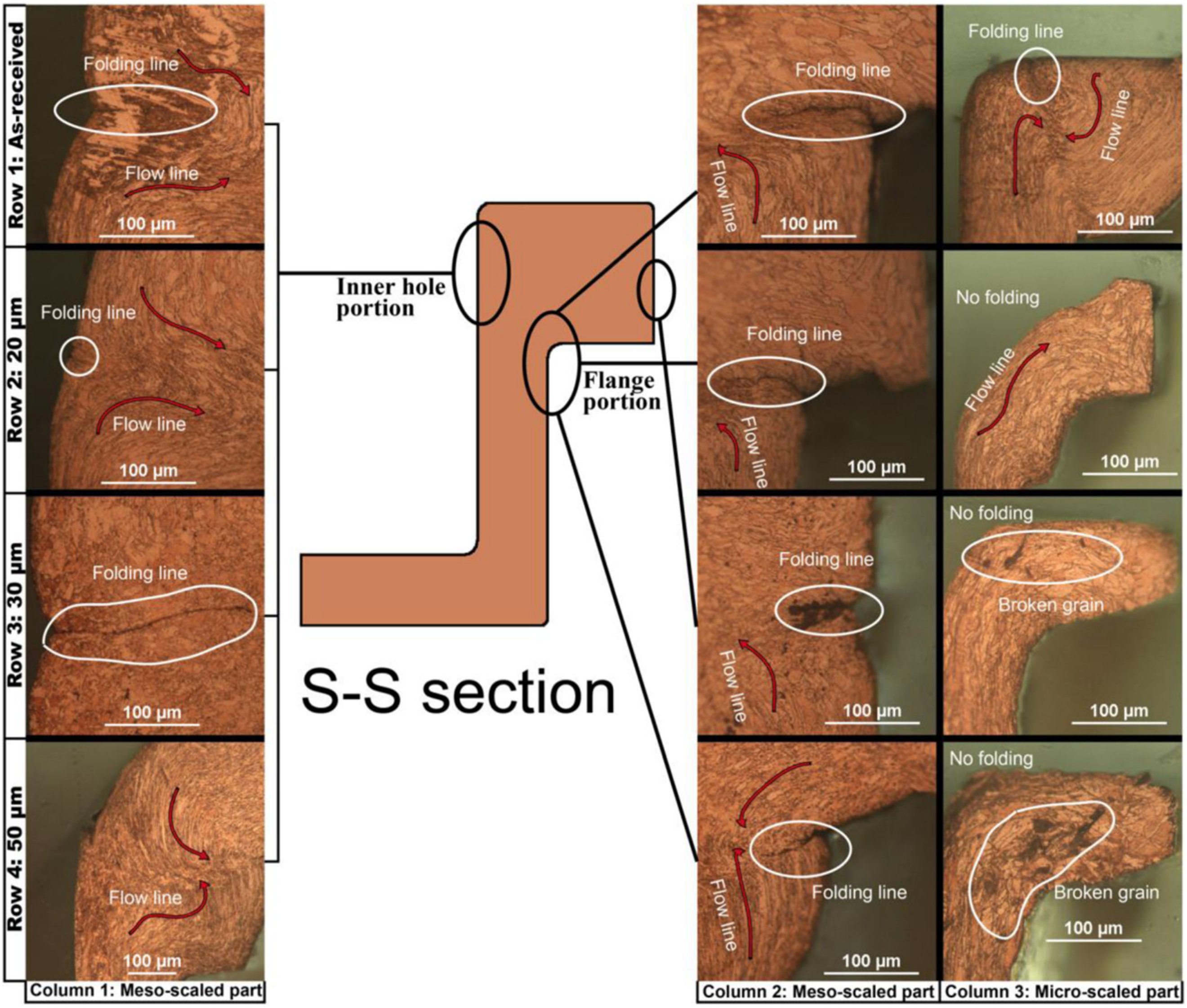

Fig. 10 Folding defect formation in the meso- and micro-scaled parts with different grain sizes in S–S section

on material deformation behavior. And this phenomenon is caused by the decrease number of grain boundaries and the random characteristics and orientation of grains.

