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Grain size and workpiece dimension effects on material flow in an open-die micro-forging/extrusion process

Ehsan Ghassemali[1,2*], Ming-Jen Tan[1], Chua Beng Wah[2], Anders E.W. Jarfors[3], S.C.V Lim[4]

[1] School of Mechanical & Aerospace Engineering, Nanyang Technological University, Singapore 639798

[2] Singapore Institute of Manufacturing Technology (SIMTech), 71 Nanyang Dr, Singapore 638075

[3]School of Engineering, Jönköping University, P.O. Box 1026, SE-551 11 Jönköping, Sweden

[4]Materials Engineering, Monash University, Wellington Road, Clayton, Victoria, Australia

Abstract

The interactive effect of grain size and specimen dimensions on the material flow and microstructural evolution was studied in a progressive open-die microforming process. Particular interest was paid on the effect of the number of grains over the initial specimen thickness, on the evolution of the dead metal zone (DMZ) in the final micro-component's microstructure. Such a DMZ is deemed unfavorable for mechanical properties of the pin. Interestingly, experimental results revealed that the DMZ can be removed at the pin surface by increasing the initial grain size. This behavior was attributed to the role of the strain gradient on the deformation. In the aspects of the forming load and dimensional measurements of the final parts, there were no significant size-effects observed in this process. This is because the neutral plane, which demarcates the two directions of material flow in the open-die forging/extrusion process, determines the amount of material flow towards the die orifice, regardless of the initial grain size.

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[*] Corresponding Author: Ehsan Ghassemali, Email: ehsa0005@ntu.edu.sg, Tel: +65-84312143

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1. Introduction

Microforming processes have gained much attention due to industries' interest for miniaturization of metallic components. There are many studies in literature about improving the microforming processes [1-3]. These processes, however, are still not widely used for mass production in industries, due to lack of process optimization.

Generally, to optimize a metal forming process, from its metallurgical aspect, one needs a wide range of knowledge about the material behavior during the process. Scaling down a conventional forming process to micro-scale, brings up the "size effects", influencing the material behaviour [4]. The size effect causes unexpected results, when the dimensions of grains in the microstructure become comparable to the dimension of the cross section of the workpeice [5].

Specifically, the mechanical behavior of a polycrystalline metal mainly depends on its microstructure and the grain size [6-8]. As modeled by the Hall-Petch relationship, for grains with diameter of larger than a few microns, a decrease in grain size leads to a general strengthening (Grain Size Effect) [9].

Nevertheless, it has been reported that the thickness of the workpeice must be considered together with the grain size to determine the mechanical response of the material during a microforming process [8]. In fact, mainly based on the stacking fault energy of the metal, there is a critical number of grains over the thickness of the workpiece, below which the mechanical behavior of the metal will not follow the Hall-Petch relationship (Grain-Specimen Size Effect) [10-16].

In this aspect, Cao et al. [17] investigated the impact of initial billet grain size on the material behavior in a micro-extrusion process. It was reported that the qualitative deformation flow pattern of the final micro-pins was slightly different using billet with different number of grains over diameter.

Using the same process, Parasiz et al. [18] also reported that the microstructure of the formed micro-pins was similar to what is seen in macro-scale extrusion, i.e. more deformation at the outer surface of the pins. It was also observed that the formed pins tend to bend for the coarse-grained specimens [18]. This tendency was due to the fact that grains in the coarse grained material deform inhomogenously according to their orientations. Since there was no supporting landing wall inside the extrusion die orifice, the pins were free to bend during forming.

Measuring the mechanical properties of the formed pins, they [19] also found that the hardness value of the coarse-grained pins were higher than that of the fine-grained pins. This is so because for the fine-grained pins, the grains at the center of the pin do not experience much shearing, since they are further away from the sheared surface grains. However, the central grains of the coarse-grained pins are just a few grains away from the sheared surface grains. Therefore, induced deformation strain from the adjacent grains, will cause a stain gradient hardening in the central grains of the coarse-grained pins [15].

Despite the huge number of the reports regarding the grain-specimen size effects during the microforming processes, there are very limited publications about the grain-specimen size effect on the material flow or microstructural behavior during these processes.

Investigating the microstructural evolution of the micro-pins manufactured by a progressive microforming process, an interesting phenomenon was reported in a previous study [20]. Due to the nature of the process, there was a dead-metal-zone (DMZ) developed at the pins surface, under some specified circumstances. The micro-pins were produced by punching a sheet metal placed on a die with a micro-hole. More details of the process can be found in [2, 20].

Using finite element simulation, the leakage of the DMZ to the die orifice (at the pin surface) was explained by monitoring the location of the "neutral plane" relative to the volume of the DMZ during the process [20]. It was found that if the neutral plane crosses the DMZ on the deforming material, it can push the DMZ material towards the die orifice, causing a narrow layer of DMZ at the pin surface. This leads to inhomogenous mechanical properties. Selection of a proper punch diameter for the desired pin diameter was suggested to avoid the existence of the DMZ on the pin structure [21].

Following those studies, the aim of this study was established to present a comprehensive experimental investigation of the grain size and specimen size effects on the DMZ behavior during the progressive microforming process (as a representative for open-die extrusion/forging processes). Dislocation cell theories were used to explain the material behavior. The effect on the dimensions of the pins and the forming force was also monitored to have a comparison with previous size-effect studies. To consider the effect of the number of grains over the cross section (grain-specimen size effect), specimens with different grain sizes and two different thicknesses were used.

2. Experimental procedure

2.1. Materials

Electrical Tough Pitch (ETP) C11000 copper (99.94%) strips, in the as-received cold-rolled condition, with 200 mm in length and 20 mm in width were used as the raw initial feed for the process. The dimensions of the strip were selected based on the primary prototype design of the die-set. To have a change in the number of grains over the thickness, two different thicknesses of 2.5 and 0.5 mm were used for the initial strips. To eliminate the possible effect of residual stress, the strips were stressed-relieved by annealing at 180˚C for 1 hr. This provides similar initial material properties for the strips with different thicknesses, without changing the initial grain size.

The initial grain size of the applied material was 14±4 μm, excluding twin boundaries (Fig. 1). The hardness test was done on the normal direction of the strips giving the value of 75±5.2 Hv.

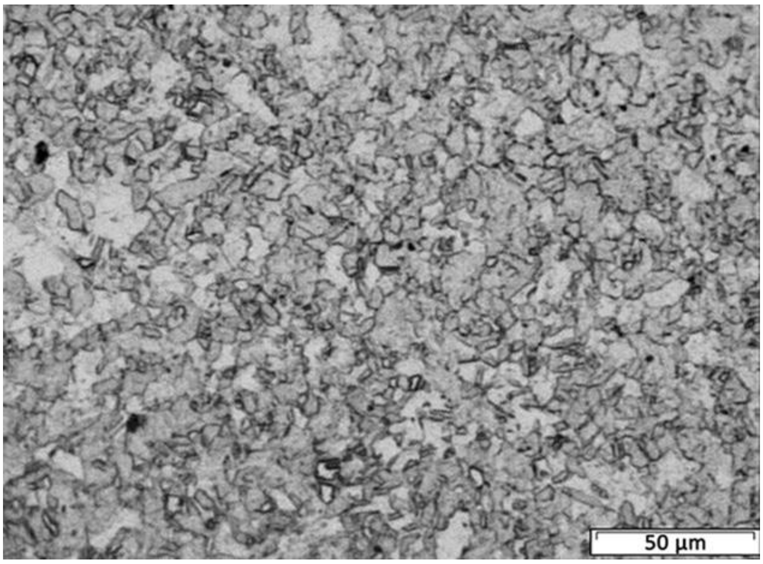


Fig. 1. Micro-graph of the microstructure of the copper C11000 used in the process.

