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Effect of the asymmetrical rolling process on the micro hardness and microstructure of brass wire

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ABSTRACT

Current experimental investigation deals with the effects of asymmetrical rolling parameters on the inhomogeneity, microstructure, mechanical, and geometrical properties of rolled brass wire. Toward this end, a roll machine with three different roll radii ratios was set up. The asymmetrical conditions are arranged using three different sets of rolls with different diameters that result into different reductions. Investigating the effects of the inhomogeneous structure of unrolled brass wire on the output radius, total width, and width of the rolled part (in the z direction) are the aim of this study. Furthermore, the influences of three unlike roll radius ratios on the grain size, inhomogeneity and mechanical properties of the rolled brass wire are considered. In addition, the micro-Vickers measurements on the rolled brass wire are performed. It is shown that the regions near to faster roll with greater strain quantities have higher values of hardness compared to the other areas.

1. Introduction

Cold asymmetrical rolling of wire is a process, where a wire with circular cross section goes into the gap of deformation. Moreover, the final output is a wire with flattened form which possesses curvature at the exit of the deformation area as well as both sides of its cross section. The performance of this process is illustrated in Fig. 1.

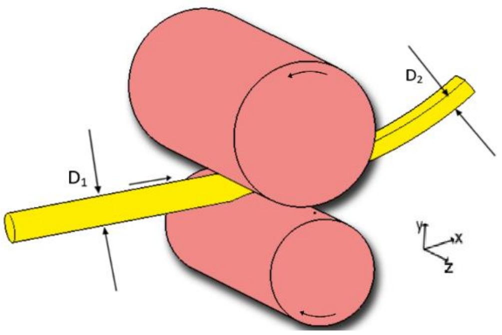


Figure 1. Schematic illustration of asymmetrical wire rolling process (x= Rolling direction, y= direction passing from center of rolls, z= direction paralleling to axis of rolls (Transverse)).

Products fabricated by asymmetrical wire rolling process have been applied in many fields such as fastening device in packaging industry, electrical device, saw blades, piston rings, springs, and flattened wire electrodes for Gas Metal Arc Welding (GMAW) [1]. A prominent application of asymmetrically rolled brass wire is in the manufacturing of springs in the mechanical micro-switches used in machines and electronic devices.

Owing to the physical contact between the revolving rolls and wire in the rolling process, frictional stresses in form of the shear stresses arise and result in development of shear strain in the interfaces as well as through the thickness from top to the bottom of the wire. The magnitude of shear strain increases as the asymmetrical condition is replaced with conventional rolling. He and Liu [2] investigated the influence of cryo-rolling on the recrystallization of Zr-4 alloy. They compared as-received and deformed sheets (inhomogeneous) after annealing and concluded that the texture orientations of Zr-4 has not been changed during rolling and annealing. Hao and Sun [3] studied the inhomogeneous deformation of aluminum alloy plate appears in hot rough rolling process. Reduction of rolling output is strongly influenced by inhomogeneous deformation and then negatively affects the rolling processes. Results showed that inhomogeneous deformation distribution in thickness direction causes two bulges at head and tail ends shown by analysis of the equivalent plastic strain distribution and deformation. Homogeneous materials intend to have a uniform structure over their volume and their mechanical properties are identical through the whole material. Inhomogeneous materials however, behave otherwise. In other words, material characteristics will differ significantly over the material. Accordingly, wires produced by drawing or rolling processes usually own an inhomogeneous structure and needs annealing.

The shear strain during the rolling process possesses maximum values at the layers near to the rolls, while it is decreased by moving towards the axis of wire. Therefore, as a result of having different values of equivalent strain through the thickness, different grains sizes and mechanical properties are expected to be obtained in different areas of cross section. Moreover, the aforementioned parameters will be changed with respect to different asymmetrical rolling conditions. Consequently, evaluation of the microstructure, inhomogeneity and mechanical properties of asymmetrically rolled wire with respect to different process parameters will provide a better understanding of the process.

