Investigation on the roll-to-plate imprinting of metallic surface micro dimples

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Abstract
Large-area functional metallic surface microstructures have been increasingly utilized in various industrial fields. As an efficient and economical method in fabricating large-area functional metallic surface microstructures, the roll-to-plate (R2P) imprinting process with the flat die was proposed to experimentally fabricate functional micro dimple arrays on the surface of the metallic substrate. The effects of the rolling direction, die cavity aspect ratio, die feature density and grain sizes on the forming results were investigated using pure copper specimens with different grain sizes. The transfer ratio of surface structures decreases with the increase of the die feature density and die cavity aspect ratio, respectively. The flowing differences of material in the rolling direction and transverse directions lead to the inconformity of section profile of formed dimples in the two directions. The depth of dimples in the rolling direction is prominently greater than that in the transverse direction. The depth difference of dimples in the two directions increases with the increase of rolling depth and reduces with the increase of die cavity width. The surface morphology of formed specimens obviously depends on the material flowing direction, grain sizes and rolling depth. The surface roughness, surface roughness scatter and flatness of the formed specimens increase with the grain size. The symmetry of cross sectional micro hardness distribution on both sides of the formed dimple in the rolling direction is poorer than that on both sides of the formed dimple in the transverse direction. The asymmetry of cross sectional micro hardness distribution on both sides of the formed dimple in the rolling direction becomes more prominent with the increase of grain sizes.

1. Introduction
Specific structures on the material surface are helpful for an enhancement of product functionality and performance, and an optimization of economic as well as ecologic aspects in production processes and product behavior. These structure features are mostly found in the micrometer range and are commonly called as functional surface microstructures that strongly influence properties and functional behavior of modern products. Metallic parts with large-area functional surface microstructures like channels, riblets and dimples have been increasingly utilized in various industrial fields, such as drag reduction, friction/wear control, energy efficiency enhancement and heat/mass transfer.

Existing manufacturing technologies have to be adapted or even new technologies have to be developed to fabricate the functional surface microstructures due to small size scale of surface geometrical features. One promising approach to achieve a low-cost, high-throughput production of large-area functional surface microstructures is continuous roller imprinting process that can transfer microstructures onto the material surface with the deformation by combining conventional manufacturing technologies of imprinting and rolling. The roll-to-roll (R2R) and roll-to-plate (R2P) imprinting technologies are the two typical methods of roller imprinting process that can utilize the roller die or flat die. The roller imprinting process presents a prospective
solution to manufacture functional surface microstructures and is steadily gaining more attention of the researchers with the advantages of continuity, better uniformity, less imprinting load, simple structure, high efficiency and low cost.

Hirt and Thome [1] investigated the effects of process parameters on the riblet formation by using riblet rolling process to fabricate the microstructures on the surface of aluminum(Al99.5) sheets with wire structured rolls via defined steel wire winding. It is found that the influence of structure pitch on the riblet formation is highlighted clearly. Moreover, the reached form filling for a given specific thickness change is independent of the structure size. Kurnia et al [2] transferred micro/nano structures onto the surfaces of metallic materials (pure Al 99%) using the combination of nano plastic forming, coating and roller imprinting process (NPF-CRI), and experimentally validated the feasibility of the NPF-CRI process. The manufacturing capability of the NPF-CRI process is demonstrated by the fabrication of cross, net and brick patterns. Zhou et al [3] experimentally and numerically studied the curvature of textured sheets, the profile of micro channels and the uniformity of micro channel depth by fabricating micro channels on the surface of thin aluminum(AA5052) sheets using deformation-based micro surface texturing system. It is found that the relative velocity of the upper and lower rolls has a significant effect on the final profile of micro channels and the flatness of textured sheets with a relative velocity ranging from 0 to 2 mm s\(^{-1}\). Later on, Bui et al [4] established a static model to predict the micro-pattern deformation behavior in the above-mentioned surface texturing process using theoretical and empirical approaches. Experimental results confirmed the feasibility of the model. Gao et al [5] developed R2P micro imprinting process with the flat die to transfer the surface micro structures from the flat die to the pure copper sheets and investigated the effects of die cavity dimensions and grain sizes on the micro forming ability of material through experiments and simulations. It is concluded that the rolling load reduces with the increase of grain sizes. The die cavity width is more significant than the die cavity fillet in improving the micro forming ability of material. Xu et al [6] carried out further investigations on the effects of geometry and grain size on the forming results in R2P micro imprinting process. They found that the forming height increases with the grain size. The inhomogeneous deformation of individual grains could improve the formability of material and the uneven nature of individual grains actually lowers the difficulty of material flow for the coarse-grained material.