2.2. The microforming process

As shown schematically in Fig. 2, a progressive microforming process was used for the manufacturing of micro-pins. The process consisted of two stages: (i) Pin forming by forward extrusion, and (ii) Blanking. In the first stage, which is the main stage, the strip is deformed by a punch of a defined diameter, and a specified displacement. As a result, a portion of the material is forward extruded into the die orifice. In the second stage, the formed pin is blanked out from the strip material. More details of the process can be found in [2].

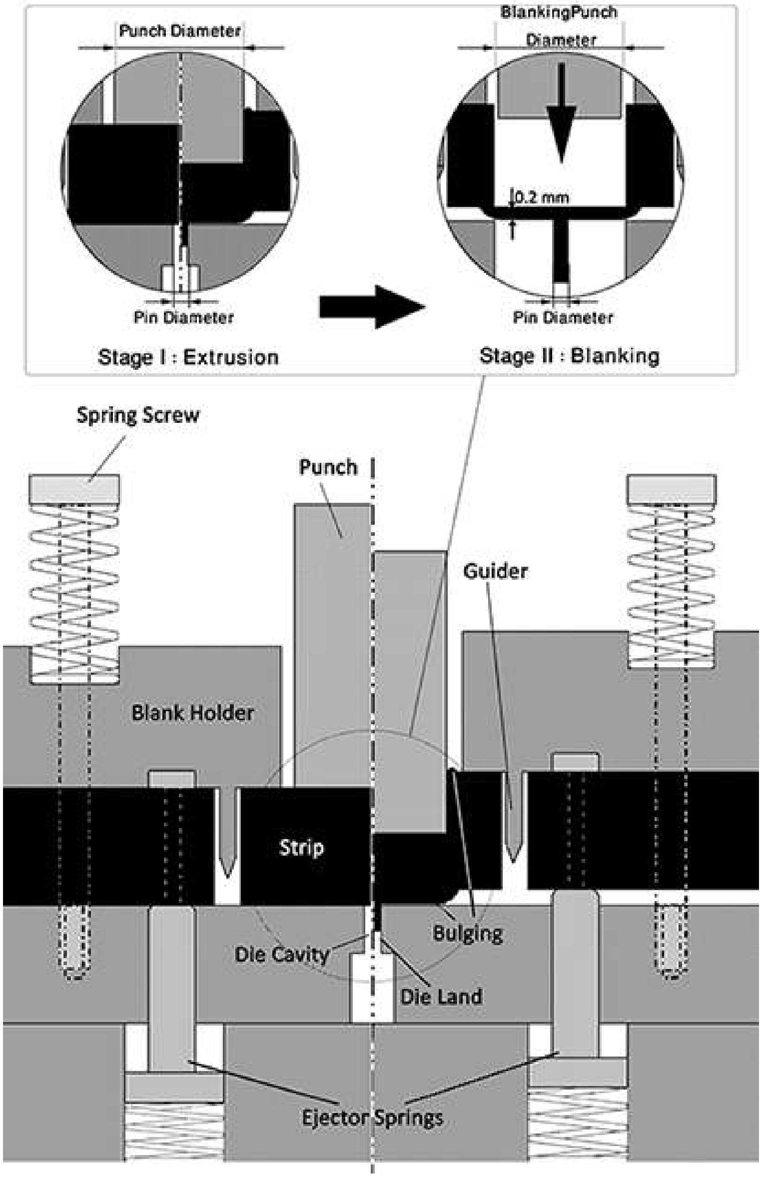


Fig. 2. Schematic of the progressive microforming process.

A punch, of diameter of 3.2 mm, was used for production of pins with diameter of 0.3 mm. It is to be noted that under this geometrical condition, there would be a DMZ formed on the pin surface as observed in a previous work [21, 22]. All the experiments were done in dry condition, without using any lubricants. The forming speed was 0.1 mm/s. The blank holder was spring-loaded with six springs producing a constant pre-load of about 2.3 kN. Both of the strips regardless of their initial thicknesses were punched till 0.2 mm of the remaining thickness (the thickness of the head part was 0.2 mm at the end as shown in Fig. 2).

2.3. Characterization methods

Due to the process boundary conditions and material flow in the process, there is a bulge appearing around the formed pins on the strip [2]. Considering the bulge around the formed pins, the method as illustrated in Fig. 3 was used to measure the pin height and actual punch displacement, using Eq. 1 and Eq. 2, respectively.

$$\textit{Pin Height} = t_t - t_c \qquad (1)$$

As will be explained in the next section, the mechanical behavior of the material can be considered as plastic in the simulation. Thus, to have a better match between the experimental and simulation results, the elastic deflection has to be eliminated in the experimental results. To do so, the actual punch displacement was considered, based on Eq. (2).

$$\textit{Actual Punch Displacement} = \textit{Initial Strip Thickness} - t_b \qquad (2)$$

All the measurements were done using a micrometer caliper with resolution of 0.001 mm. To ensure about the accuracy, all the measurements were confirmed with the AM7013MT Dino-Lite Premier digital microscope.

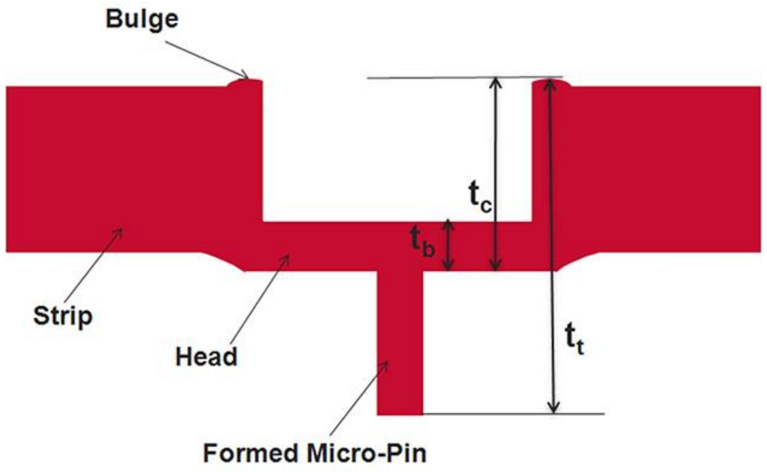


Fig. 3. Measurement method used for measuring the pin height after Stage I.

A programmable servo press (SCHMIDT ServoPress 420) was used for the deformation process. The load-displacement behavior of the punch was monitored by the machine precisely, with resolution data acquisition of 0.01 kN for the force and 0.005 mm for the displacement.

To compare the mechanical properties, upsetting test was done on cylindrical specimens machined in the normal direction of the strips having different grain sizes. The electrical discharge machining (EDM) was used to fabricate the upsetting specimens with a diameter of 1.67 mm and 2.5 mm in height (ratio of 1.5). Two layers of Teflon, with thickness of 0.1 mm, were used as lubricant on the top and bottom surface of the specimens. To further eliminate the friction effects on the upsetting test results, the tests were stopped at steps of 10% reduction to renew the lubricant layer. An average of the 3 upsetting test results was presented as the stress-strain behavior of the copper strips annealed at different temperatures.

An Olympus light microscope was used for cross-section microstructural observations. The micro-pins were mounted, ground and polished to half diameter and subsequently etched using an Ammonia Persulfate solution.

Field Emission Scanning Electron Microscope (FESEM, JEOL JSM-7600F) was used for surface quality observations. This microscope was also used for Electron Backscatter Diffraction (EBSD) analysis. The FESEM was conducted with an Oxford Instruments HKL EBSD system working at 20 kV with a working distance of 28 mm and a 70° tilt angle. The CHANNEL 5 suite of programs, developed by Oxford Instruments, was adopted to manipulate, analyze and display EBSD data in the current work.