3.3 Microstructure and flow behavior

Figures 10 and 11 present the microstructure and flow behavior of the formed parts in micro-extrusion process. The formed parts of Columns 1 and 2 have a bigger ratio of geometry to grain size than that in Column 3. It can be seen that the defect-free deformation occurs in the cases with coarse grains, while the flow line in accordance with part shape and structure occurs in the cases with fine grains. The parts with fine grains have the obvious flow lines which not only cause the outstanding mechanical properties but also the flow-induced defects due to irregular material flow in the micro extrusion process. For the parts with coarse grains, there is no flow-induced defect and even no obvious flow line due to the fact that the material flow line is mostly represented by the shape of grain boundary. The increase of grain size leads to the decrease of grain boundary fraction, which further results in the unclear flow lines [28]. The advantage of this phenomenon is that flow-induced defects could be avoided, but the mechanical properties would be inferior.

In micro-extrusion process, billet undergoes large plastic deformation. For the case with fine grains, the billet has a considerable number of grains, and each grain is subjected to a relative very small plastic deformation, and thus, the billet can maintain strain continuity. For the case with coarse grains, however, each grain undergoes a relatively large deformation, and the grain boundary blocks the plastic deformation. The grains in free surfaces have irregular shape due to the orientation of single grain and lack of constraints. The grains