Recently, Ghai et al [7] developed micro-dimple rolling apparatus to rapidly generate micro dimples on the surface of metals. The system is able to form hundreds of dimples in less than a minute and was used to texture square dimples with sides of approximately 175 \(\mu\)m and depth of 30 \(\mu\)m on the surface of structural steel for investigating the effect of generated texture on friction and wear. Gaddam et al [8] employed sieve wire masks as imprinting stamps to investigate fabricating micro dimples on the surface of metal sheets by the cold rolling process through experiments and numerical simulations. It is concluded that a decrease in the reduction ratio with the plain weave wire mask ensued in a pattern similar to that of the one achieved with the Dutch weave wire mask and the numerically extracted depth profiles of micro-dimples are in good agreement with the experimentally obtained ones under different reduction ratios.

Although the above researches have made significant achievements on the investigations of roller imprinting process, the focus is mostly on R2R imprinting process. More work is needed to investigate R2P imprinting process.

In this paper, metallic surface micro dimple arrays were experimentally fabricated by R2P imprinting process. A series of experiments using pure copper specimens with different grain sizes were conducted to investigate the effects of the rolling direction, tool geometrical parameters, and grain sizes on the forming results from the perspectives of transfer ratio, geometrical shape and dimensions, surface morphology and hardness. The flowing and deformation of material in the three dimensional space were also explored.

## 2. Experimental setup and procedure

### 2.1. Materials preparation

The metal sheets of T2 pure copper with the thickness of 1.5 mm were utilized in the experiments. The as-received material was annealed and recrystallized to obtain different grain sizes with the heating and cooling speeds of 10 °C min\(^{-1}\) at three different temperatures of 400°C, 700 °C and 900 °C. The argon atmosphere was adopted to prevent the oxidation of material during the annealing process. The material were etched with a solution of 10 g FeCl\(_3\), 30 ml HCl and 120 ml H\(_2\)O for about 15 s after the heat treatment. The microstructures of material under different annealing temperatures are shown in figure 1. The average grain sizes were measured and calculated by transversal method (general intercept procedure) according to the standard of ASTM-E112 (Standard Test Methods for Determining Average Grain Size). The results are summarized in table 1.

The uniaxial tensile experiments were designed according to ASTM-E8. The tensile specimens with the dog-bone shape were prepared by using wire electric discharge machining (WEDM) as shown in figure 2. And then,
the specimens were tested using a universal testing machine of SUNS-UTM4000 with the moving velocity of 1 mm min\(^{-1}\) at room temperature.

The flow stress curves of the specimens with different grain sizes are presented in figure 3 and the mechanical property parameters are summarized in table 2. The significant reduction of flow stress with the increase of grain size can be observed, which can be explained according to the normal Hall-Petch relation presented by Greer and De Hosson [9]. The fraction of grain boundary in the unit volume of polycrystalline structure decreases as the grain size increases. Considering that the grain boundary impedes the dislocation movement, the strengthening effect of grain boundary thus becomes less significant with the increase of grain size, which gives rise to the reduction of flow stress.

