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Study the Ductility of Aluminum Alloy Processed by Asymmetric Rolling Process

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K E Y W O R D S

Aluminum alloy, asymmetric rolling, ductility.

A B S T R A C T

Asymmetric rolling refers to the conditions wherein velocities or diameters of two work rolls are different. Compared to symmetrical rolling, asymmetric rolling is more effective on microstructure modification and texture evolution. Intense shear deformation can be introduced into asymmetric rolling to enhance the ductility and formability of aluminum alloy and this is the aim of current research. The process of the asymmetrical rolling was done on specimens with different reductions (10%,15%, and 20% reductions). Then the tensile test was conducted at room temperature at the strain rate range between 0.33×10-3s-1 - 3.33×10-3s-1 to study the ductility property of the asymmetric rolling-deformed samples and also compared with as-received samples. The results show that the as-received specimen gave the highest elongation of 42.7%, while the lowest elongation of 22.4% was obtained by the (20%) thickness reduction specimen. Also, the as-received sample at an initial strain rate of 3.33×10-3s-1 gives the highest tensile strength value equal to 550MPa.

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1. Introduction

Aluminum alloy sheets are gradually becoming important since it has a low weight, they will be a successful substitute for steel alloy sheets especially in the automobile industry to reduce the weight of the automobiles, in the same time the formability of these alloys is low due to the lower ratios of plastic strain. There are many different methods used to increase the plastic strain ratio of aluminum alloy sheets by generating shear deformation through the thickness of the sheet. One of the common and favorable processes to impose shear-deformation texture through the sheet thickness is an asymmetric rolling process in which the velocities of working rollers are different [1]. 2024-T351 aluminum alloy was chosen, it is one of the more common and important aluminum alloys, because alloys have a quite good fatigue resistance, especially in thick plate form, the alloy is specified for use in fuselage applications in the military and aerospace section in such areas as wing tension

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members and structures. Alloy 2024 continues to maintain strength characteristics with improving fatigue crack growth and fracture toughness. Over the past decades, considerable attention has been paid to the development of the metallic material's structure using severe plastic deformation (SPD) techniques [2].

There are a lot of techniques that reduce the size of material grains up to micrometer level by subjecting these grains to severe plastic deformations, such as equal channel angular pressing (ECAP) and high-pressure torsion (HPT). One of the importance of these continuous severe plastic deformation techniques is the asymmetric rolling process which has industrial potential in addition to the mention above. In ASR the work rolls rotate at different speeds by using different diameters to impose shear-deformation and therefore would improve the properties of the materials [3-5]. The effective ratio of speed roll on the elongation-to-failure, strength, and texture was studied by Loorentz and Y. Gun Ko [6], sheets were used in this study were 5020 Al alloy which was deformed by using differential speed rolling process (DSR), it is noted all samples were rolled by DSR without appearing of any cracks clearly. Tensile tests were done to measure the mechanical properties of deformed samples by the DSR process and results were compared with one by the equal speed rolling process, they concluded the grain size of 0.5 µm can be attained after two passes during differential speed rolling at a 1:4 ratio of speed roll. Also increasing in roll speed ratios would largely affect the values of the microhardness of this alloy.

Xinsheng et al. [7] studied the effect of reduction per pass on the microstructure and texture of Mg alloy sheets processed by DSR over the range of 9–63% at the same total reduction of 63%. They observed that the microstructure and the texture of the DSR-processed sheet were strongly affected by the reduction per pass. With increasing reduction per pass, the amount of the unidirectional shears bands resulted in a more homogeneous microstructure. The poor plasticity of the AZ31B alloy at room temperature improved by the differential speed rolling process was studied by Hisab et al. [8] the differential speed rolling with different speed ratios 1:1,1:1.4, 1:1.8 and1:2.2 and reductions 20%,25%,30%, 35% were done in order to study the superplastic properties and microstructures of the AZ31B alloy. As well as, conventional rolling processes were done, and the result was compared with the differential speed rolling process under the same conditions. The results of observation showed that the modification of the microstructure had been affected by applied route, rolling speed ratio and reduction and the elongation to failure of rolled samples was increased with the increase of speed ratio and/or thickness reduction in the same initial strain rate and the same rolling route.

