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Research Article

Repetitive Upsetting Extrusion Process of Al 5452 Alloy: Finite Element Analysis and Experimental Investigation

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ABSTRACT

In the last decade, the repetitive upsetting-extrusion (RUE) process has proved its potential in the bulk metal forming process in several investigations on severe plastic deformation (SPD) processes. The RUE process is currently being used to process bulk materials through grain refinement and consequently reaching better mechanical properties such as high strength and high toughness. Different process parameters affect the RUE process and the quality of the processed specimens. In the present investigation, the finite element analysis was carried out by using ABAQUS/CAE software to study the effect of die design on the RUE process, to find the minimum extrusion ratio for processing the Al 5452 alloy using the RUE process and determine the perfect height for the deformation zone in the RUE die. To that end, four cycles of successive RUE were performed on the Al 5452 alloy in the designed die. Microhardness distribution of the processed specimens was found to be more homogeneous and, by raising the RUE cycles, the average microhardness value in the processed specimens increased from 71.5 Hv (Non-cycle RUE processed specimen) to 145.1 Hv (specimen processed by 4 RUE cycles). It was also found that, by augmenting the RUE cycles, the compressive yield stress of the processed specimen increased from 136.622 MPa (Non-cycle RUE processed specimen) to 432.221 MPa (specimen processed by 4 RUE cycles).

1. Introduction

The improvement of mechanical properties in accordance with the application of materials is one of the main concerns and aims of researchers in the field of material and metallurgical engineering. To this end, during the last decade, severe plastic deformation (SPD) methods have attracted the attention of researchers [1-3]. The SPD techniques have been proven as valuable methods for the transformation of the coarse-grained metals into the ultrafine-grained materials, and in some cases, into the sub-micron (100 nm to ≤1μm) or nano scale (≤100 nm) grain sizes [4, 5]. These techniques impose high strains on materials [6] and result in the grain refinement with the repetition of the processes, where, the initial cross-section dimensions of the specimen remain approximately unchanged at the end of the process [7, 8]. The main mechanism of the grain refinement has been established which increases the dislocation density at the earlier stage of the deformation and then, the formation of grains including high angle boundaries occurs by applying further deformation [9]. So, the SPD processed materials exhibit superior

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mechanical properties, such as, high strength, toughness, wear resistance, fatigue, etc. [10-12]. In order to obtain nanostructured bulk materials, various methods of SPD [13, 14] are used. The most well-known methods in many recent studies are channel angular pressing (ECAP), high pressure torsion (HPT) [15] and accumulative roll bonding (ARB) [14]. Among these methods, HPT provides the largest applied strains, thus leading to the smallest grain size and a high fraction of the high angle boundaries [16, 17]. Despite the advantages mentioned for the HPT process, it also has some limitations; one being the fact that the strain applied across the diameter of the disk-shaped specimen is not constant; as a result, the microstructure is inhomogeneous throughout the disk. Another important limitation is the small size of the specimen, which is usually 1 cm in diameter and 1 mm in thickness [18]. These limitations restrict the potential for the widespread use of HPT process in industries. To overcome these limitations, in many literatures, Die-based methods have been used, in which the specimens are in the form of bars with a circular or rectangular cross-section. One of the newest techniques is the Repetitive Upsetting is Extrusion (RUE) method.

A typical RUE process consists of two stages: (1) Upsetting, in which the height of the cylindrical shape specimen is reduced and its cross-sectional area is increased, and (2) Extrusion, in which the height increases while the cross-section area decreases [19, 20]. During the upsetting, material flows perpendicularly in the upsetting direction, whereas, during the extrusion, the material flows parallel with the upsetting or extrusion directions. This redirection of the material flow leads to grain refinement [21].

The RUE method was primarily developed by Aizawa and Tokimutu to process the powder materials for bulk mechanical alloying [19, 22]. Then, Hu Lianxi et al. used this method with the same die design to induce the severe plastic deformation in a bulk LY12 Aluminum alloy and proved that the RUE could produce ultrafine grained materials [19, 23]. It was concluded that by increasing the number of the RUE passes to 10, the approximately accumulated true strain reached 8.926, and the offset yield strength and the hardness were improved from 318.5 MPa and 112.3 Hv to 513.6 MPa and 176.5 Hv, respectively [23]. By using the finite element method, Balasundar and Raghu investigated the axial hole or funnel defect and the parameters affecting its formation, such as extrusion ratio (R), extrusion die angle (θ), deformation zone height (h), friction (μ) and the constitutive material behavior, which were prevalent in the extrusion process and based on the obtained results, a die was designed to prevent this defect [24]. Although the designed die was effective in preventing the formation of defects, the deformation was inhomogeneous due to the large strain content in the specimen. To enhance the homogeneity of the strain distribution, Balasundar et al. proposed that upsetting and extrusion process should be combined in different ways which were called the RUE and REU. In addition, the specimen was rotated 180° after upsetting both the RUE and REU [25] processes. They concluded that REU with a 180° rotation after upsetting provided a higher average strain per cycle and a better homogeneity [26].