Meanwhile, it can be observed that the percent elongation first increases and then decreases with the increase of grain sizes. This finding is different from that reported by Chan and Fu [10]. They found that the percent elongation decreases with increasing of grain sizes. The reason for this difference may be attributed to the fact that the as-received material is not fully softened through the recrystallization in the annealing process of 400 °C. The plasticity of material is thus enhanced by removing the effect of cold working as the annealing temperature increases from 400 to 700 °C, which results in the increase of ductility. However, the grain coarsening of specimens occurs in the annealing process of 900 °C and the uneven deformation of individual grains causes the significant stress concentration at the early stage of deformation. Therefore, the percent elongation distinctly decreases under this condition.

In addition, it can also be noticed that the scatter of flow stress increases with the annealing temperature, which means that the repeatability of experimental data becomes worse with the increase of grain size. This is because there are fewer grains in the deformation region as the grain size increases. The influence of individual grains on the flow stress thus becomes more prominent with the dwindling of grain boundary density. As a

| Temperature (°C) | Holding time (h) | Average grain size (μm) | Grain size deviation (μm) |
|------------------|------------------|-------------------------|--------------------------|
| 400              | 1                | 12                      | ±3                       |
| 700              | 2                | 35                      | ±8                       |
| 900              | 1                | 180                     | ±20                      |
result, the uneven distribution of grains with different sizes, shapes and orientations in the deformation region causes the significant inhomogeneous deformation, which makes the experimental data scatter.

### 2.2. Experimental setup

In this study, the used experimental setup with the flat die is a lab-scale prototype of R2P micro imprinting process system as shown in figure 4. It consists of the roller imprinting unit, control unit of parameter input and data acquisition unit. The travelling table is actuated to move horizontally by the AC-servo motor of Panasonic. The flat die is mounted on the travelling table. The chrome-faced roller with a diameter of 100 mm and a width of 120 mm can rotate freely. The system has a maximum radial rolling force capacity of 30 kN and the rolling speed can range from 0 to 100 mm s$^{-1}$. The rolling force data can be acquired and recorded by the load cell during R2P imprinting process.

In this research, the flat die with the size of 50 mm $\times$ 70 mm was fabricated using the tool steel of Cr12MoV by micro EDM (electrical discharge machining). The HRC hardness and surface roughness (Ra) of the flat die are 65 and 0.8 $\mu$m, respectively. Considering the industrial application requirements of surface microstructures, the micro protrusion arrays with square cross section and different spacings on the surface of flat die were designed, which means that the die cavities are orthogonal grooves. The geometrical parameters of the micro protrusion

| Temperature ($^\circ$C) | $\sigma_s$ (MPa) | $\sigma_t$ (MPa) | $\delta$ (%) |
|-----------------------|-----------------|-----------------|--------------|
| 400 $^\circ$C          | 72.22           | 331.27          | 39.36        |
| 700 $^\circ$C          | 49.84           | 323.03          | 43.73        |
| 900 $^\circ$C          | 30.54           | 251.96          | 27.13        |
**Table 3.** Geometrical parameters of surface structures on the flat die.

| Parameter                      | Value 1 (μm) | Value 2 (μm) | Value 3 (μm) | Value 4 (μm) |
|--------------------------------|--------------|--------------|--------------|--------------|
| Die cavity width (Protrusion spacing) | 250          | 400          | 600          | 200          |
| Die cavity width (Protrusion spacing) |              |              |              |              |
| Die cavity depth (Protrusion height)   | 200          |              |              |              |

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![Diagram of surface structures on a flat die.](image)
arrays are listed in table 3. The surface microstructures on the flat die can be transferred by R2P imprinting process and micro dimple arrays with square cross section are formed on the surface of metal sheets. The distribution density of micro dimples can be indirectly changed by modifying the die feature density (i.e. distribution density of micro protrusions). The die feature density is defined by the formula:

\[
F_d = \frac{S}{(S + W)}
\]

Different die feature densities can be gained by changing the value of W and keeping the value of S constant. The transition fillet of 50 μm and the draft angle of 5 degree were designed to reduce the stress concentrations of the die cavity corner and be helpful for demolding. The micro protrusion arrays on the flat die surface are illustrated in figure 5.