Ismail and Hussein [9] studied the effect of temperature on the ductility and texture of the AZ31B Magnesium Alloy by using a differential speed rolling process, the received AZ31B Magnesium Alloy strips with thickness 2mm rolled between two rollers with different diameters under the constant speed ratio 1.15. The optical microscopy was used to investigate the temperature on the microstructure of the rolled strips, and the tensile testing machine was used to test the rolled strips at temperature 623K and different initial strain rates to measure the elongation-to-failure. It can be seen from the result; the differential speed rolling is an effective process to refine the grain size of the rolled sheets. The sheet DSR at 473K showed the highest values of elongation-to-failure 340% and a sensitivity of strain rate (m) 0.35.

In this study the ductility of the 2024-T351 Aluminum alloy processed asymmetric rolling process is investigated, three thickness reductions (10%,15%,20%) are conducted. The tensile test is done for all samples produced by asymmetric rolling and as-receive samples at different initial strain rates to measure the elongation of these samples.

2. Experimental Procedures

I. Material Selection

The material used in this work is the 2024-T351 Aluminum plate. The initial thickness of this plate is 6 mm. The spectrometer devices used to find out the chemical composition of this material. The weight percentage of compositions are shown in Table I.

TABLE I: Chemical composition of the 2024-T351 alloy (wt %), ASTM

Elements	Cu	Cr	Zn	Mg	Ti	Si	Fe	Mn	Al	Other
Composition	4.5	0.1	0.25	1.6	0.15	0.5	0.5	0.7	Bal.	0.5

II. Experimental Tooling for Asymmetric rolling (ASR)

To deform the 2024-T351 Aluminum alloy plate by Asymmetric rolling (ASR) operations. A conventional laboratory rolling mill device as shown in Figure 1 was used, this rolling mill device has two rolls with different diameters. The diameter of the first roll is (55mm) and the second roll (47·8mm) with a speed ratio of 1:15. The ASR process was carried out for different samples using different thickness reductions (10, 15, 20) %.

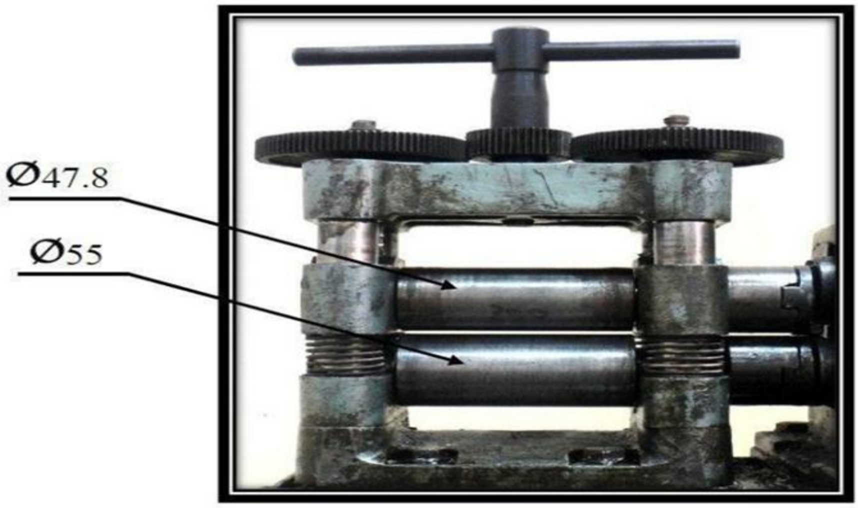


Figure 1: Asymmetrical rolling device.