In the recent years, owing to numerous advantages of asymmetrical rolling process over the conventional one (less rolling force and torque, more uniform distribution of the shear-deformation through thickness, improved microstructure and mechanical properties), a striking attention was paid to this process. Although several studies have been published in field of asymmetrical sheet rolling, the researches in field of asymmetrical wire rolling are too far beyond the hope.

Kazeminezhad and Karimi Taheri [4] studied the inhomogeneity in the symmetrically rolled flattened wire. Their results revealed that the inhomogeneity in the microstructure of the flattened wire increases by having wire with lower height and higher friction factor. Kazeminezhad and Karimi Taheri [5] considered the influence of roll velocity, rolling reduction, and wire material on the width of the rolled part and lateral spread of the deformed wire, developed in symmetrical cold flat rolling. Applying an experimental method, the influence of wire thickness reduction, roll angular speed and friction coefficient on the rolling force and deformation behavior of the as-rolled wire were also evaluated by Kazeminezhad and Karimi Taheri [6].

Parvizi et al. [7] studied the influence of the roll speed ratio, roll radii ratio, and reduction in height on the radius of the deformed material and width of the rolled part of the wire in asymmetrical process. In addition, Parvizi et al. [8] presented a three dimensional analytical solution to present the pressure of the process, force and torque in asymmetrical wire rolling where the rolling rolls, their speeds of rolls and the interfacial frictions may be various.

Until now, a number of surveys have been considered to study the effect of the asymmetrical rolling state on the outcome structure of rolled material and the mechanical properties of copper, magnesium, and aluminum sheets. Salari and Akbarzadeh [9] studied the influences of cold rolling thickness reduction, finish rolling temperature, and annealing temperature on microstructure development and texture in the brass sheet. To study the texture and microstructure evaluation, Rohini et al. [10] evaluated deformation of brass with two phases by assuming various initial microstructure and texture.

Konkova et al. [11] studied grain texture formation over the rolling of alpha brass at cryogenic circumstances. Moreover, taking different rolling thickness reductions into account, Yan et al. [12] evaluated some metals with FCC structures such as nickel, copper, and α-brass with different staking fault energy (SFE) to determine the microstructure and local orientation distributions. Polkowski et al. [13] inspected the texture evolution of copper sheet varied by the asymmetrical rolling parameters. They found that asymmetrical condition of the process causes high angle boundaries, large strain hardening and sharpening texture compared to the symmetrical condition. Wang et al. [14] studied the effect of the asymmetrically accumulative rolling-bond (AARB) and annealing on the organizational controlling and developing mechanism of ultra-fine-grain (UFG) copper.

Stepanov et al. [15] evaluated the effects of cold rolling on the mechanical properties of copper and microstructure evolution focused on ECAP by a number of passes. Gu et al. [16] evaluated differences of the texture of the pure rolled copper versus the size of the grain. They considered 97% thickness reduction with two various initial grain sizes, i.e. coarse-grained (CG, 24 μm) and ultrafine-grained (UFG, 360 nm). Ucuncuoglu et al. [17] analyzed the influence of the asymmetrical rolling parameters on texture, mechanical properties and microstructure of the magnesium sheets produced by twin roll casting process. Chen et al. [18] investigated the influences of hot and cold rolling parameters on plastic strain ratio and microstructure of high strength ultra-low carbon steel.

In this paper, the geometrical, mechanical, and microstructure properties of asymmetrically rolled brass wire are investigated for the first time. A wire with initial inhomogeneous structure along with another wire with more homogeneous structure which was achieved from annealing process are taken into account. The effect of the structure inhomogeneities on deformation characteristics such as final width, width of the rolled part, and the output radius of rolled wire are studied. Specimens are cut out in a direction perpendicular and parallel to the rolling axes and optical microscope is utilized to observe the microstructure. Furthermore, to study the influence of the roll radii ratio on grain size, distribution of the hardness, and geometrical properties, three brass wires are rolled with various roll radii ratios at fixed 30% reduction. Results are then compared with the symmetrical output. Finally, the micro-Vickers measurements are performed on section of the rolled materials produced by different asymmetrical configurations.