The specimens with the size of 85 mm × 20 mm in the experiments of R2P imprinting were prepared according to the annealing process parameters shown in table 1. The displacement load was used in the experiments and the designed rolling depths (RD) are 100, 250 and 350 μm. The rolling speed is kept at a constant of 0.5 mm s⁻¹ during R2P imprinting. The direction in which the flat die moves is defined as the rolling direction (longitudinal direction) and is normal to the transverse direction (roller axis direction). The metal sheet is gradually fed and bitten into the rolling gap with the friction force in the rolling direction. Finally, the micro dimples with the side length of 200 μm were acquired. The profile and depth of dimples, and the hardness and surface roughness of imprinted specimens were used to evaluate the effects of the rolling direction, die geometrical parameters, grain sizes on the final quality of micro dimples. The profile of micro dimples was measured using the optical measurement system of KEYENCE KS-1100 with a laser sensor of 0.05 μm resolution. The hardness of the imprinted specimens was tested using the Vickers hardness tester of HV-1000. The true color confocal microscope of Axio CSM 700 with a step accuracy of 10 nm was utilized to measure the surface roughness of the imprinted specimens. Five specimens were tested to assure the repeatability and accuracy of the experimental data for each case.

Figure 5. Photo, 2D and 3D scanned images of surface structures on the flat die (W = 250 μm).

Figure 6. SEM images of dimple arrays with different spaces (d = 35 μm, RD = 350 μm).
3. Results and discussion

A series of experiments with pure copper specimens of different grain sizes were performed to investigate the effects of the rolling direction, die cavity width, die feature density, die cavity aspect ratio, grain size on the final quality of the formed specimens with the transfer ratio, geometrical shape and dimension, surface morphology and hardness based on the above experimental procedure and process parameters. The typical experimental results are shown in figure 6.

3.1. Transfer ratio of surface structures

In this research, transfer ratio was introduced to evaluate the forming results of surface structures, which reflects the manufacturing efficiency of R2P imprinting process. It is defined as the ratio of the average depth of micro dimples on the surface of formed specimens to the height of micro protrusions on the surface of flat die. The effect of different die feature density on the transfer ratio of surface structures was experimentally investigated. Three kinds of die feature densities are 0.25, 0.33 and 0.44. The experimental results are indicated in figure 7. It is obvious to observe that the transfer ratio of surface structures decreases with the increase of die feature density, but increases with the rolling depth. The transfer ratio is 0.31 when the die feature density is 0.25 and the rolling depth is 150 μm. The transfer ratio decreases from 0.31 to 0.19 with increasing of the die feature density from 0.25 to 0.44. The transfer ratio reduces from 0.86 to 0.55 when the rolling depth is changed to 350 μm. The above
analysis indicates that the transfer ratio is influenced by the die feature density and rolling depth. In fact, the variation of die feature density depends on the change of die cavity width. The die feature density increases when the die cavity width becomes smaller. The material area squeezed by the roller and flat die increases, which is beneficial to flowing of material in the rolling direction. But the filling of material becomes more difficult, which finally results in the decrease of transfer ratio. In addition, the effect of the die feature density becomes prominent with the increase of the rolling depth.

The aspect ratio of die cavity (h/W) is an important structure parameter for R2P micro imprinting process because it both characterizes the processing capacity of roller imprinting process and determines the forming depth of micro dimples on the surface of formed specimens. The larger aspect ratio of formed structures means the stronger processing capacity. The die cavity aspect ratio of 0.33, 0.5 and 0.8 were designed. Figure 8 shows the
The effect of die cavity aspect ratio on the transfer ratio. It is proved that the transfer ratio of surface structures obviously reduces with the increase of aspect ratio and instead increases with the rolling depth. The transfer ratio decreases from 0.31 to 0.19 as the aspect ratio of die cavity changes from 0.33 to 0.80 at the rolling depth of 150 μm. The corresponding transfer ratios change from 0.86 to 0.55 with increasing of rolling depth up to 350 μm.