Due to the RUE potential being used extensively for industrial applications, researchers have always attempted to modify and optimize the RUE process to reach the enhanced properties of materials. For example, a research was performed by Binesh et al. on using the RUE process (250°C) for the semi-solid processing (580-620°C for 2-35 min) on the Al 7075 at different cycles [27]. In other research conducted by Gao et al., the continuous repetitive upsetting and extrusion (CRUE) processing was performed, and their effects on the microstructures, mechanical properties of the 2A66 Al–Li alloy were investigated. After 3 CRUE passes, it was concluded that the average grain size was effectively refined from 140 µm to 4 µm, and the elongation-to-failure was significantly improved from 18.2% to 34.2% [28]. Therefore, the RUE had various advantages such as providing the accumulated high plastic strains, a significantly refined grain size, an increased elongation of alloys, a homogeneous microstructure, and an optimized yield strength [29].

Based on several studies on the RUE process of aluminum alloys, no research has been reported on the 5xxx series of aluminum alloy and the relationship between the microhardness distribution and compressive strength with the strain distribution. In this research, the simulation by ABAQUS/CAE software was used to obtain the minimum extrusion ratio which was an important factor in the formation of defects and provided a perfect specimen. The resulting samples could be used to obtain the perfect height for the deformation zone in the RUE die. To verify the validity of the results obtained from the simulation, four cycles of the successive RUE were tested on the Aluminum-Magnesium alloy 5452 in the die, which was created by using the simulation results, then compared with experimental results. Furthermore, the compressive and microhardness tests were conducted on the RUE processed specimen, then the results and the microhardness distribution were analyzed.

2. Experimental Procedure

2.1 Preparing materials

Four cylindrical AA 5452 aluminum alloys with the diameter of 20 mm and the height of 26.2 mm were used in this research. The chemical composition is given in Table 1. The dimensions of the cylindrical specimen were determined by the volumes in the RUE die. A RUE die was divided into three regions, volumes V1, V2 and V3, as shown in Fig. 1. These volumes were designed in a way that V1 + V2 = V2 + V3. During the upsetting stage, the work piece filled the volume V_{up}=V1+V2 and during the extrusion stage, it filled the volume V_{ex}=V2+V3. Therefore, the volume of the work piece (V_w) can be given by V_w= V1 + V2=V2 + V3. So, the volume of the cylindrical specimen should be equal to V1 + V2=V2 + V3 and by this equation the diameter and height of the cylindrical specimen could be found which was equal to 26.2 mm. The initial materials were annealed at 345°C under a soaking time of 2 h. To carry out the RUE process, we used the minimum deformation zone height (h) and extrusion ratio (R) (obtained from the simulation) that could prevent the defects and provided the most homogeneous deformation applied to the sample. Therefore, in the die designing, the deformation zone, height and extrusion ratio were held constant at 10 and 2, respectively. The annealed specimens were processed by 1 to 4 cycles of the RUE processes with a constant speed of 65 mm/min. After finishing the RUE process, to investigate the resulting mechanical properties, two mechanical experiments including the micro hardness test and the compressive yield stress test were carried out.