To get the overall EBSD maps, the pixel by pixel scan method was used by using step size of 0.2 µm to be able to detect small subgrain/dislocation cell size with the least error. For the data sets obtained from EBSD mapping, all the fractions of successfully indexed data pixels were higher than 70%, which is reliable for determining the crystallographic texture [23].

In the high-resolution EBSD, low angle boundaries (between 2° and 10°) were depicted as white lines, and high angle boundaries (>15°) as black lines. In order to avoid spurious boundaries, misorientation below 2° was not taken into account. It is worth noting that although most of researchers consider the upper limit of 15° as for the low angle grain boundaries (LAGBs), but some do the 10° as a threshold misorientation [24]. Therefore, to be in a safe zone, misorientations between 2 to 10 degrees were considered as LAGBs. Grain size measurement was carried out in the EBSD software by determining the grain areas exclusive of border grains. The mean values of the subgrain/grain size of the microstructures were obtained from the statistical evaluation tool embedded in the EBSD software. The same route has been used before [24-27].

The microhardness test was conducted using MTS Vickers Microhardness tester machine with the load of 0.5 N based on ASTM E 384 standard. This load was sufficient to make a measurable indentation mark of at least 35 µm in width on the copper alloy with the least error. The microhardness results presented are the mean value of at least 3 tests on 3 different micro-pins manufactured under the same process conditions. The standard deviation for each hardness value was less than 10% of the mean value. The distance between individual indentations was selected based on ASTM E 384 standard.

To alter the grain size, the strips were annealed at 400, 600 and 800˚C in a Lenton tube furnace under vacuum of 10^{-5} mbar using a ramp of 3˚C/min for 1 hr. Longer dwelling time for annealing had no significant effects on the grain size.

The dies and punches were manufactured from SKD11 steel material, with diameter tolerance of ±0.005 mm.

3. Results and discussion

3.1. Initial material properties

Figure 4 shows the microstructure of the strips annealed at different temperatures for 1 hr. As can be seen, there is a good range of grain sizes (from about 14 µm to around 110 µm) for investigation. The annealing process at 400, 600 and 800°C decreased the hardness value of the initial strips to 65±3.2, 63±2.5 and 62±3.0, respectively.

To normalize the results, the number of grains over the thickness of the strips was calculated, as presented in Table 1. The 2.5 mm strips were used to study the grain size effect, while the 0.5 mm strip with coarse grains was used to investigate the grain-specimen size effects.

Table 1. Mean number of grains over the thickness for different strip thicknesses annealed at different temperatures for 1 hr.

Annealing temp.(˚C) Strip thickness (mm)	As-received	400	600	800
2.5 (thick)	180	45	26	23
0.5 (thin)	36	9	5.2	4.5

It is worth mentioning that for the samples annealed at 600 ˚C and 800 ˚C, the number of grains over the thickness for the 0.5 mm strip, are below the critical number for the copper, which is around 8 [8]. Therefore, it can be expected to see the grain size effects in those cases [8].

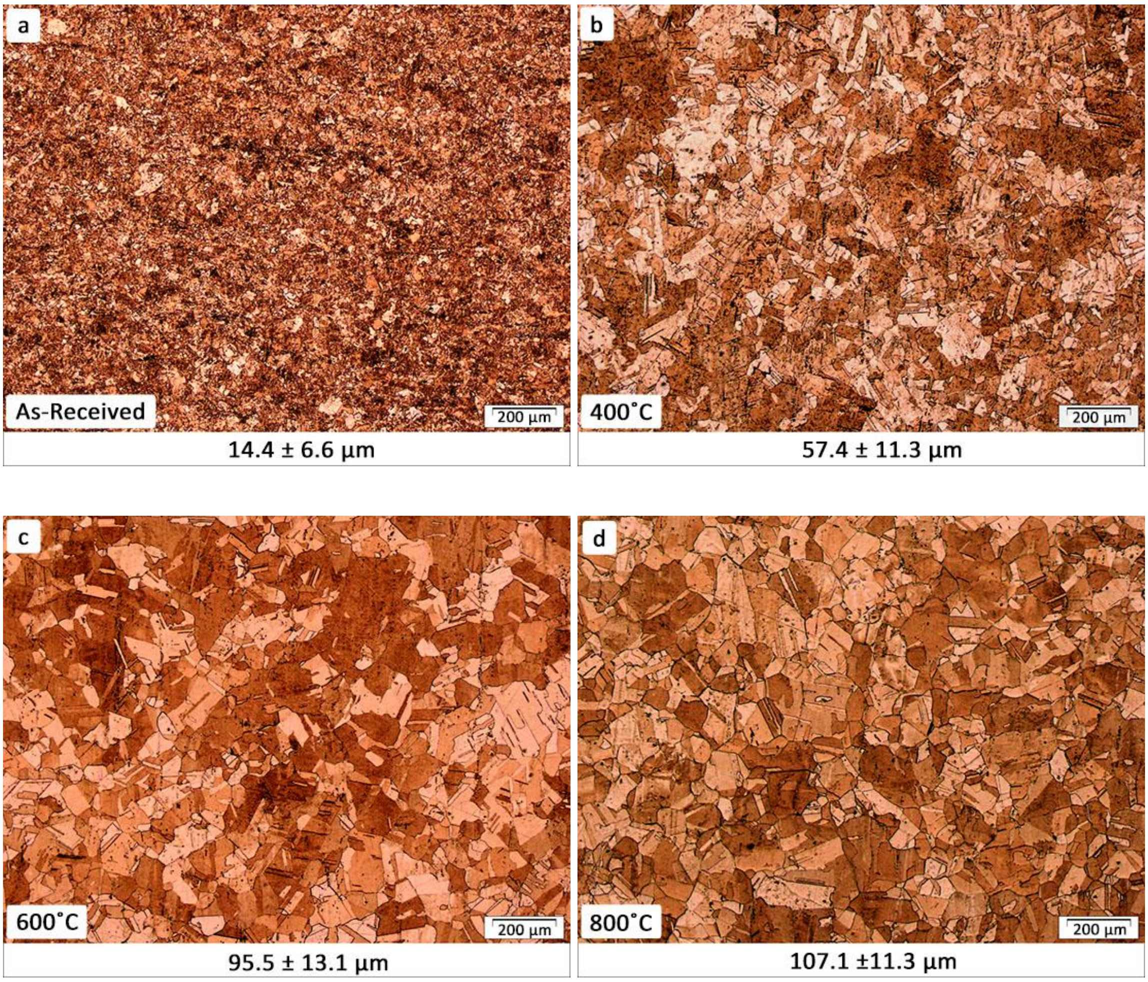


Fig. 4. Optical micrograph and mean grain size of the C11000 copper alloy annealed at different temperatures of: a) as-received; b) 400°C; c) 600°C; d) 800°C; for 1 hr.

Figure 5 illustrates the effects of the annealing temperature on the mechanical properties of the C11000 copper alloy. From the slope of the flow curves of the annealed specimens, it can be concluded that annealing above 400˚C has a limited effects on the strain hardening of the alloy. Therefore, by annealing at the before-mentioned temperatures, it was ensured that there was only the grain size being altered, without significant changes in the general mechanical behavior of the metal.