III. Specimens for the asymmetric rolling process (ASR)

Specimen's dimensions are 85 mm long, 65 mm wide and 6 mm thick. The directions of rolling were parallel to the as-received rolling direction. The asymmetric rolling process was conducted at different reductions of 10%, 15%, and 20% to study the effect of reduction on the mechanical properties of 2024 aluminum alloy.

To investigate the effect of reductions on the ductility, the specimens were cut and divided into 4 groups. And for studying the effect of strain rate on the mechanical properties each group divided into three specimens. These specimens were rolled without any lubrication. The differential speed rolling processes were done to get several reductions (10, 15, 20) %. The first group was as-received. The second group with thickness reduction (10%) was attained in one pass rolling, the third group (15%) reduction was attained in two passes, and the fourth group (20%) reduction with three passes. Many passes were used to get the final given reductions using rolling direction (the successive rolling directions were rotated through 180 about the rolling direction). Table II shows the details of the experimental works. Figure 2A shows the shape of strips and Figure 2B shows asymmetrical rolling tool assembly respectively.

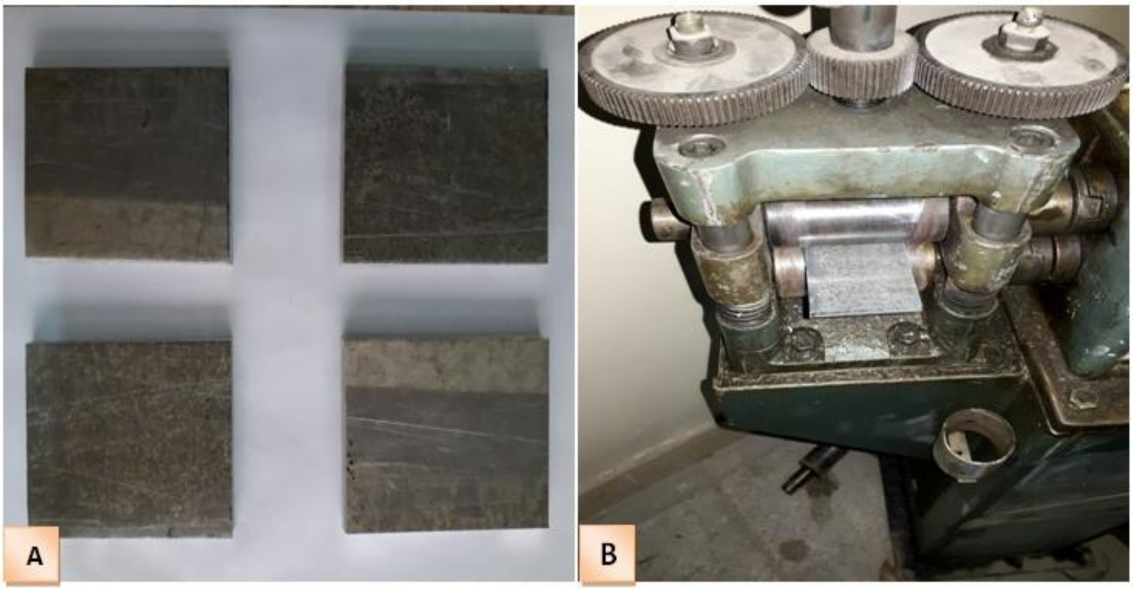
3. EXPERIMENTAL PROCEDURES

I. Tensile Specimen

The ASTM standard is used to design tensile specimens of bone shape geometry, with 25 mm gauge length, 6 mm width and 6 mm shoulder radius was cut along the plane coinciding with the rolling direction as shown in Figure 3.