The analysis of results indicates that the transfer ratio of surface structures is also affected by the aspect ratio of die cavity. Larger aspect ratios mean larger die cavity depth or smaller die cavity width, which makes the filling of material become more difficult. So, smaller transfer ratios are obtained. Furthermore, the effect of the die cavity aspect ratio becomes more obvious with the increase of the rolling depth.

The density of die feature and the aspect ratio of die cavity have obvious effects on the transfer ratio of surface structures. The transfer ratio of surface structures decreases with the increase of the die feature density and die cavity aspect ratio, respectively. Moreover, the increase of rolling depth strengthens the effect of the die feature density and die cavity aspect ratio on the transfer ratio. However, the transfer ratio can be effectively enhanced by increasing the rolling depth.

3.2. Geometrical shape and dimension of surface structures

The geometrical shape and dimension of surface structures have a direct effect on their functionality. The deformation of material in every direction of the three-dimensional space during R2P micro imprinting process are different from each other and the longitudinal flowing of material is dominant because of the characteristics of R2P imprinting process, which affects the flowing and filling of material. Consequently, the geometrical shape and dimension of formed surface structures are influenced, which finally determines the functionality of surface structures.

The uniformity between the rolling directional section profile and transverse directional section profile of single dimple was first investigated. The rolling directional section and transverse directional section of individual dimple were selected as shown in figure 9. By comparison in figure 10, it can be seen that the rolling directional section profile and the transverse directional section profile have obvious difference around the upper corner region of dimples. Moreover, the depth difference of dimples in both directions is clearly observed. This can be attributed to the effect of material flowing difference in the two directions. But, the profile
differences of dimples in both directions can be improved by increasing the die cavity width. While the increase of rolling depth enhances the depth difference of dimples in both directions.

The uniformity of different directional section profile of dimple arrays in different directions was also studied. The rolling directional section profile and transverse directional section profile of dimple arrays in the rolling direction were compared, respectively. As seen from figures 11(a) and (b), the uniformity of the rolling directional section profile is poorer than that of the transverse directional section profile for the dimple arrays in the rolling direction because of the effect of longitudinal flowing of material. The rolling directional section profile and the transverse directional section profile of the dimple arrays in the transverse direction have the similar uniformity as shown in figures 11(c) and (d).

In addition, the pileup of material on the surface of specimens near both sides of the dimples in the rolling direction is found during the profile uniformity analysis of single dimple in the rolling direction and the transverse direction in figure 12. The die cavities on the surface of flat die are orthogonal grooves during the roll forming of surface micro dimples. The grooves parallel to the rolling direction are helpful for the longitudinal flowing of material. While the grooves perpendicular to the rolling direction impede the longitudinal flowing of material. The material flowing in the rolling direction is restrained by the two neighboring protrusions on the surface of flat die. The material squeezed by the protrusions on the surface of flat die and the roller only flows along the die cavity wall and piles up on the free surface of specimens to form the bumps with the effect of longitudinal flow of material. However, the pileup of material on the surface of specimens near both sides of dimples in the transverse direction does not occur. It is because the squeezed material is not restricted in the rolling direction and may flow along the die cavity parallel to the rolling direction. The pileup of material directly influences the geometrical shape of dimples and the surface morphology of the formed specimens.