2. Experimental procedure

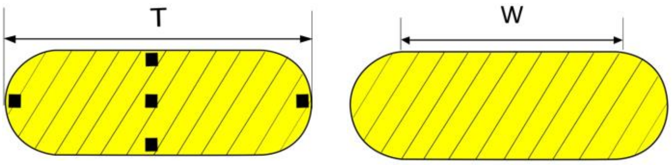
The configuration of asymmetrical wire rolling with different rolling mills are depicted in Fig.2. Six main rolls with diameters of 73, 69, 64.4, 53.6, 49 and 45 mm were fabricated using steel CK60. Applying six rolls, three different roll diameter ratios (i.e. $d_{11} = 64.4/53.3 = 1.2$, $d_{22} = 69/49 = 1.4$ and $d_{33} = 73/45 = 1.6$) were chosen for asymmetrical rolling of brass wire. Rolls on the upper and lower sides of the wire were driven by a DC electromotor with the rotational speed of (n=50 rpm). It is transparently visible that asymmetrical configurations were established due to differences in roll diameters resulted from various tangential speeds at the interfaces of lower and upper rolls.

(a) (b)

Figure 2. (a) Rolling process equipment set up (b) different rolling mills.

Two brass wires with initial diameter of 2 mm were considered for the experiments. One of them was annealed at temperature of 500 °C for 45 minutes. For fixed roll radii ratio of 1.4, both wires were rolled with three different thickness reductions, i.e. 22, 30 and 45%. After that, both annealed (AW) and not-annealed brass wires (NAW) were asymmetrically rolled and the output radius, entire width and width of the rolled part, as shown in Fig. 3, were investigated. In addition, brass wires were rolled with three various roll radii ratios along with symmetrical condition at a constant rolling reduction. Finally, the influences of roll radii ratios on inhomogeneity, grain size, mechanical and geometrical properties of the rolled wire were evaluated.

In order to study the microstructure of rolled wires, the specimens were cut out from the section of the rolled wire in z-y plain. Optical microscope was also applied to inspect the microstructure properties. To indicate the influences of asymmetrical rolling parameters on mechanical properties of the rolled brass wire, the micro-Vickers hardness measurement was carried out on five different positions in the cross section, see Fig. 3 (a).

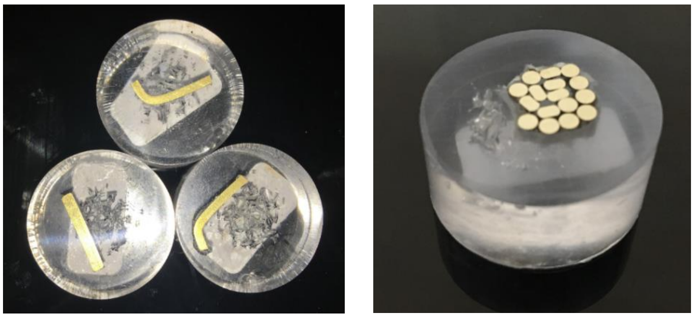


(a) (b)

Figure 3. (a) Entire width of the rolled brass wire (T) and five positions in the section to measure the micro-Vickers (b) width of the rolled part in Z direction (W).

3. Sample Preparation

In order to study the microstructure and hardness, the specimens taken from rolled wire, were cold mounted. After polishing by SiC paper, an etching reagent with chemical composition of 50 ml ethanol, 2.5 gr Iron(III) chloride ($FeCl_3$) and 2 ml hydrogen chloride (HCL) was used. The views of samples cut in the y-z and x-y planes are illustrated in Fig. 4. The b×52m optical microscope was applied to magnify the shots. Moreover, Koopa MH3 machine were used to perform Vickers micro-hardness measurements on five positions in the x-y plane.