TABLE II: The details of the experimental works

groups	No. of specimens	Reduction	No. of passes	Route of passes
First	Three (as-received)	------	-------	------
Second	three	10%	1	Rolling direction
Third	three	15%	2	Rolling direction
Forth	three	20%	3	Rolling direction



a) Strips b) rolling device

Figure 2: The shapes of the strips and the asymmetric rolling device

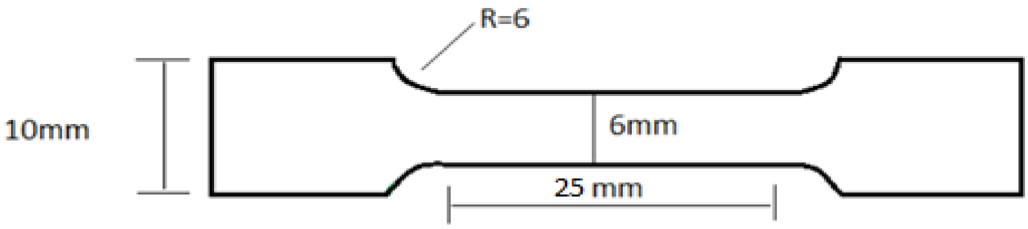


Figure 3: Tensile specimen

II. Tensile Test

To study the mechanical properties of rolled and unrolled samples, a tensile test was done. After preparing and designing of the tensile test specimens according to standards, the tests were conducted at room temperature, at different strain rates ($0.33\times10^{-3}s^{-1}$, $1.66\times10^{-3}s^{-1}$, and $3.33\times10^{-3}\ s^{-1}$). The tensile test machine model (WDW-200E III) was used to do these tests as shown in Figure 4.

4. Results and discussion

This part shows results from tensile tests at room temperature at various initial strain rates for asymmetric rolling-deformed and as-received specimens of the 2024-T351 aluminum alloy strips.

I. Elongation-to-failure

Tensile specimens after being pulled to fracture for the experiments are shown in Figure 5. It can be noticed throughout the test operation the specimens showed uniform stretching within the gage length region and continue increasing in length and decreasing in width for this gage region up to reach to fracture without the appearance of clear necking or with the appearance of a small amount of necking within these regions of gage length. The elongation-to-failure was measured for ASRed and as-received 2024-T351 aluminum alloy plates after the tensile test, the results are listed in Table III. It can be seen from the table that the ASRed 2024-T351 aluminum alloy sheets exhibit different elongation with different reductions. All elongation-to-failure of the alloy is higher than 22%, the lowest elongation 22.4% can be obtained by ASRed with (20%) thickness reduction and the higher elongation of 42.7% was obtained for the as-received specimen. As shown in Table 3. The ductility of the sample can be determined as follows:

$$EL\% = \frac{lf - l0}{l0}\ X\ 100\% \qquad (1)$$

Where El% is the percentage elongation to failure, l0 is the length of the specimen's gauge region, if is the final length of the specimen's gauge region after the test.

Figure 4: WDW-200E III machine

Figure 5: Image illustrated of the specimens after the tensile test

TABLE III: Tensile testing results of 2024-T351 aluminum alloy

specimen	Initial strain rate X 10-3	Elongation %	Maximum strain
As-received	0.33	42.7	0.35
	1.66	41.3	0.34
	3.33	36.1	0.30
10% thickness reduction	0.33	29.1	0.25
	1.66	33.9	0.29
	3.33	26.0	0.23
15% thickness reduction	0.33	30.8	0.26
	1.66	26.3	0.20
	3.33	26.9	0.23
20% thickness reduction	0.33	25.4	0.22
	1.66	24.4	0.21
	3.33	22.4	0.20

II. True Stress-Strain Curve

The true stress and strain curves for asymmetric rolling-deformed and as-received specimens of the 2024-T351 aluminum alloy plates are shown in Figures 6 and 7. The flow curve of the specimens can be got from the engineering stress-strain curve which directly obtained by the computer connected with the tensile test machine as follows:

$$\sigma t = \sigma 0(1 + e) \quad (2)$$

$$\in = \ln(1 + e) \quad (3)$$

where σt is the true stress, σo is the engineering stress, ϵ is the true strain and e is the engineering strain. Figure 6a-6d shows the true stress-true strain curves for as-received specimens and asymmetric rolling-deformed specimens with different reductions (10, 15, 20%) respectively, and each specimen of them have tested under three initial strain rates (0.33, 1.66, 3.33)$10^{-3}s^{-1}$.