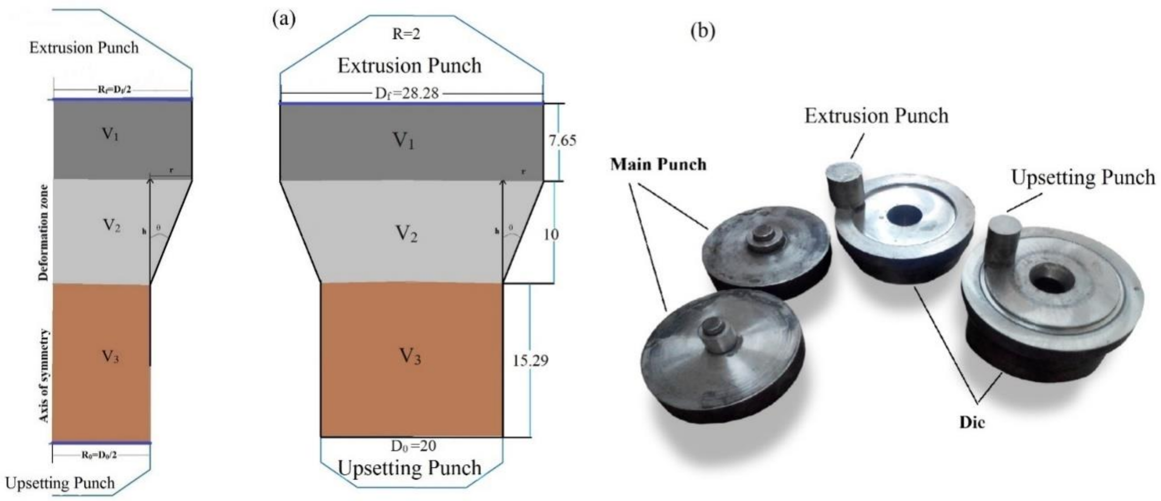

Fig. 1. Axisymmetric model of the RUE process, (a) The dimensions of the RUE die (mm) and (b) 3-D images of the RUE die.

Table 1. Chemical composition of the AA5452 used in this research (wt.%)

Al	Mg	Mn	Fe	Cr	Si
Main	2.7	0.61	0.27	0.11	0.21

For the microhardness test, each RUE that processed cylindrical specimen was cut by cross section into two pieces. One of them was polished and smoothened. The microhardness test was done by BUHLER digital microhardness device, MMT-7 model by weight of 25 g. To estimate the microhardness homogeneity distribution, the microhardness was estimated equidistantly along seven vertical lines along the sample cross-section, as shown in Fig. 2. Along each vertical line, fifty locations were tested at equidistant points. Using the measured microhardness values, the microhardness contour was plotted by the Tecplot 360 software.

The room temperature compressive yield stress test was applied to a fully annealed non-processed RUE specimen of AA5452 and various passes of the RUE were applied to the AA5452 specimens. The Test was carried out by the Santam-STM50 compressive test machine.

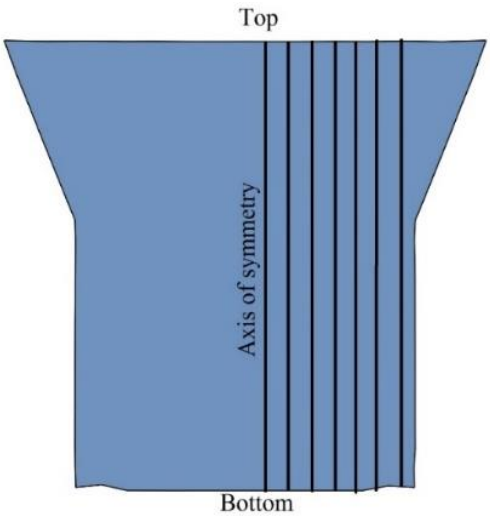

Fig. 2. Vertical lines with equidistant for measurement of the microhardness.

2.2. Simulation and finite element analysis and designing die

Three-dimensional (3-D) elastic-plastic commercial Abaqus 6.14/Explicit software was used to perform the finite element simulation of the Repetitive Upsetting-Extrusion (RUE) process. Firstly, the parts of the die, upsetting and extrusion punches and the work-piece designed in axisymmetric modeling space; in which, the parts of die and punches were assumed to be rigid, and the work-piece was considered as a deformable type and then they were assembled together as shown in Fig. 3 (a). Then, the AA 5452 alloy was subjected to a tensile test by the Santam-STM50 tensile machine according to the ASTM E8 standard. Using the SI units (mm), the results of the tensile test were entered to the software as the mechanical properties of the material. The sample was assumed to be deformable and the material properties of the die and punches were non-deformable, so they were considered to be rigid and stationary during the process. Considering the effect of friction between the die and specimen surfaces, Coulomb friction (coefficient μ = 0.1) condition was applied as a vertical friction parameter in this simulation [24] and the RUE process was carried out under isothermal conditions (room temperature). Since the RUE process was carried out for 1 to 4 cycles, in FEM simulation, each cycle of the RUE was defined into 4 steps. According to the boundary conditions, four steps were considered for the RUE process, the first step of which, the upsetting punch was assigned to an upward displacement in order to compress the specimen to V_{up} (V1+V2). Secondly, the upsetting punch was returned to its first position. After the upsetting punch was returned to its first position, the third step was initiated by extruding the compressed specimen from V_{up} to V_{ex} (V2+V3) by using the extrusion punch. At the fourth step, the extrusion punch was returned to its first position. The constant punch velocity of 60 mm/min was used for deformation during the RUE process. In order to define the periods of steps, we used the velocity of punch and the height of each zone, so for the extrusion section with the height of 7.65 mm and the punch velocity of 1 mm/sec; the step needs 7.65 seconds to finalize the extrusion process. Considering this relationship, the time period for the upsetting section with the height of 15.29 mm was calculated to be 15.29 seconds. In order to mesh the die and punches, the linear element with a size of 1 mm was considered during the process and for meshing the deforming work-piece, structured quad-dominated with a size of 0.3 mm was used. Moreover, to accommodate a large deformation, the initial mesh that took place during the deformation was refined with the use of automatic re-meshing. From the mesh sensitivity analysis, 3300 elements were found to be sufficient to reliably model the deformation behavior as shown in Fig. 3(b). Simulations were carried out for four cycles of the RUE process at different extrusion ratios (R) and deformation zone heights (h) to evaluate the separate effect of the extrusion ratio (R) and deformation zone height (h) on the deformation behavior, defect initiation and its characteristics.