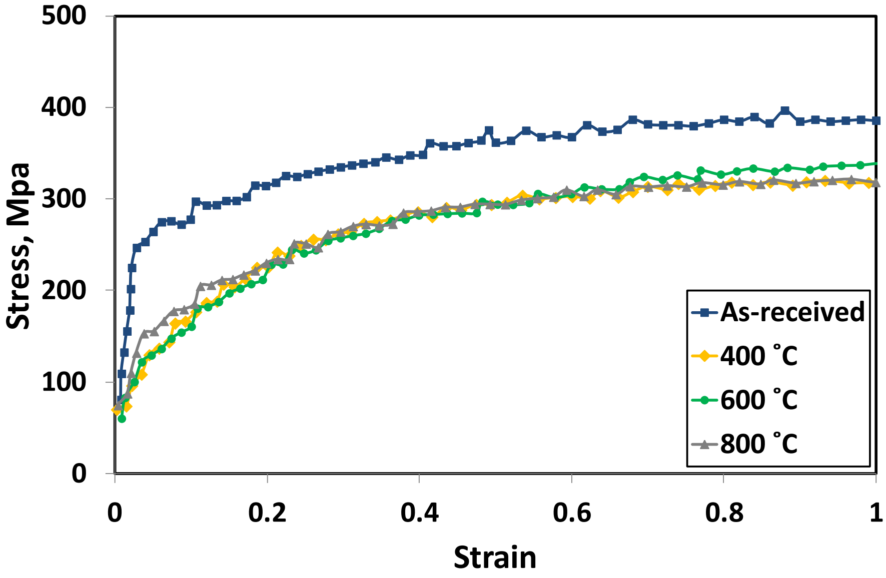


Fig 5. Flow stress curves of the CC11000 copper alloy achieved by upsetting test after annealing at different temperatures for 1 hr.

3.2. Grain size effect (for the 2.5 mm thick strip)

The pin height and the maximum forming load were recorded in the progressive microforming process. As can be seen in Fig. 6, there is a slight increase in the average pin height from 2.5 to 2.6mm by increasing the initial grain size. This marginal increase can be attributable to the annealing treatment that softened the material, leading to a slight ease of material flow into the die orifice in the initial stages of the process. However, it is difficult to make a robust conclusion from this figure, as the results overlap on their standard deviation.

As mentioned in previous studies [20, 28], the final micro-part dimensions in this type of open-die process is determined by the process geometrical conditions. In more details, the geometry of the process together with the frictional conditions govern the location of the neutral plane [29]. The location of the neutral plane determines the amount of material flowing towards the die orifice, which forms the final micro-part. Therefore, the initial properties of the forming metal theoretically have no effect on the final part dimensions under these circumstances.

It is worth noting that a pin aspect ratio (Pin height/Pin diameter) of more than 8.3 was achieved by this process, in dry conditions (Fig. 6).

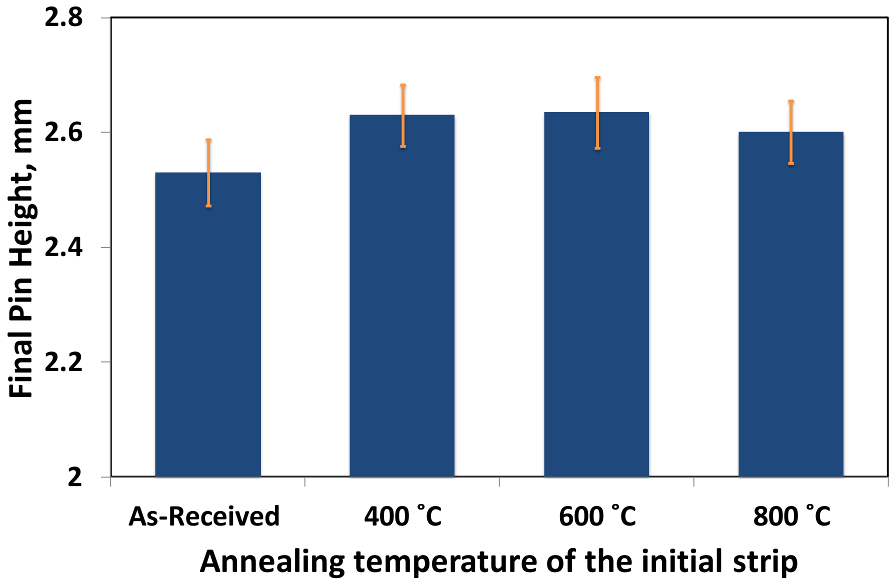


Fig. 6. The effect of grain size (annealing temperature in 1 hr) on the final part dimensions in the open-die micro-forming process. (For the pin diameter of 0.3 mm manufactured from the 2.5 mm strip thickness).

The required forming load during the process is plotted in Fig. 7, for specimens with different grain size. As explained in more details in [2], the load-stroke curve consisted of three stages including indentation at the beginning, the middle stage of upsetting with lower slope, and the final extrusion stage with a relatively sharper slope. As can be seen in this figure, increasing the grain size leads to lowering the forming load during the first two stages. Indeed, at the beginning of the process, the material only goes through upsetting. In upsetting, by increasing the grain size, there is less force required for metal flow. However, by reaching the final stage, where the metal mainly flows towards the die orifice (extrusion), there is no significant difference in forming load for different specimens. This is due to the fact that by increasing the grain size relative to the die diameter, it would be more difficult for the metal to flow inside the die orifice, as reported by Wang et al. [30]. Therefore, by increasing the grain size, although the metal gets softer, more redundant work must be done to develop shear deformation to flow the material inside the die orifice. In shear deformation a network of dislocation cells develops inside the grains and break up the grains to smaller ones to flow inside the die orifice. As a consequent, the balance between softening caused by coarse grains and the redundant work makes the total force relatively closer to the as-received one at this stage. This interestingly implies no significant grain size effect in forming load.

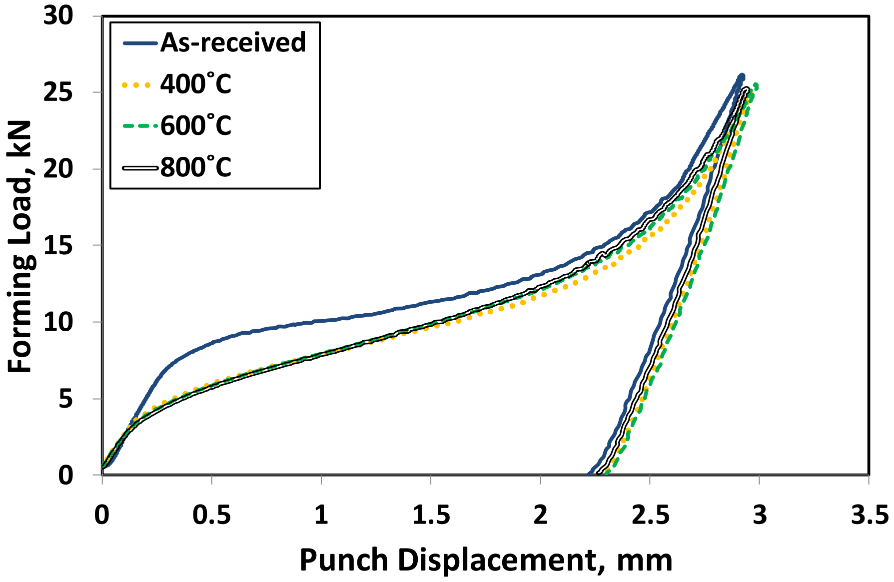


Fig. 7. Load-Stroke curve for pin forming using samples with different grain sizes (For the pin diameter of 0.3 mm manufactured from the 2.5 mm strip thickness).

The grain size effect is, however, observed more in the microstructural observations. Figure 8 represents the cross-sectional microstructure and hardness profile of the 0.3 mm pins formed from the strips with various grain sizes. As explained in a previous study [20], there is a DMZ leakage to the die orifice for the 0.3 mm pin formed by the 3.2 mm punch from the as-received metal.

Interestingly, the volume of the DMZ in the pin microstructure was decreased by increasing the initial grain size. The main reason for this behavior can be attributed to the strain gradient through the microstructure associated with the formation of dislocation cells inside the grains [31-34].