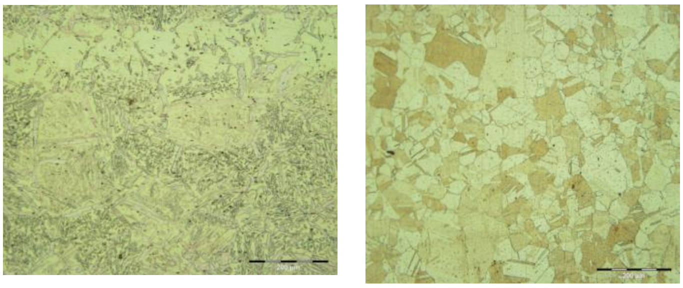


(a) (b)

Figure 4. Samples cut in (a) x-y (b) y-z planes.

4. Results and discussions

Fig. 5 depicts the structures of the unrolled brass for homogeneous and inhomogeneous conditions taken by optical microscope. It is seen that performing an annealing process on brass will result in rising the grains sizes. However, there is no obvious elongation in the grains.



(a) (b)

Figure 5. Structures of unrolled brass for (a) inhomogeneous (not annealed) (b) homogeneous (45 min annealing time at 500 ºC).

The influence of thickness reduction on the output radius of rolled wire for both homogeneous and inhomogeneous brass wires are illustrated in Fig. 6. As it is seen, due to uniform and large grains which allows material to be deformed easily, homogeneous initial wires are resulted into higher curvature at exit. Furthermore, due to the excessive shear strains imposed during production of NAW, the equivalent strains are accumulated the grain boundaries of inhomogeneous material. Consequently, it leads to higher curvature radius in case of inhomogeneous material.

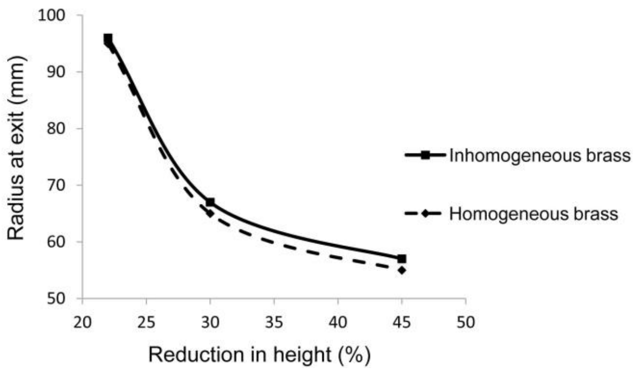


Figure 6. Effects of thickness reduction on the output radius of rolled wire for both homogeneous and inhomogeneous brass wires ($n = 50 rpm$, $d_{22} = 69/49 = 1.4$, $D_1 = 2 mm, \mu = 1.4$).

Fig. 7 depicts how thickness reduction affects the entire width of the deformed wire for both AW and NAW. According to this figure, inhomogeneous structure resulted into slightly greater quantities concerning entire width of the deformed wire. Curvature at sides of the rolled wire is somehow similar to the barreling condition at forging process which depends on parameters such as frictional conditions between rolls and wire, properties of material, reduction on thickness, roll speed, etc. Due to the intensive increase in the quantities of grains boundaries in rolling direction in inhomogeneous brass and non-uniform distribution of shear strains through the thickness, the slip systems cannot move easily towards the direction perpendicular to the rolling axes at the layers near to the upper and lower rolls. Therefore, it prevents upper and lower layers from being widened easily. Consequently, the layers at the middle can easily flow and lead to the condition that the entire width of the deformed wire be risen. However, the differences between the quantities are not great; especially for high degree of reduction in height. Actually, the maximum difference between total width quantities occurs at the reduction in height of 22% with the value of 2.2%.