In order to initiate the RUE process, it is essential to design a die which is perfect for this process. An unperfected RUE die can form defects in the processed specimens. The most common defects in the RUE process are axial hole or funnel, fold and vortex. The fold or lap or cold shut is a defect which is produced when two surfaces of metal are pushed against each other without a good welding property and formation of these defects extremely depends on the extrusion ratio and the deformation zone height [19]. To carry out the FEA, the initial work piece height (H_o) and diameter (D_0) were held constant at 26.2 mm and 20 mm, respectively. Simulations were carried out to ascertain the separate effect of the deformation zone height (h) and extrusion ratio (R) on the formation of defects and to investigate the pattern of the deformation behavior by changing the extrusion ratio (R) and deformation zone height (h) in the RUE die. Two steps were considered for the RUE process during the simulation, in which, in the first step, various extrusion ratios were investigated by changing the upset diameter (D_f), while the other parameters were kept constant, and, in the second step, the effect of various deformation zone heights on the RUE process was studied.

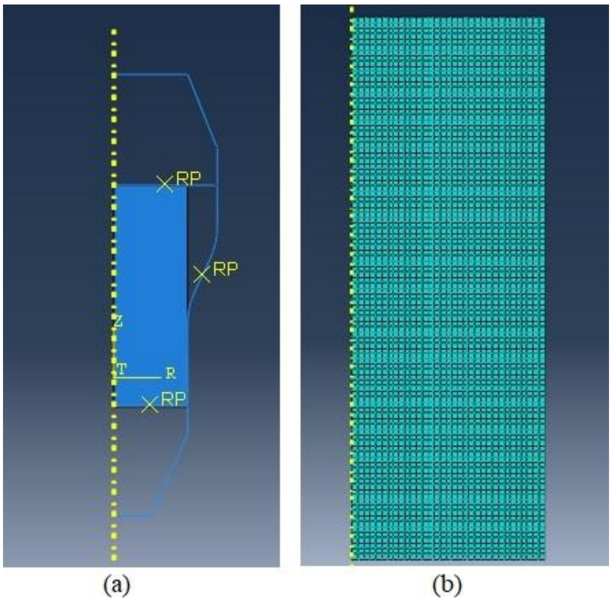

Fig. 3. (a) the assembly of RUE process simulation, (b) the meshed work-piece by Abaqus simulation.

3. Results and Discussion

3.1. Finite element analysis

The deformation pattern obtained after four cycles of the RUE process by the varying extrusion ratio (R) and the deformation zone height (h), are shown in Fig. 4 and Fig. 5. Based on the Fig. 4, it can be stated that in a constant deformation zone height (10 mm), increasing the extrusion ratio created defects. Furthermore, for a constant deformation zone height or die angle, the deformation applied to the sample became more homogeneous and increased by increasing the extrusion ratio to 2, and, then, this homogeneity was changed to the heterogeneity and reduced. Moreover, it can also be observed that, by increasing the extrusion ratio, the defects in fold and vortex were formed. As can be seen in Fig. 5, for a constant extrusion ratio of 2, increasing the deformation zone height (h), decreased the depth and radius of the axial hole and subsequently decreased the value of fold and vortex. Surveying Fig. 5 shows that when the deformation zone height was decreased, the number of folds and the width of these folds also increased. Furthermore, by increasing the deformation zone height (h), the value of deformation applied to the sample was reduced. Therefore, considering the results acquired from Fig. 4 and Fig. 5, if $h \geq D_0/2$ and $R \leq 2$, the creation of common defects can be prevented during the RUE process on the Al 5452 alloy.