It is seen from figures 13(a) and (b) that the depth of dimples in the rolling direction is prominently greater than that in the transverse direction. Moreover, the depth difference of dimples in the two directions increases with the increase of rolling depth and reduces with the increase of die cavity width. The above findings are in
good agreement with that in the comparison of uniformity between the rolling directional section profile and transverse directional section profile of single dimple in figure 10. It can be found in figure 13(c) that the dimple depth of the specimens with different grain sizes shows no obvious difference with the increase of grain sizes under the same process conditions. But the scatter of dimple depth becomes larger as the grain sizes increase, which shows good agreement with the scatter change of flow stress with the increase of grain size in figure 3. The deformation amount of material is the same under the same deformation conditions, which determines the forming depth of dimples. While the scatter of experimental data is caused by the uneven deformation of material due to the inhomogeneously distributed grains with different orientations and sizes at the micro scale.

3.3. Surface morphology of formed specimens

Surface roughness is micro geometrical shape error that is one of main technical parameters characterizing surface morphology of parts. The surface roughness of parts influences their wear resistance, fatigue strength, corrosion resistance and contact stiffness, etc. Smaller surface roughness means that the surface of parts is smoother and more flat.

The surface roughness of different regions on the surface of formed specimens was investigated by selecting representative regions as shown in figure 14. Region A is the region between the neighboring dimples in the rolling direction. Region B is the region between the neighboring dimples in the transverse direction. Region C is the intersection region in the rolling and transverse directions. The surface of material in the three regions is free. The surface roughness of specimens is Ra 0.459 before roller imprinting. After roll forming, the surface of formed specimens is roughened. The surface roughness (Ra 3.26, 1.12 and 0.97) in regions A, B and C are all larger than that before deformation as seen from figures 14 and 15(a). The surface roughness in region A is much larger than that in regions B and C. While the surface roughness in region B is slightly greater than that in region C. The main reason is that the deformation of material in three regions is distinct from each other due to the effect of longitudinal flowing of material and the restraining of the die cavity wall. Different deformation leads to different surface roughness because the surface roughness is related to the strain which characterizes the value of deformation [11]. Besides, the pileup of material on the surface of both sides of dimples in the rolling direction also affects the surface roughness in region A. As observed from figure 15(a), the surface roughness in three
regions increases with the rolling depth because the deformation of material becomes larger as the rolling depth increases.

Additionally, it is found that both the surface roughness and its scatter in region A increases with the increase of grain size in figure 15(b), which is consistent with the findings in the tensile test of pure copper samples with different grain sizes \cite{12}. The number of grains in the material surface layer of region A reduces when the grain size increases. The effect of individual grain on the deformation of material surface layer becomes prominent due to much fewer constraints from the grain boundary. The orientation differences among the grains dominate the deformation discrepancy of surface layer in region A. The uneven distribution of grains with different sizes, shapes and orientations in region A leads to the inhomogeneous deformation of material, which makes the surface roughness and its scatter increase. Furthermore, the effects of grain sizes on the surface roughness become more significant with the increase of rolling depths, especially for the material of coarse grain. The increase of rolling depth results in larger deformation of material, which aggregates the effect of grain sizes. To sum up, the revolution of surface roughness depends on the grain sizes, rolling direction and rolling depth.

As seen from figure 16, it is also noticed that the surface of formed specimens becomes obviously uneven when the grain sizes increase, which is extremely similar to the phenomena observed in the R2P imprinting of two-dimensional micro features \cite{5}. The irregularity of surface directly affects the geometrical shape of surface
structures and the surface flatness of specimens. The microstructures of material in R2P micro imprinting directly determine the surface layer deformation of material, which influences the surface morphology of specimens. The effect of grain boundary on the deformation weakens due to the decrease of grain boundary density and the effect of grain orientation on the deformation is dominant in the surface layer of material with fewer restrictions when the grain size becomes larger. The orientation differences of grains with random distribution make the uneven deformation of surface layer with large grains more significant than that with small grains. So, the surface of formed specimens with the large grains appears to be fluctuant.