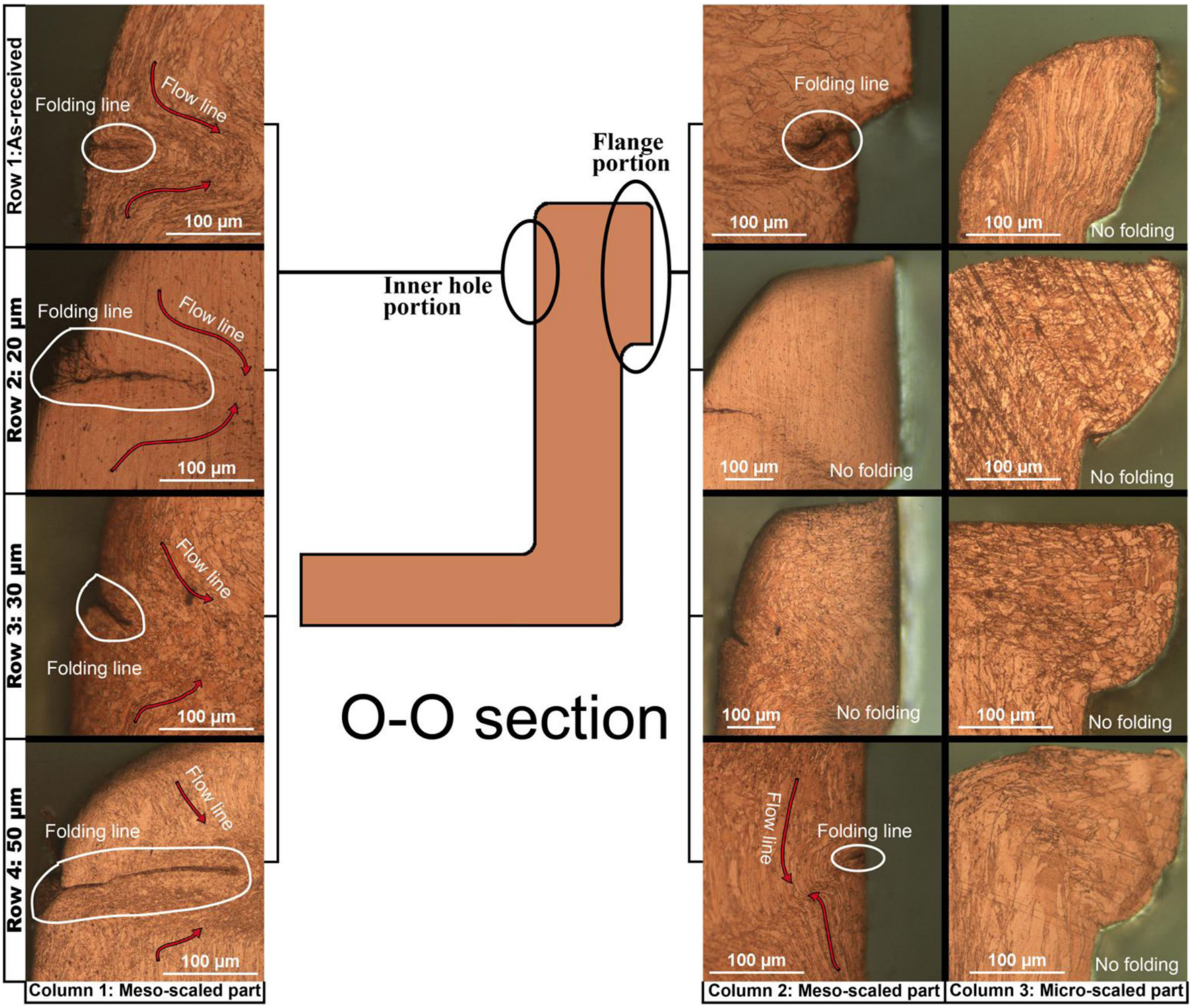

Fig. 11 Folding defect formation in the meso- and micro-scaled parts with different grain sizes in O–O section

located in the interior of the part are restricted by neighboring grains, and each grain undergoes a severe deformation in order to keep strain continuity. Once the plastic deformation exceeds a certain limit, the grains could be broken and become a potential insecurity factor, as shown in Column 3 in Fig. 10 with the grain size of 30 and 50 μm. The large deformation portion of the formed parts became rough with the increase of grain size in micro-extrusion process.

Based on the microstructure and the flow pattern of the formed parts, it can be seen that the case with fine grains has flow-induced defects; meanwhile, the case with coarse grains has broken grains as shown in Column 3 Fig. 10. However, even though, under such a severe deformation condition, there is a balance between flow pattern and degree of deformation. Column 2 in Figs. 10 and 11 with the grain size of 20 μm shows the unsharp flow lines, which means these have good mechanical property and do not have any broken grains. In micro-extrusion of the complicated parts, the relationship of geometry and grain sizes has a significant effect on flow-induced defects.

4 Conclusions

In microforming process, the occurrence of size effect affects the deformation behavior and micro-formed part quality. To fabricate high-quality microparts, the flow-induced defects such as folding defect caused by the irrational material flow in microforming process should be avoided. In this paper, the experimental investigation on flow-induced defects, microstructure, and flow pattern in micro-scaled extrusion of the parts with complicated shape was conducted. The following conclusions are drawn from this research:

1. Flow-induced defects are generally caused by the irregular material flow in micro-extrusion process, which is

similar to the scenario in macro-forming process. However, the flow line tends to be obvious with the increase of specimen size.
2. Geometry size effect has a greater influence on the formation of folding defects than grain size effect. With the decrease of geometry size, the folding defect in the deformed parts has a remarkable improvement no matter what grain size it has.
3. For the billets with fine grains, the deformed parts have the flow lines which are in accordance with part shape and structure, but the abnormal metal flow results in folding defects due to the complicated part geometry. For the case with coarse grains, there is no obvious flow line due to few grain boundaries in the deformation region. The improvement of folding defects is caused by the large deformation the individual grain undergoes and the grain boundary blocking the flow behavior.
4. Due to the individual grain undergoing large plastic deformation, several grains of the deformed micro-scaled parts with the grain size of 40 and 50 μm are broken. The micro-scaled part with the grain size of 20 μm balances the relationship between grain size and geometry size successfully, and the flow-induced defects and grain broken are avoided simultaneously.