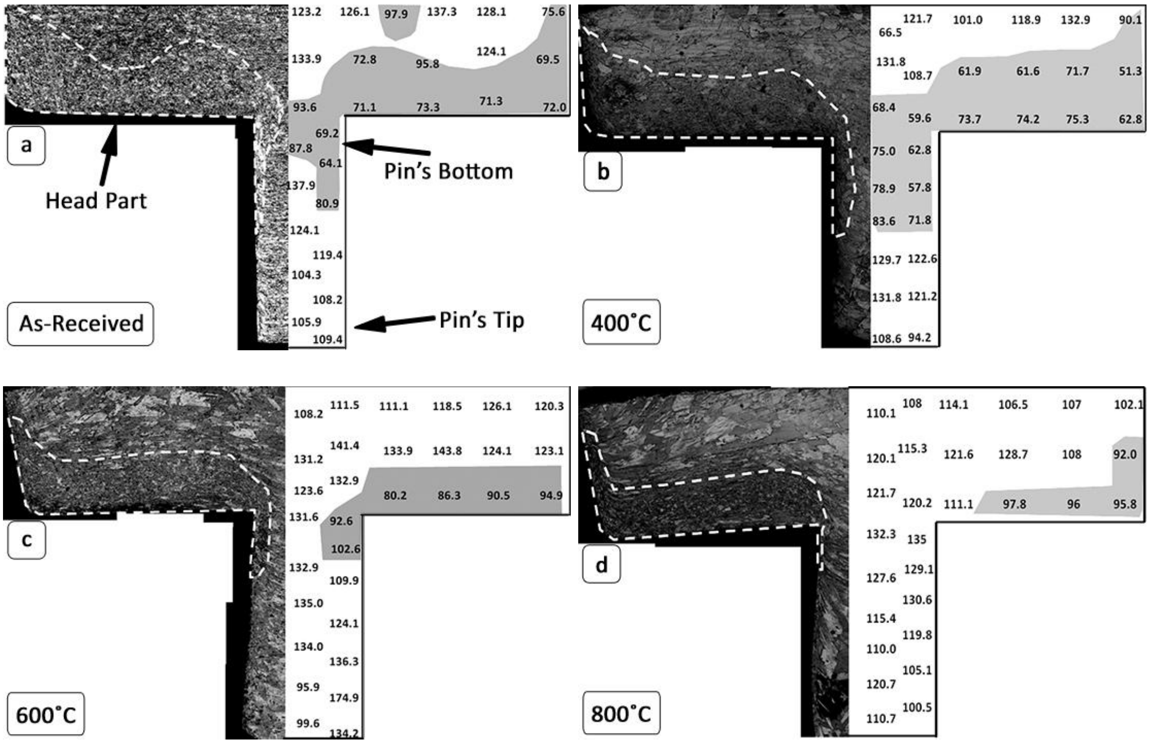


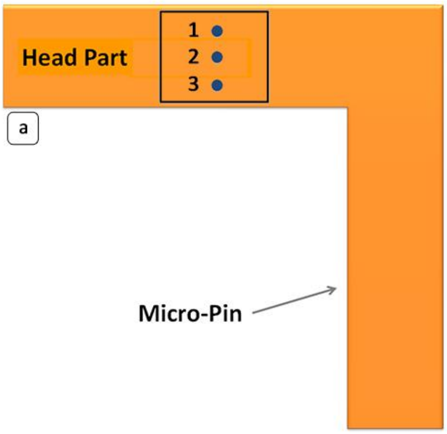
Fig. 8. Microstructure and microhardness profile (Hv) of the 0.3 pin manufactured from the 2.5 mm strips which were annealed at different temperatures of: a) as-received; b) 400°C; c) 600°C; d) 800°C, for 1 hr. Gray zones show the soft zones (DMZ), identified as regions having hardness value of lower than 70% of the maximum hardness value on the cross section.

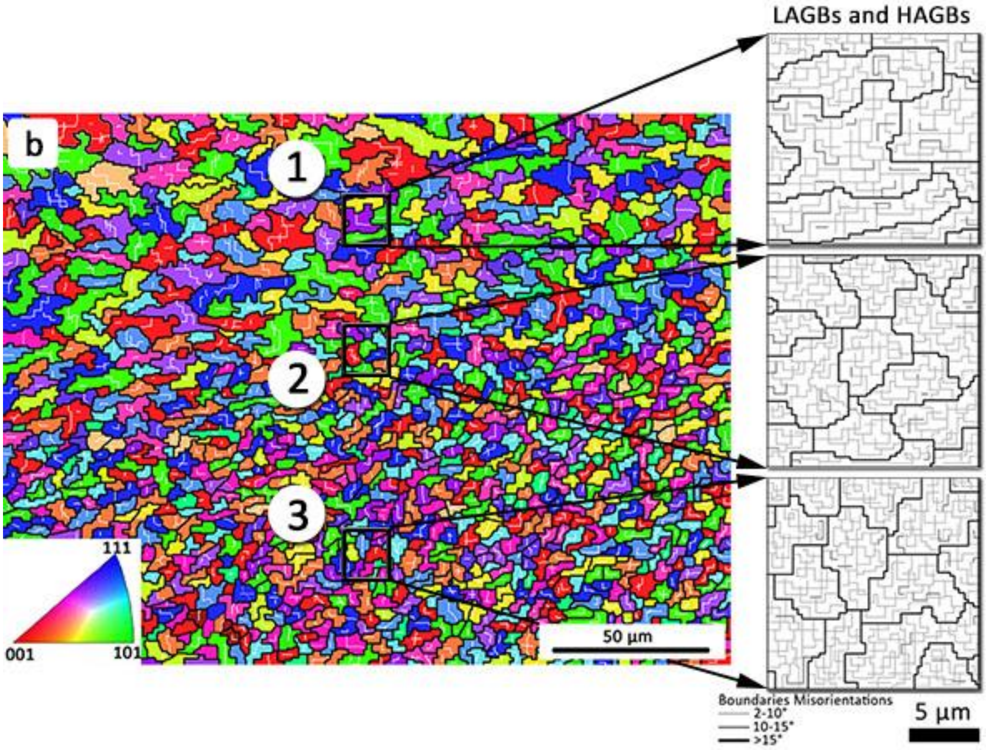
Indeed, a larger DMZ is related to more inhomogeneous metal flow [35]. The inhomogeneity in the metal flow is identified via investigating the strain gradient distribution in the microstructure [36, 37].

It has been found that the amount of the effective-strain-distribution is directly related to the dislocation cell size and/or subgrain size [38]. In fact, smaller dislocation cell size corresponds to higher strain distribution in the microstructure. Decreasing the dislocation cell size (or subgrain size [39]) leads to a decrease in the dislocation free path which in return affects the effective strain value inside the grains. On the other hand, the dislocation cell size depends on the initial grain size by square root relationship: a smaller initial grain size leads to smaller dislocation cell after forming, for a given strain [40].

To justify this fact, the EBSD technique was used. Figure 9 presents the EBSD maps of the head-part of the 0.3 mm pins manufactured from strips with various initial grain sizes. Un-deformed grains on the top (region 1), follows by elongated grains at the middle (region 2) with an elongated shape relative to the flow direction, and relatively smaller equi-axed grains at the bottom (region 3) correspond to the DMZ. In fact, the grains at region 3 (inside the DMZ) are stationary and only flatten under compression.

By increasing deformation, due to extrusion of subgrains, grain boundaries serrate progressively. Once the thickness of the original grain decreases to about the size of two subgrains, the grain boundaries come into contact and hence the grains split up [41]. Having that mentioned, by increasing the initial grain size, there would be a delay in formation of the subgrains from dislocation cells with critical size, which could lead to a delay in development of DMZ, and thus reducing the DMZ volume. As reported by Guzel et al. [41], this fact can be monitored by measuring the subgrain size through the microstructure.