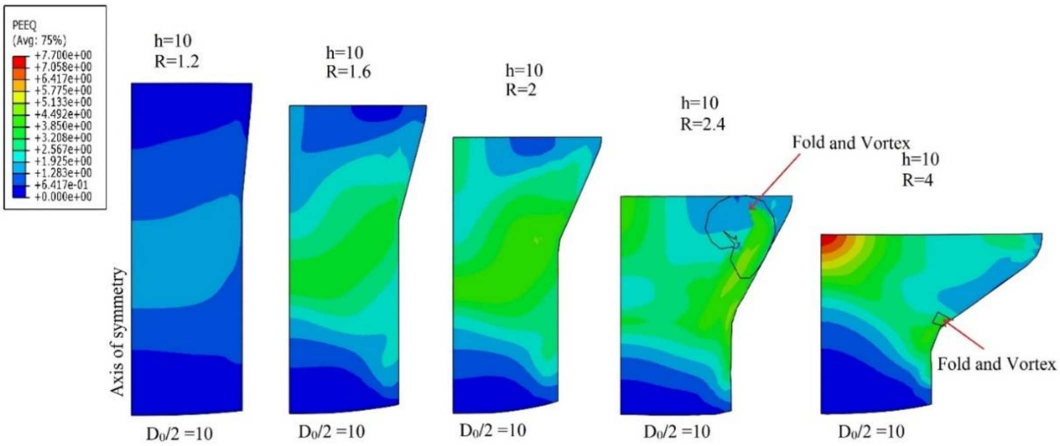

Fig. 4. The deformation pattern obtained by varying 'R' for a deformation zone height (h) of 10.

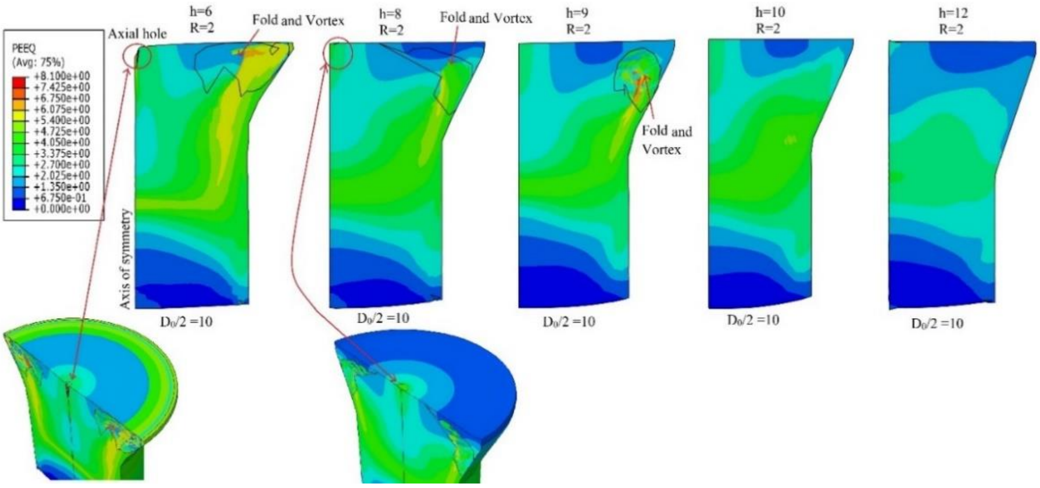

Fig. 5. The deformation pattern obtained by varying 'h' for an extrusion ratio (R) of 2.

3.2. Microhardness and plastic strain distribution

The bar chart of the average microhardness value for a fully annealed specimen after the completion of the first to fourth passes of the RUE process, is shown in Fig.6. The average value of microhardness for a fully annealed specimen was found to be about 71.5 Hv. After the chart has been studied, it can be vividly comprehended that the average value of microhardness increased with an increase in the RUE cycles and reached 97.4 Hv, 121.5 Hv, 134.4 Hv and 145.1 Hv at cycles 1 to 4 of the RUE processes, respectively. Thus, it can be clearly seen that after 4 cycles of RUE, the value of microhardness was doubled and the RUE process at the modified die was capable of producing bulk nanostructured metals. The reason of the increase in the microhardness values in the specimens during the RUE cycles can be attributed to strain hardening, increment of the dislocations density due to applying a large deformation, and finally grain refining in the specimens.

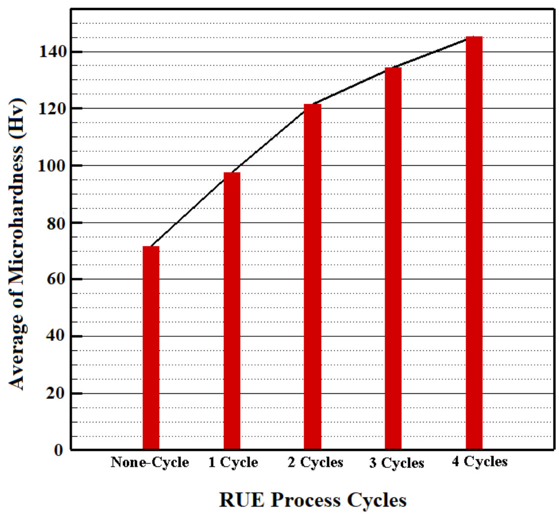

Fig. 6. The average microhardness value for the fully annealed specimen and the specimens after the RUE cycles.