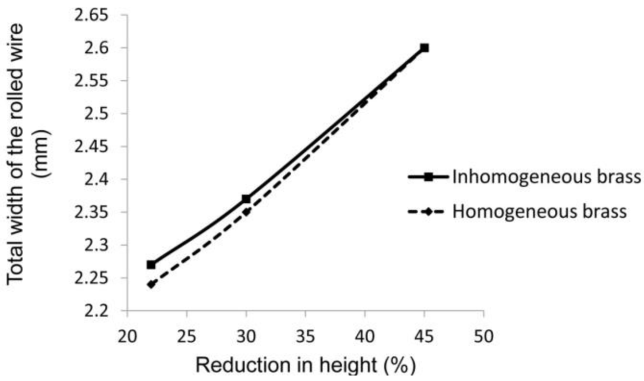


Figure 7. Influence of the thickness reduction on entire width of the rolled wire for both homogeneous and inhomogeneous brass wires ($n = 50 rpm$, $d_{22} = 69/49 = 1.4$, $D_1 = 2\,mm, \mu = 1.4$).

The variation for width of the contact area regarding the rolled wire, (see Fig. 3-b), with respect to reduction in height for homogeneous and inhomogeneous initial brass wires are illustrated in Fig. 8. No major differences between two conditions and the maximum variance were observed in the 30% reduction. In fact, as a result of the intense interactions between surfaces of the wire and rolls, shear stresses are developed at aforementioned zones; especially at the layers near to the upper and lower interfaces with rolls. Hence, the presence of the local shear strains in the rolling direction at those regions provides some difficulties for material to flow easily in the Z direction. Therefore, the width of the contact area was slightly increased in homogeneous brass compared to the inhomogeneous one.

As mentioned before, two types of deformation mechanisms including normal rolling and shear models occur in the asymmetrical rolling process. Shear deformation created by the asymmetrical rolling resulted into the additional equivalent strains at microstructure and consequently it results in finer grains sizes. Having risen the equivalent strain values, the dislocation density stored at grain boundaries increases which prevent the free movements of the slip systems. Hence, this action causes rolled material to have higher strength.

The microstructure of brass after rolling for symmetrical case and asymmetrical conditions with different values of rolling radii ratios are illustrated in Fig. 9. All micrographs are taken by optical microscope for rolling reduction of 30%. As it is seen, as roll radii ratio gets higher, the size of grain decreases significantly.

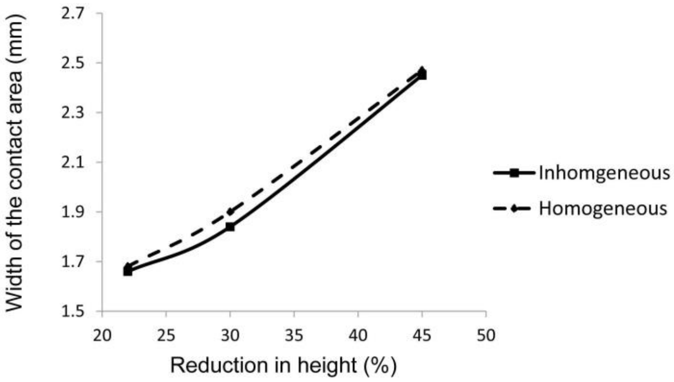
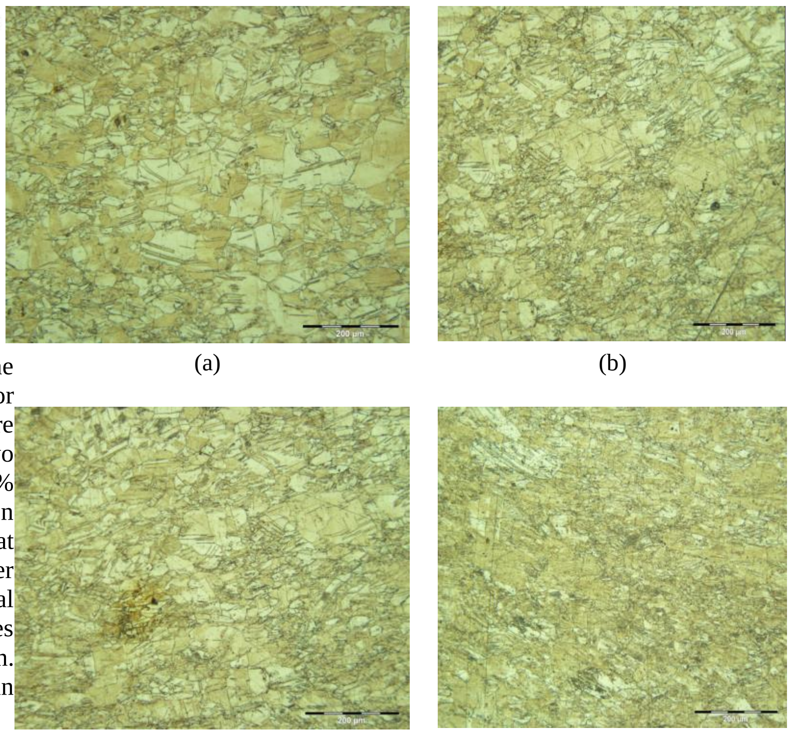