1
2
3
Head Part
a
Micro-Pin


LAGBs and HAGBs
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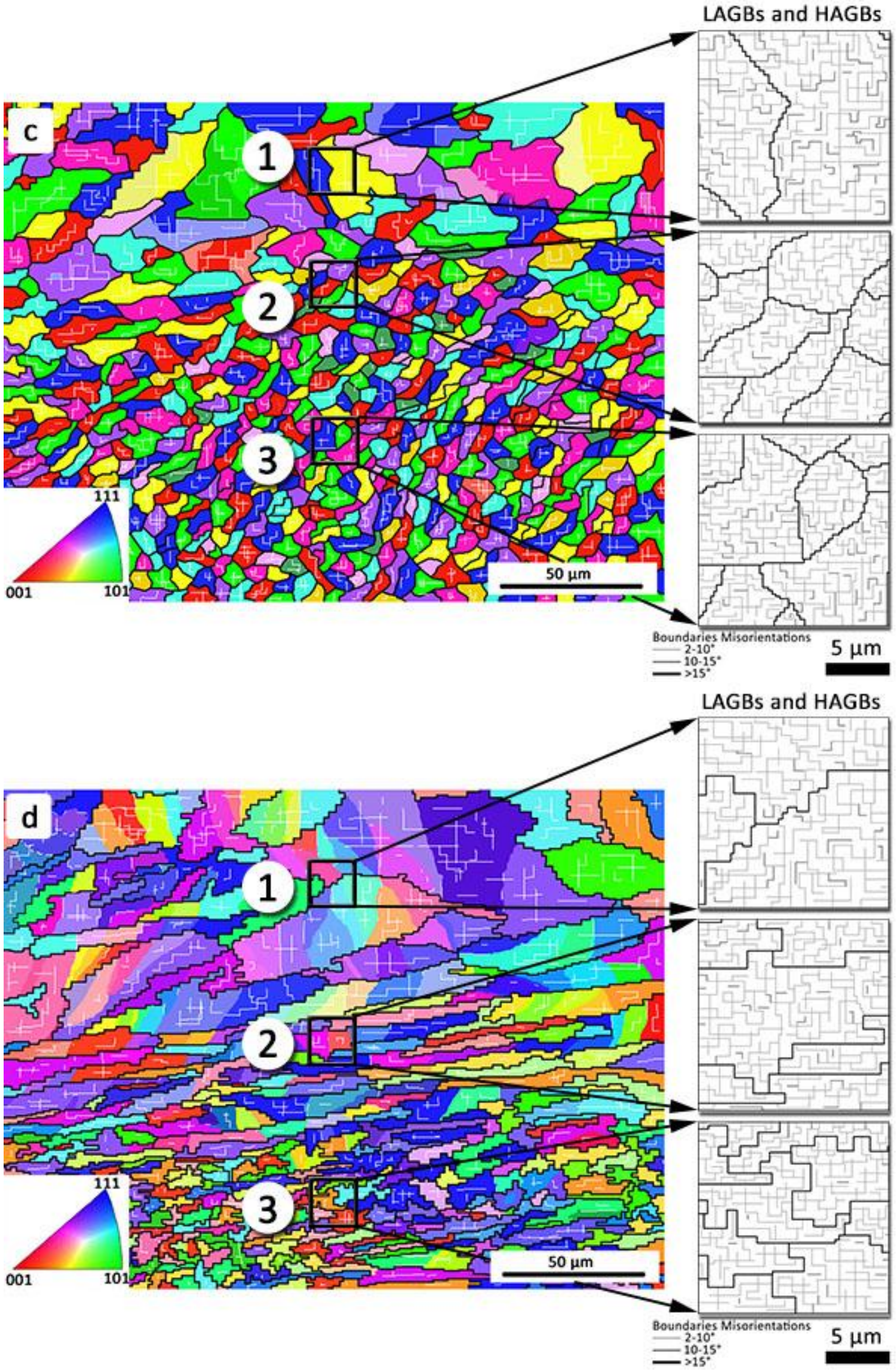
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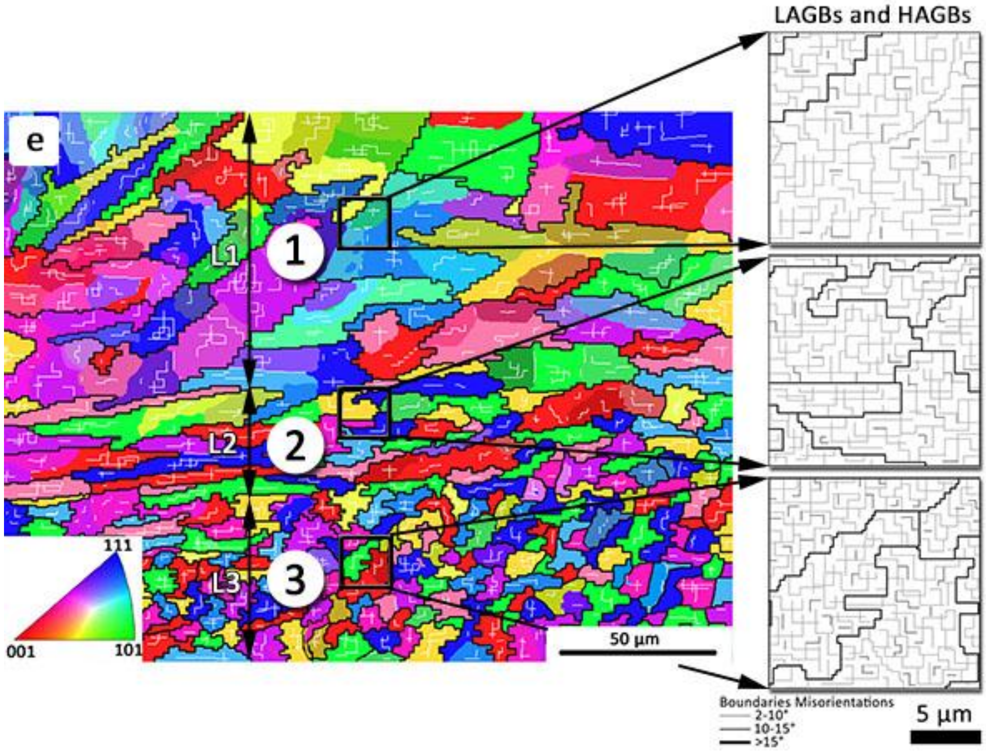

Fig. 9. a) schematic of the half-cross section of the micro-pin showing the location of the inverse pole figure (IPF) EBSD maps taken from 0.3 mm pins, manufactured from different strips under initial conditions of: b) As-received; annealed at: c) 400°C; d) 600°C; e) 800°C. Regions assigned as 1, 2 and 3 represents the regions with different grain structures. Length of these regions has been schematically shown in Fig. 9-e. The substructure of a random bunch of grains in each region has been shown in the magnified images at right, showing grain boundaries with different misorientation angles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

As illustrated in Fig. 10, for each sample the subgrain size decreases by moving from the top part of the head towards the bottom (from region 1 to region 3). This, as mentioned, is related to the strain gradient that exists within the microstructure in the head part. In another view, by increasing the initial grain size, the subsequent subgrain size became bigger (Fig. 10-b).

Dislocation theories determine lower stresses being applied on the bigger dislocation cells/subgrains [42]. The overall applied stress (which is the same for all samples) in coarse-grained samples is consumed for generation of new dislocations and development of dislocation cell structures. In fine-grained metals, however, the cell size and subsequently the dislocation free path is smaller, and therefore, higher fraction of overall applied stresses is concentrated on the subgrain boundaries by dislocation pile-ups. This induces a plastic strain gradient inside the microstructure of the fine-grained metals. Chan and Fu [40] reported a similar behavior and they mentioned that this phenomenon becomes clearer by increasing the number of grains over the cross-section of the specimen. This fact will be investigated in sections ahead.