The trend of these curves is the same as the change in used different strain rates. It can be seen that flow stress follows different patterns to different strain rates, the flow stress will increase with an increase in strain rates, where Figure 6a, shows the true stress-strain curves for the as-received a 2024-T351 alloy sheet tested with initial strain rate 3.33×10^{-3}, which exhibit a maximum tensile strength value equal to 550 MPa. While The ductility decreases as the strain rate increases from 0.33×10^{-3} s^{-1} to 3.3×10^{-3} s^{-1}, whereas the flow stress Increases significantly. In general, the flow stress increases while the elongation decreases with increasing strain rate during the test. Figures 7 shows the true stress versus true strain curves of the as-received and ASR samples with different reductions (10%,15%,20% reductions) specimens were obtained by tensile testing at room temperature. It can be roughly seen that the as-received sample shows a more ductile behavior when compared with ASR processed samples. This is because the decrease in the values of the ductility resulting from the process of strain hardening during the rolling operations is greater than the increase in values of the ductility resulting from imposing shear deformation through the thickness by using the ASR process, In addition to mentioned above, There were some important points which must point at them which caused reducing the ductility in the rolled samples to these levels which are the samples after asymmetric rolling process would subject to some curvatures due to the mechanism of asymmetric rolling, so must subject these samples with simple curvatures to some simple auxiliary pressing in order to return these samples to their straightness, accordingly will be suitable and ready to tensile tests, as well as don’t using annealing operations through the rolling process would lead to decreasing in ductility up to these levels. The highest strain value of 0.36 at the initial strain rate of 0.33 x 10^{-3} for the as-received and the lowest value was 0.2 for the (20% thickness reduction) specimen at $3.33X10^{-3}$ strain rate. While the flow stresses increase with the increase in thickness reduction due to strain hardening which subjects to the samples during the rolling process.