Figure 8. Impact of the thickness reduction on width of the contact area (rolled part) for both homogeneous and inhomogeneous brass wires ($n = 50 rpm$, $d_{22} = 69/49 = 1.4$, $D_1 = 2\,mm, \mu = 1.4$).

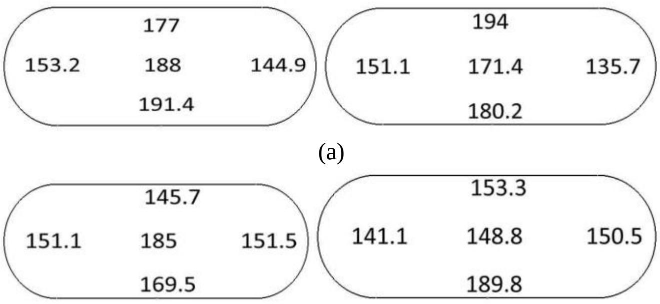


(a) (b)

(c) (d)

Figure 9. Structure of brass after rolling for different rolling diameter ratios with rotational speed ($n = 50 rpm$) for rolls, $\mu = 0.19$ ($D_1 = 2\,mm$) (a) symmetrical case (b) $d_{11} = 1.2$ (c) $d_{22} = 1.4$ (d) $d_{33} = 1.6$.

Fig. 10 shows the influences of different roll radii ratios as an inhomogeneity parameter on hardness variations in the y-z plane of the deformed wire with a constant rolling reduction of 30%. Compared to the center and top of the section, the values of the measured hardness are higher at the bottom of the section where the roll circumferential speed is greater. Actually, faster roll (smaller radius) results into higher degree of strain rates. Moreover, it is remarkable that in both symmetrical and asymmetrical conditions, the values of hardness at both sides of the rolled wire are less than those ones at the top and center of the cross section. In fact, both sides of the rolled wire are almost dead areas where the minimum plastic deformation is taken place. This evidence is illuminated in Fig. 11. It is also obvious to point out that, as the process of rolling converts to asymmetrical configuration, the quantity of hardness in the center of cross section of the rolled wire approximately decreases as shown in Fig. 12.



(a) (b) (c) (d)

Figure 10. Micro-Vickers hardness distribution for brass at different roll diameter ratios with rotational speed ($n = 50rpm$) ($\mu = 0.19$) , ($D_1 = 2mm$) (a) symmetrical case (b) $d_{11} = 1.2$ (c) $d_{22} = 1.4$ (d) $d_{33} = 1.6$.