3.4. Hardness of formed specimens

Hardness is an important mechanical property parameter which characterizes the resistance of material to local deformation, reflects the distribution of plastic deformation and local flow behavior of material, and affects the wear resistance and fatigue strength of parts. In this investigation, the hardness of specimens was tested with the indenter load of 50 gf. The rolled specimens were cut along the transverse and longitudinal directions using micro EDM as shown in figure 17. The transverse section and longitudinal section of formed dimples were selected as the hardness testing zones. The sections of formed dimples were ground and polished to remove the effects caused by the cutting process.

Before and after imprinting, the hardness of specimens with different grain sizes was studied by hardness testing. Before imprinting, the average hardness of specimens with the grain sizes of 12 μm, 35 μm and 180 μm are HV70.5, HV65.6 and HV59.9, respectively. After imprinting, the mean hardness of the formed specimens with three kinds of grain sizes at the rolling depth of 350 μm are HV94.0, HV91.0 and HV94.0, respectively. The hardness of the above imprinted specimens increase by 33%, 38% and 56%, respectively. The hardness of specimens with various grain sizes are extremely close after undergoing the deformation of the same rolling depth although the hardness of specimens with different grain sizes are significantly different before imprinting. This may be explained that the deformation region contains lots of grains for the material of fine grains and the same deformation is shared by these grains. Each grain only needs to undergo smaller plastic deformation to keep compatible and continuous strain. Smaller plastic deformation leads to lower hardness due to the strain-hardening effect. The hardness of each fine grain makes less contribution to the hardness increase of formed specimens, which results in the smaller hardness change of specimens with fine grains after imprinting. It is just the opposite for the material of coarse grains. In summary, the hardness of material can be enhanced by R2P micro imprinting process.
The cross sectional micro hardness distribution at different rolling depths in different directions were investigated as indicated in figure 18. It is evident that the cross sectional micro hardness distribution is uneven. First, the hardness in the adjacent zones around the formed dimples is clearly higher than that in other zones. The highest hardness is located in the near region beneath the bottom of dimples, which implies that the deformation in this region is largest. The cross sectional micro hardness distribution with different rolling depths in the rolling and transverse directions shows similar trend. The material close to the dimples undergoes larger plastic deformation due to the squeezing of the roller and flat die, which leads to strain hardening of material. So, the hardness is enhanced. Second, the micro hardness difference value on both sides of the formed dimple in the rolling direction is HV5.3 and the micro hardness difference value on both sides of the formed dimple in the transverse direction is HV6.2 at the rolling depth of 150 μm. The former and the latter is extremely close, which reflects the better symmetry of flowing and deformation of material in both directions. At this moment, the effect of longitudinal flowing of material on the filling of material is not quite obvious. The micro hardness difference value (HV9.8) on both sides of the formed dimple in the rolling direction is greater than that (HV2.1) on both sides of the formed dimple in the transverse direction when the rolling depth increases to 350 μm because the increase of the rolling depth aggregates the effect of longitudinal flow of material on the filling of material, which results in the significant asymmetry of flow and deformation of material on both sides of the formed dimple in the rolling direction. Furthermore, it is also observed that the microstructure evolution of material is different at different rolling depths during R2P imprinting process. The flow line of material in the zone near the bottom of the formed dimple is not formed at the smaller rolling depth because the material in this zone undergoes smaller plastic deformation. The flow line of material is obviously formed in the zone near the bottom of the formed dimple with increasing of the rolling depth because the material in this zone experiences larger plastic deformation. It is also revealed that the dead metal zone is formed on the flow line of material, in which the plastic deformations of material don’t occur as a result of restraining of top surface of protrusion on the flat die.