The contour graph of the microhardness distribution and the variations of the equivalent plastic strain (PEEQ in Abaqus) for a fully annealed specimen and after the first to fourth passes of the RUE process are shown in Fig. 7 and Fig. 8, respectively. The results of the microhardness distribution in the RUE processed specimens were compared with the variation of equivalent plastic strain (PEEQ) in order to verify the results. As clearly explicit in Fig. 7, the microhardness distribution homogeneity and the average value of microhardness in each specimen increased with the increase in the RUE cycles. From Fig. 7 and Fig. 8, two regions including B and C can be clearly observed, in which, by increasing the amount of equivalent plastic strains during the RUE cycles, the average value of microhardness increased. There is also a region A which experienced an insignificant strain at the first cycle; however, the extent of this region decreased by increasing the RUE cycles and it experienced a medium strain. Considering region A, in Fig. 7 and Fig. 8, it can be clearly seen that the medium strain experienced by this region brought about a medium microhardness. Having analyzed region B, we can clearly comprehend that the specimens experienced a higher strain in this region during the RUE cycles (Fig. 7); therefore, the higher homogeneous microhardness was achieved in this region (Fig. 7), which indicates the use of a perfect deformation zone height and a perfect extrusion ratio. Experiencing less strain at regions A and C during the RUE process can be probably attributed to their lower extrusion ratio (θ at Fig. 1) in comparison with region B. By comparing regions A and C, it can be clearly seen that region A experienced less strain during the first cycle than region C, which continued up to cycle 4. This may be due to the fact that the RUE started with upsetting at the first step and during this step, region A did not experience as much deformation as region C. Therefore, at the next step, when the compressed bulk material was extruded, region A experienced less strain than region C. In addition, by studying region C in Fig. 8, it can be asserted that both amounts of applied strain and homogeneity distribution of the strain were improved by increasing the RUE cycles, although the amount of the applied strain in this region was lower than that in region B during the RUE cycles. Hence, by comparing Fig. 7 and Fig. 8, it can be affirmed that the evolution of microhardness in the RUE processed specimens of the Al 5452 was consistent with the simulation results.

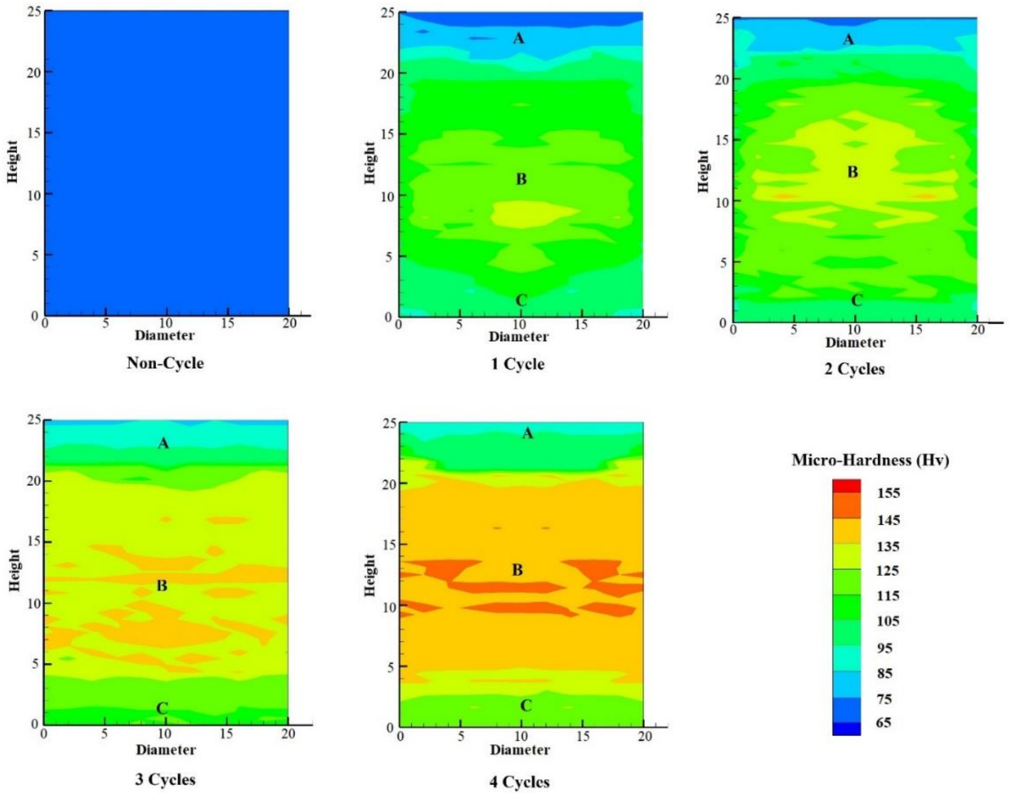

Fig. 7. Microhardness distribution for the fully annealed specimen and the specimens after the RUE cycles.