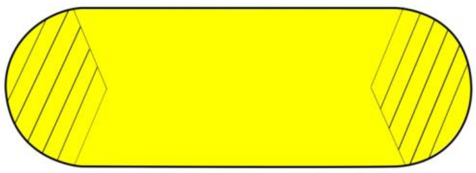


Figure 11. Dead areas on the cross section (y-z plane)of the rolled wire defined by hatches.

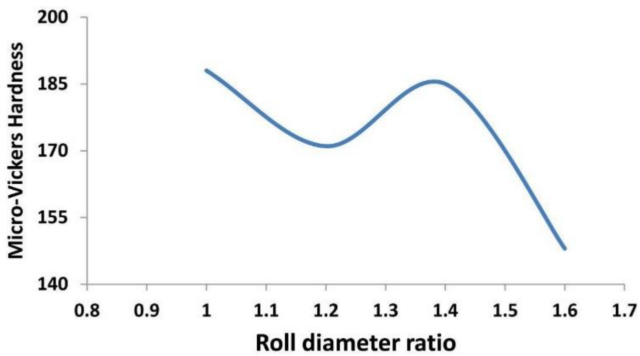


Figure 12. Micro-Vickers hardness versus the different roll diameter ratios with rotational speed ($n = 50rpm$)($\mu = 0.19$) , ($D_1 = 2mm$).

Fig. 13 states the inverse proportionality of the roll radii ratio and the grain size. Considering the figure, the grain sizes drastically decrease as the ratio of roll radius increases. Essentially, ability to produce fine grains sizes by developing additional shear strain is one of prominent advantages of the asymmetrical rolling process. Hence, this process can be considered as a severely plastic deformation (SPD) technique by which finer material structure can be achieved.

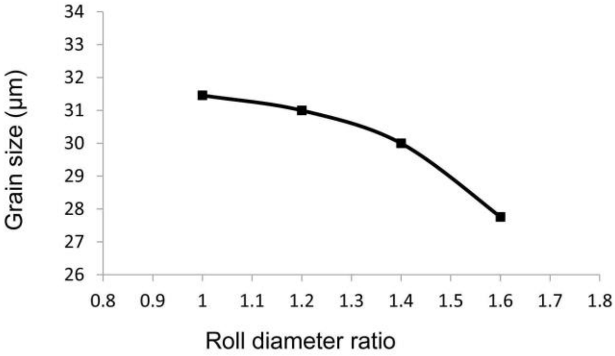


Figure 13. Impact of the roll diameter ratios on the grain size of the rolled brass wire with rotational speed ($n = 50rpm$) , ($\mu = 0.19$) .

5. Conclusion

In this paper, the influence of initial homogeneous and inhomogeneous material on microstructure, geometrical, and mechanical properties of flattened rolled brass wires are studied. Results from experimental analyses indicated that primary homogeneous structure resulted into lower values for output radius of wire at output of the deformation area. It is also concluded that inhomogeneous material would yield smaller values for width of the rolled part (in the z direction) and larger values for entire width of the rolled part. Moreover, the findings revealed that as roll radii ratio for brass rises, the resulting size of grain and the average value of hardness in cross section of wire decrease. Furthermore, the hardness value of material close to the faster roll is higher than the other zones. However, in both symmetrical and asymmetrical rolling conditions, the values of hardness at both sides of the rolled wire section have lower quantities compared to the other areas. Briefly, the capability of asymmetrical rolling process to produce finer grains sizes through developing extra shear strain is a significant advantage by which this process can be categorized as a severely plastic deformation (SPD) technique. Finally, interpreting the above-mentioned findings can be listed as the followings:

- The material with homogenous structure and their absence of random orientations allow slip systems to move easily through rolling process and thus, more plastic deformation can occur.
- Strain rate affects the rate of the strain hardening and causes higher strength in surfaces close to the rolls.
- The anisotropy in the wire in the rolling direction prevents material from flowing in the transverse side.

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