The cross sectional micro hardness distribution of the formed specimens with different grain sizes in the rolling direction is shown in figure 19. As seen from figure 9, the cross sectional micro hardness distribution of the coarse-grained specimens is similar to that of the fine-grained specimens. The hardness on the left side of the formed dimple (HV99.2, HV102.0) are higher than that (HV92.0, HV90.5) on the right side of the formed dimple for the specimens with the grain sizes of 12 μm and 180 μm, which suggests that the cross sectional micro hardness distribution on both sides of the formed dimple in the rolling direction is asymmetrical because of the effects of longitudinal flowing of material. Moreover, the hardness difference on both sides of the formed dimple

![Figure 18. Cross sectional micro hardness distribution and microstructures of micro dimples with different rolling depths in different directions (d = 55 μm, W = 600 μm); (a) RD = 150 μm, in the transverse direction (b) RD = 150 μm, in the longitudinal direction (c) RD = 350 μm, in the transverse direction (d) RD = 350 μm, in the longitudinal direction.](image-url)
in the rolling direction is more obvious for the specimens of coarse grains. The distinct difference can be addressed that the effect of grain statistics becomes weaker and the grain anisotropy effect becomes predominant at small scales when the grain size increases. The size, orientation and distribution of grains significantly affect the deformation of material. The random distribution of grains with different sizes and orientations results in inhomogeneous deformation of material. So, the differences of size, orientation and distribution among coarse grains strengthen the effect of longitudinal flowing on the deformation difference of material on both sides of the formed dimple in the rolling direction, which finally causes the big discrepancy of hardness.

In addition, the microstructure evolution of material changes with the increase of grain sizes. The obvious flow line is formed in the zone near the bottom of the formed dimple for the specimen with grain size of 12 μm because much more grains in the deformation zone participate in the flowing deformation of material. The number of grains in the deformation zone sharply decreases and only several grains are in the deformation zone when the grain size is changed to 180 μm, which makes the grain boundary reduce. The flow line of material is not formed although each grain experiences larger deformation and distortion.

4. Conclusions

In this paper, square cross-section micro dimples with the side length of 200 μm were experimentally fabricated on the metallic surface by R2P imprinting process. A series of experiments using pure copper specimens with grain sizes of 12 μm, 35 μm and 180 μm were conducted to investigate the effects of the rolling direction, die cavity aspect ratio, die feature density and grain sizes on the forming results. The following conclusions can be drawn based on the investigations.

(1) The density of die feature and the aspect ratio of die cavity have obvious effects on the transfer ration of surface structures. The transfer ratio of surface structures decreases with the increase of the die feature density and die cavity aspect ratio, respectively. For both the feature density of 0.25 and the die cavity aspect ratio of 0.33 (i.e. W = 600 μm), the transfer ratio of 86% can be acquired at the rolling depth of 350 μm.

(2) The flowing differences of material in the rolling direction and transverse directions lead to the inconformity of section profile of formed dimples in the two directions. The depth of dimples in the rolling direction is prominently greater than that in the transverse direction. The depth differences of dimples in the two directions increase with the increase of rolling depth and reduce with the increase of die cavity width. The grain sizes have no obvious effects on the dimple depth but influence the scatter of the dimple depth value.

(3) The surface roughening of formed specimens occurs during R2P imprinting process. The surface between the neighboring dimples in the rolling direction is more easily roughened. The surface roughness and flatness of the formed specimens increase with the grain size and rolling depth. Moreover, the scatter of surface roughness value becomes larger with the increase of grain sizes.

(4) The hardness of specimens with the grain sizes of 12 μm, 35 μm and 180 μm can be increased at least by 33% through R2P imprinting process. The cross sectional micro hardness distribution of the formed dimples is uneven and asymmetric. The symmetry of cross sectional micro hardness distribution on both sides of the formed dimple in the rolling direction is poorer than that on both sides of the formed dimple in the transverse direction. The asymmetry of cross sectional micro hardness distribution on both sides of the
formed dimple in the rolling direction becomes more prominent with the increase of grain size from 12 μm to 180 μm.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflicts of interest

The authors declare no conflict of interest.

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