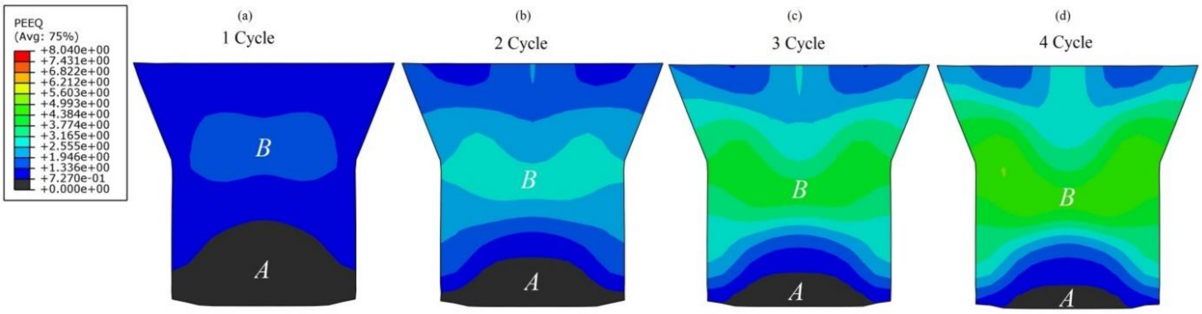

Fig. 8. The variations of the equivalent plastic strain (PEEQ in Abaqus) with an increase in the RUE cycles.

Considering Fig. 8, the equivalent plastic strain can be calculated for a fully annealed specimen and after the first to fourth passes of the RUE process; therefore, according to the true strain equation ($\varepsilon = 4\ln(D_2/D_1)$), after cycles 1, 2, 3 and 4, the values of the true strain reached about 1.39, 2.77, 4.16 and 5.54, respectively. According to the PEEQ contour at Fig. 8, the strain values raises from 1.336 to 5.603, by applying the RUE cycle from 1 to 4; therefore, the theoretical and simulation strain values are close to each other with a good approximation.

For a better understanding of the microhardness distribution in specimens after the RUE cycles, the homogeneity of the surface microhardness distribution is shown in Fig. 9 for the RUE processed Al 5452 alloy. The microhardness distribution of the fully annealed Al 5452 alloy specimen was approximately homogeneous Fig. 9(a); however, by applying a plastic deformation in the specimens during cycle 1 to cycle 2 Fig. 9 (b and c), the microhardness values in zone (*B*) became higher than that of zone (*A*) and zone (*C*), and these values approximately rose from 115-125 Hv to 125-135 Hv from cycle 1 to cycle 2, and, by increasing the RUE cycles to 3 and 4 Fig 9 (d and e), they reached 135-145 Hv and 145-155 Hv respectively. It is also obviously clear that, not only the values of microhardness in the zone (*B*) increased by increasing the RUE cycles, but also the zone (*B*) expanded and its surface became much smoother. In other words, the difference between the maximum and minimum microhardness values which caused grooves in zone (*B*) became less, which indicates the enhancement of the homogeneity in this area.