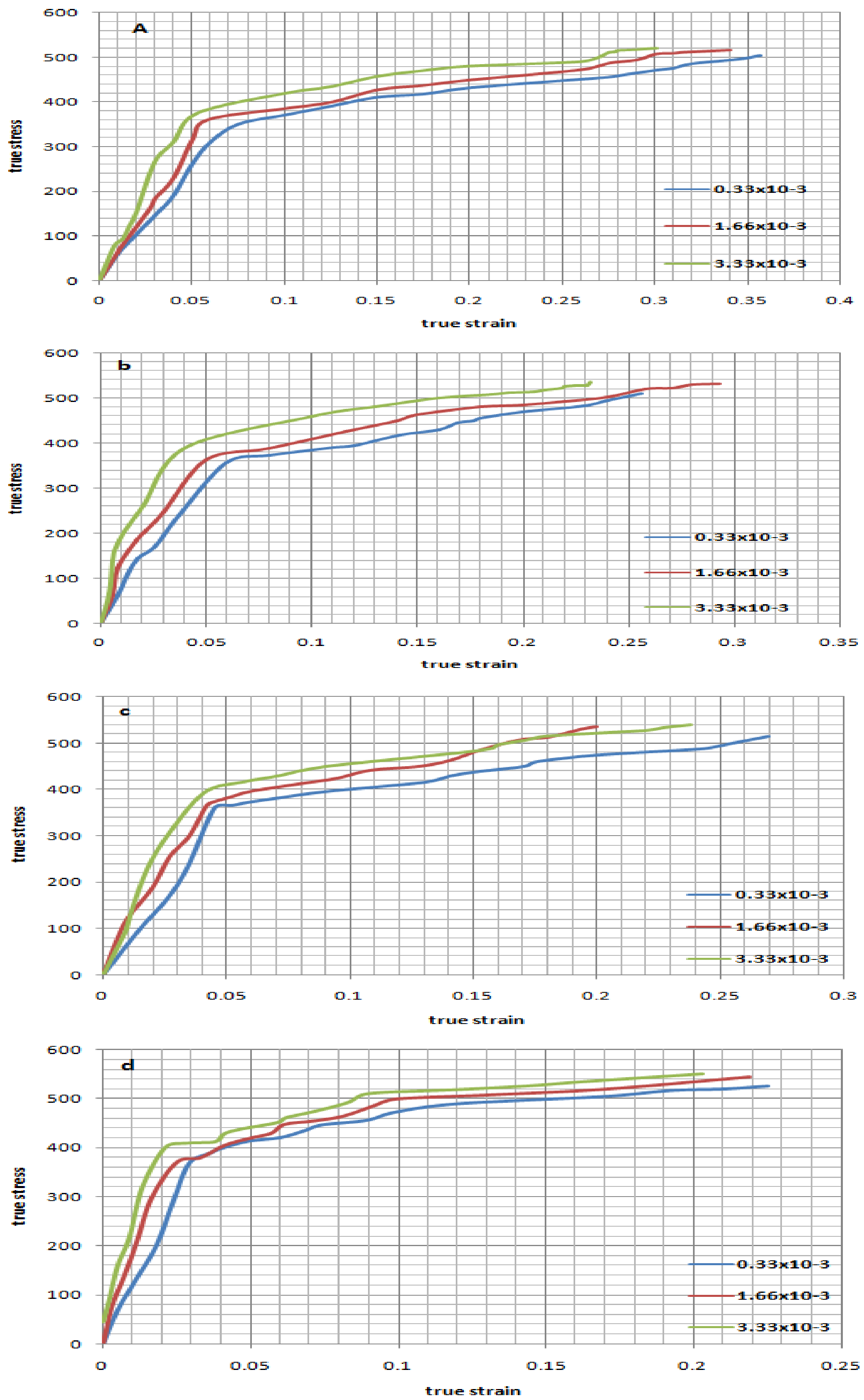


Figure 6: True stress-strain curves of the tensile test at different initial strain rates for 2024-T351 specimens (a) As-received (b) 10% thickness reduction (c) 15% thickness reduction (d) 20% thickness reduction