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References

1. Geiger M, Kleiner M, Eckstein R, Tiesler N, Engel U (2001) Microforming. CIRP Annal-Manuf Technol 50:445–462
2. Engel U, Eckstein R (2002) Microforming—from basic research to its realization. J Mater Process Technol 125:35–44
3. Fu MW, Luo ZJ (1995) The simulation of the viscoplastic forming process by the finite-element method. J Mater Process Technol 55: 442–447
4. Fu MW, Shang BZ (1995) Stress analysis of the precision forging die for a bevel gear and its optimal design using the boundary-element method. J Mater Process Technol 53:511–520
5. Vollertsen F, Biermann D, Hansen HN, Jawahir IS, Kuzman K (2009) Size effects in manufacturing of metallic components. CIRP Annal-Manuf Technol 58:566–587
6. Chan WL, Fu MW, Lu J, Liu JG (2010) Modeling of grain size effect on micro deformation behavior in micro-forming of pure copper. Mater Sci Eng A 527:6638–6648
7. Chan WL, Fu MW (2012) Studies of the interactive effect of specimen and grain sizes on the plastic deformation behavior in microforming. Int J Adv Manuf Technol
8. Wang CJ, Shan DB, Zhou J, Guo B, Sun LN (2007) Size effects of the cavity dimension on the microforming ability during coining process. J Mater Process Technol 187:256–259
9. Ike H (2003) Surface deformation vs. bulk plastic deformation—a key for microscopic control of surfaces in metal forming. J Mater Process Technol 138:250–255
10. Diehl A, Engel U, Geiger M (2010) Influence of microstructure on the mechanical properties and the forming behaviour of very thin metal foils. Int J Adv Manuf Tech 47:53–61
11. Chan WL, Fu MW (2011) Experimental studies and numerical modeling of the specimen and grain size effects on the flow stress of sheet metal in microforming. Mater Sci Eng A 528:7674–7683
12. Messner A, Engel U, Kals R, Vollertsen F (1994) Size Effect in the Fe-simulation of micro-forming Pprocesses. J Mater Process Technol 45:371–376
13. Shan DB, Wang CJ, Guo B, Wang XW (2009) Effect of thickness and grain size on material behavior in micro-bending. T Nonferr Metal Soc 19:S507–S510
14. Siopis MS, Kinsey BL (2010) Experimental Investigation of grain and specimen size effects during electrical-assisted forming. J Manuf Sci E-T Asme: 132
15. Geiger M, Messner A, Engel U (1997) Production of microparts—size effects in bulk metal forming, similarity theory. Prod Eng 4:55–58
16. Fu MW, Chan WL (2013) A review on the state-of-the-art microforming technologies. Int J Adv Manuf Tech 67:2411–2437
17. Chan WL, Fu MW, Yang B (2012) Experimental studies of the size effect affected microscale plastic deformation in micro upsetting process. Mater Sci Eng A 534:374–383
18. Chan WL, Fu MW, Lu J (2011) Experimental and simulation study of deformation behavior in micro-compound extrusion process. Mater Des 32:525–534
19. Balendra R, Qin Y (2000) Identification and classification of flow-dependent defects in the injection forging of solid billets. J Mater Process Technol 106:199–203
20. Arentoft M, Wanheim T (1997) The basis for a design support system to prevent defects in forging. J Mater Process Technol 69:227–232
21. Lee DJ, Kim DJ, Kim BM (2003) New processes to prevent a flow defect in the combined forward–backward cold extrusion of a piston-pin. J Mater Process Technol 139:422–427
22. Chan WL, Fu MW, Lu J (2010) FE Simulation-based folding defect prediction and avoidance in forging of axially symmetrical flanged components. J Manuf Sci E-T Asme: 132
23. Wang JL, Fu MW, Ran JQ (2013) Analysis and avoidance of flow-induced defects in meso-forming process: simulation and experiment. Int J Adv Manuf Technol: 1-14
24. Petrov P, Perfilov V, Stebunov S (2006) Prevention of lap formation in near net shape isothermal forging technology of part of irregular shape made of aluminium alloy A92618. J Mater Process Technol 177:218–223
25. Fu MW, Luo ZJ (1992) The prediction of macro-defects during the isothermal forging process by the rigid viscoplastic finite-element method. J Mater Process Technol 32:599–608
26. Rosochowski A, Presz W, Olejnik L, Richert M (2007) Micro-extrusion of ultra-fine grained aluminium. Int J Adv Manuf Technol 33:137–146
27. Parasiz SA, Krishnan N, Li M, Cao J, Kinsey B (2006) Investigation of deformation size effects during microextrusion. J Manuf Sci Eng 129:690–697
28. Chan WL, Fu MW, Yang B (2011) Study of size effect in micro-extrusion process of pure copper. Mater Des 32:3772–3782