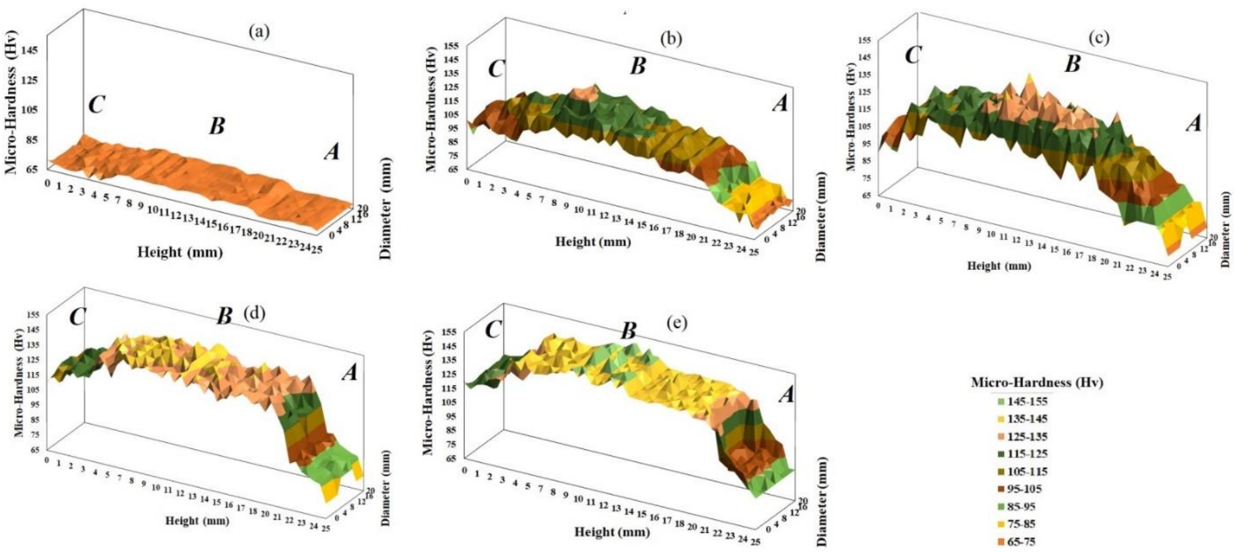

Fig. 9. Surface Micro-hardness distribution graph for fully annealed specimen and the specimens after RUE cycles.

3.3. Compressive yield stress

The room-temperature compressive yield stress of the Al 5452 alloy that was subjected to various cycles of the RUE processing is shown in Fig. 10. As visible in Fig. 10, the compressive yield stress of the Al 5452 specimens was enhanced by increasing the RUE cycles. The compressive yield stress of the fully annealed specimen was 136.622 MPa. Indeed, as the RUE process cycles increased, the compressive yield stresses increased from 136.622 MPa to 243.225 MPa, 337.056 MPa, 386.169 MPa and 432.221 MPa after the first to the fourth cycles of the RUE process, respectively. Thus, it can be asserted that the compressive yield stress of the Al 5452 alloy climbed up with an increase in the RUE cycles.

The rate of increase in the compressive yield stress at the first and second pass was steeper, whereas it slightly decreased in the next cycles and this can be apparently attributed to the work hardening created during the RUE process. Also, the reason of enhancement of the compressive yield stress of the Al 5452 alloy by increasing the RUE cycles from 1 cycle to 4 cycles, can be attributed to the occurrence of the strain hardening, the increase in the dislocations density due to applying a large deformation and finally grain refining in the specimen. By enhancing the plastic deformation, grains will be crushed and the grain size will decrease. By studying the Hall-Petch equation, we can comprehend that the yield stress has an inverse relationship with the grain diameter ($d^{-0.5}$); therefore, by decreasing the grains diameter, the yield stress values will be improved.

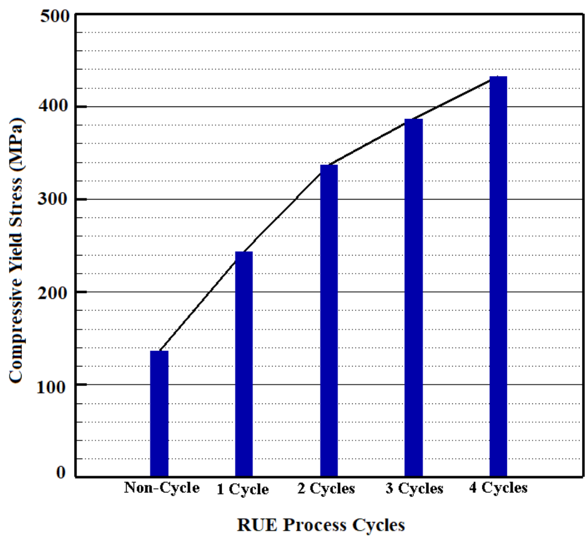

Fig. 10. Compressive yield stress of the Aluminum- magnesium 5452 alloy subjected to various cycles of the RUE process.

4. Conclusions

The perfect deformation zone height (h) and the perfect extrusion ratio (R) for the RUE process on the Al 5452 alloy were determined by simulation which brought no defect and accordingly, a RUE die was built for this experiment. The average microhardness value increased by increasing the RUE cycles. In addtion, it was demonstrated that, after applying 4 RUE cycles to the Al 5452 alloy, the microhardness values would increase (135-155 Hv) making the microhardness distribution more homogeneous and increasing the compressive yield stresses by about 300% (from 136.622 MPa to 432.221 MPa after 4 cycles). The evolution of microhardness was consistent with the simulation results. Also, the theoretical and the simulation values of the strain were in agreement with a good approximation. Therefore, it can be asserted that the RUE process is a quite effective method for enhancing the mechanical properties of the Al 5452 alloy.

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