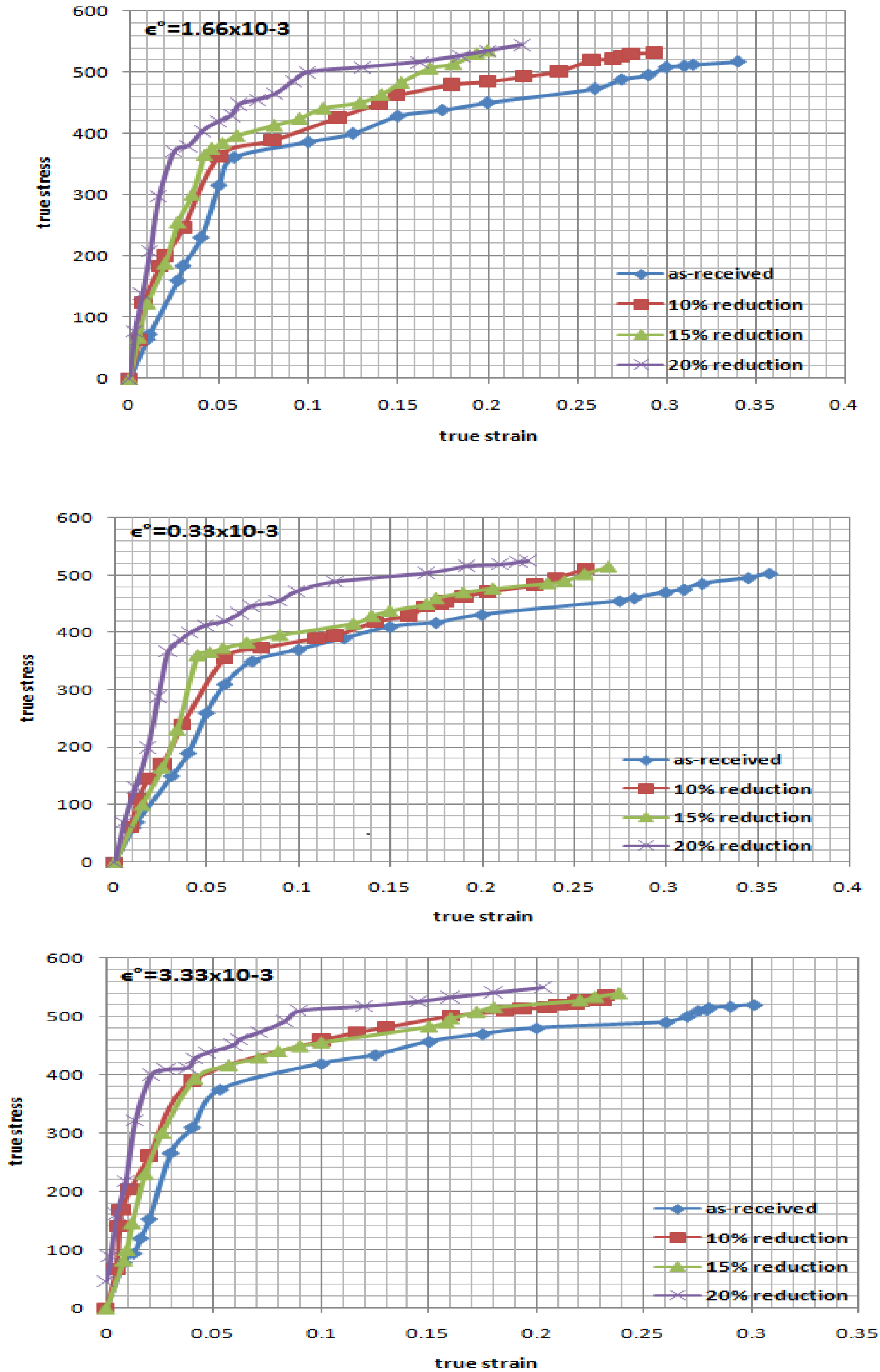


Figure 7: True stress-strain curves of tensile test for different ASRed specimens and constant initial strain rate 0.33× $10^{-3}s^{-1}$, 1.66× $10^{-3}s^{-1}$, 3.33× $10^{-3}s^{-1}$ respectively

5. Conclusions

2024-T351 aluminum alloy was deformed at room temperature, by applying different thickness reductions and strain rates with a speed ratio of 1.15. The tensile properties of as-received and asymmetric rolled alloy was examined.

The conclusions drawn are as follows:

i. The elongation-to-failure depends on the thickness reduction, the number of reductions and the strain rates, the ductility is affected by asymmetric rolling associated with the following elements (speed ratio, thickness and passes) .

ii. Improve the ductility of this 2024-T351 alloy by imposing sheer thickness by doing asymmetric rolling at room temperature under these given conditions is a bit less.

iii. Because the decrease in the values of the ductility resulting from the process of strain hardening during the rolling operations is greater than the increase in values of the ductility resulting from imposing shear deformation through the thickness by using the ASR process.

iv. The maximum elongation to failure of (42.7) % had been obtained in the as-received specimen with 0.33×10^{-3} initial strain rate. Whereas lowest elongation 22.4% was obtained by the (20%) thickness reduction specimen at 1.33 x 10-3 strain rate .

v. It appeared that the increase in the initial strain rate leads to a decrease in the elongation of DSRed specimens .

vi. No using annealing operations leads to a decrease in elongation-to-failure values with increasing reduction thickness ratios.

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