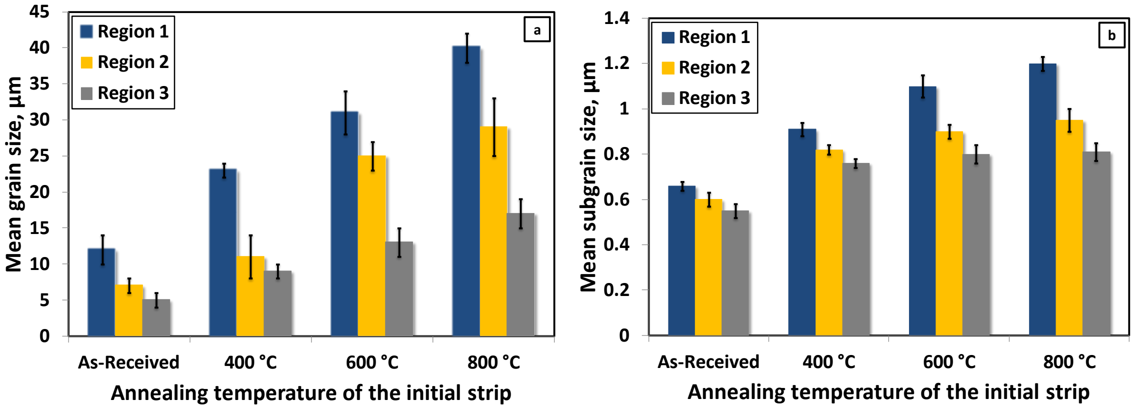

Fig. 10. a) Mean grain size, and b) Mean subgrain size of the 3 regions shown in Fig. 9, for the 0.3 mm pin manufactured from strips annealed at different temperatures.

As shown in Fig. 11 (Extracted from Fig. 9), increasing the initial grain size of the metal strip leads to decrease in the fractional length of the Region 3, corresponds to the DMZ. This literally proves the data shown in Fig. 8 (increasing the volume of DMZ by increasing the initial grain size of strips before forming).

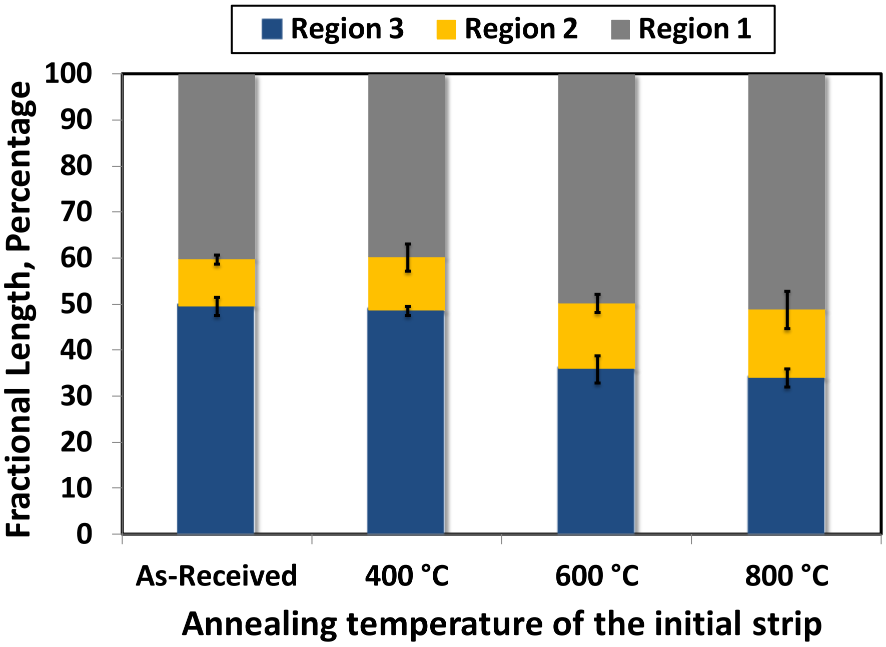

Fig. 11. Fractional length of the three regions throughout the cross section of the head part of the 0.3 mm pin manufactured from strips having different grain sizes.

To summarize, in metals with larger grain size, there is a delay in development of DMZ due to a larger dislocation cell size in the microstructure. Thus, the DMZ volume will be smaller, and subsequently there will be no leakage of the DMZ inside the die orifice (no DMZ at the pin surface).

It is to be noted that by looking in detail of the microstructure in the Fig. 8-d, there is a very narrow DMZ leakage to the die orifice. However, the volume of this DMZ was very small and could not be captured by the micro-indentation test. Therefore, it is not obvious in the hardness profile.

To have a better understanding about the development of such a DMZ within the structure, the microstructure of the micro-pin manufactured from the coarse-grained specimen (annealed at 800˚C), were investigated during the process in different punch displacements of 1, 1.5, 2 mm (Fig. 12). As can be seen, the DMZ first develops under the punch, at the top surface of the head, due to interfacial friction forces. Interestingly, at the beginning, there is no DMZ at the die surface (bottom part of the head) and it develops only at the end of the process. This trend is a bit different from what has been observed for the as-received specimen with smaller grain size [21].

In this case, using a coarse-grained metal as the initial strip, the dislocation cells were not developed thoroughly within the microstructure. Consequently, there would be less inhomogenous deformation, and therefore, there were smaller less-deformed zones (DMZs) in the head part.

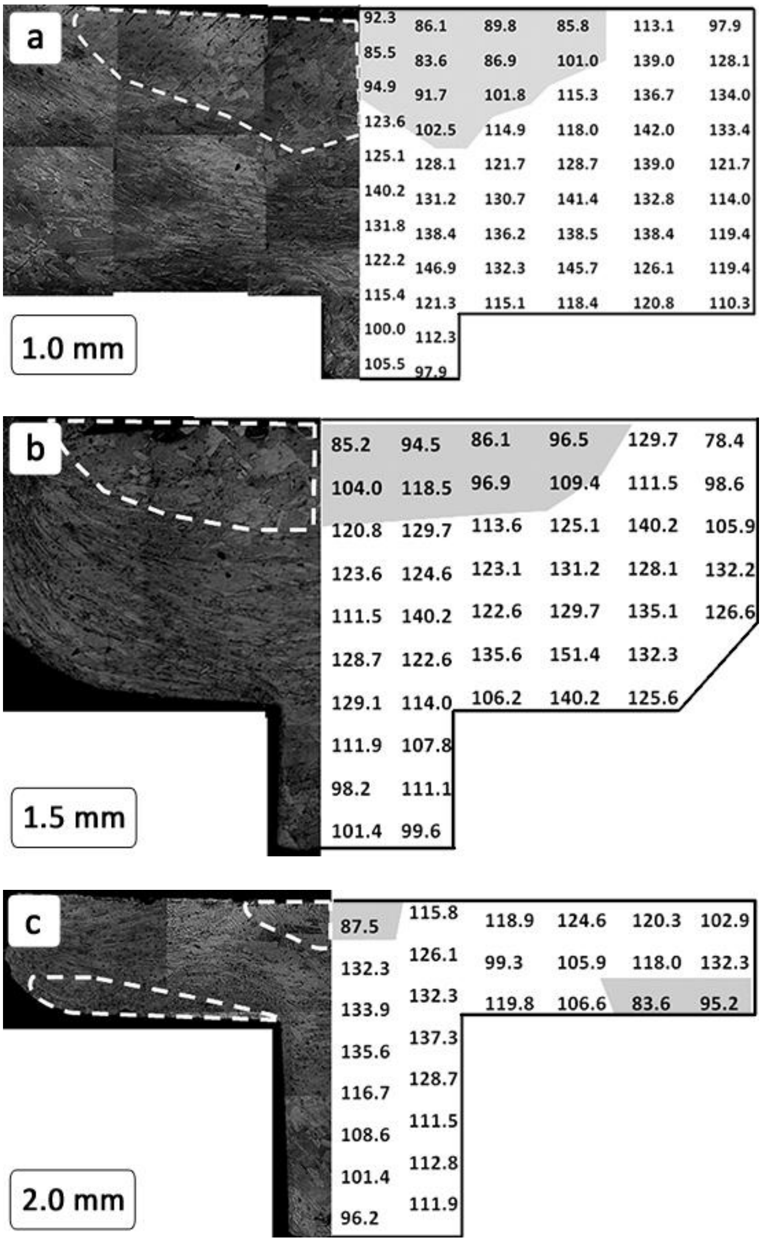

Fig. 12. Development of the DMZ in the "head" part of the micro-pins' structure through the process in different punch displacement of: a) 1 mm; b) 1.5 mm; c) 2 mm (for the 0.3 mm pin manufactured from the coarse-grained strip). Hardness values in Hv.

3.3. Grain-Specimen size effect (for the 0.5 mm thick strip)

As mentioned by Keller [8], the size effect would be only obvious if the number of grains over the cross-section of the metal goes below the critical number, which is around 8 for copper. Based on Table 1, in this work, using the annealed strip at 800°C with thickness of 0.5 mm, provides such a condition. Figure 13 compares the dimension of the 0.3 mm pins manufactured from the thin and thick strips (0.5 mm thickness) with different grain size. As can be seen, there is again negligible grain size effects on pin height, which again supports the hypothesis of the key role of the neutral plane on determination of the part dimension in open-die forming processes.

Moreover, in Fig. 13 comparing the pin height achieved at two different strip thicknesses for each annealing condition, shows that the main portion of pin forming (about 70%) occurred at the very end stroke of the process (the last 0.5 mm thickness). This implies that there must be a critical strip thickness, after which the metal flows mainly towards the die orifice. This fact has been reported in a previous study [28].

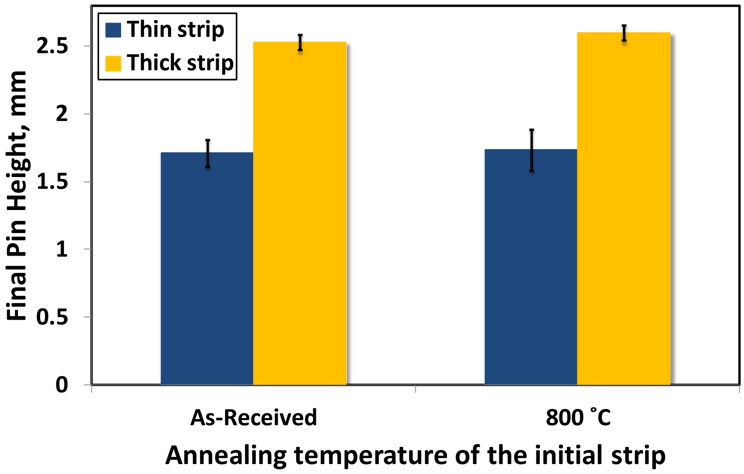

Fig. 13. The effect of grain size on the final part dimensions in the open-die micro-forming process. (For the pin diameter of 0.3 mm manufactured from strips with initial thicknesses of 0.5 and 2.5 mm)

Comparing the forming load in the pin forming of the thin and thick strips revealed that the amount of the upsetting phenomenon was decreased for the pins manufactured from thinner strips (Fig. 14). This is so because decreasing the strip thickness results in the earlier development of the neutral plane under the punch [20]. As a result, the metal would mostly flow towards the die orifice at the early stages, reducing the relative share of the upsetting phenomenon in the process, using thinner strips.

Moreover, it was seen that the maximum forming load is almost similar to the required forming load of the thicker strip, with a very slight decrease, which is due to the reduced amount of the upsetting phenomenon on the overall process.

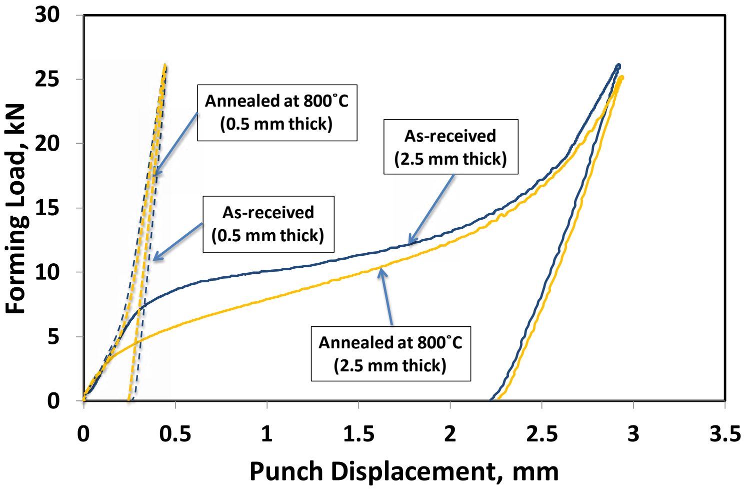

Fig. 14. Load-Stroke curve for 0.3 mm pin forming using samples with various thicknesses and different grain size.

From the microstructures in Fig. 15, it was observed again that there was no DMZ formed at the pin surface for the case of the thinner strips. In comparison, as can be seen in Fig. 8-d, there is a small region at the bottom of the pin, in which the grains are highly deformed and a bit elongated along the deformation route. This region was not seen for the case of the coarse-grained pin manufactured from the thin strip (Fig. 15). For this case, Keller et al. [8] mentioned that as the number of grains over the thickness of the workpeice is decreased to below its critical value, there is insufficient number of grains to develop deformation (shear) bands in the microstructure. As a result, for specimens having just a few grains over the cross-section (below the critical value), it is hardly expected to see very obvious shear bands being developed in the grains' structure. Therefore, the grains on the pin microstructure (Fig. 15) appear like equi-axed grains without any significant deformation (shear) occurred on them through the process.

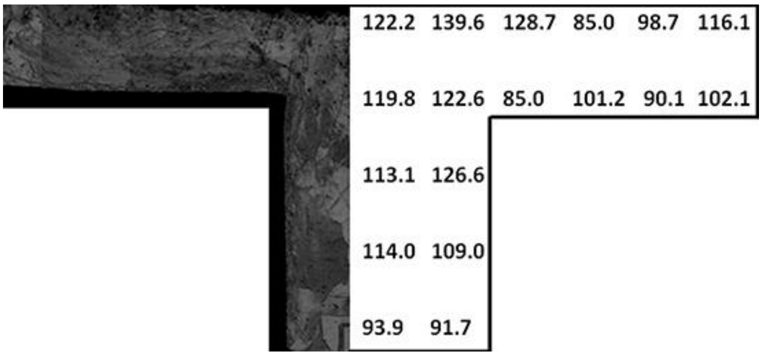

Fig. 15. Microstructure of the 0.3 mm pin manufactured from the strip with the thickness of 0.5 mm, which was annealed at 800°C for 1 hr.

4. Conclusion

The grain size effect together with the thickness size effect in an open-die micro-forging/extrusion was experimentally analyzed. The microstructural size effect was also studied. The main conclusions can be summarized as below:

- With respect to the mechanical response of the metal and also the final part dimensions, open-die forging/extrusion processes can be introduced as processes which are not very sensitive to grain size effect. Indeed, in these processes, the location of the neutral plane and its development throughout the specimens play the key role.
- Decreasing the number of grains over the thickness of the specimen only affects the microstructural evolution during the process. In coarse-grained specimens, there is a delay in development of DMZ due to a larger dislocation cell size in the microstructure. Thus, increasing the grain size can be used as another alternative solution for preventing the DMZ development through the pin’s microstructure.
- Having just a few number of grains over the thickness of the initial workpeice (below its critical value), prevents developing shear bands throughout the microstructure and the final properties of the part will therefore be more uniform.

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