Experimental and Simulation Study the Effect of Different Reduction Ratios in Cold Rolling Process on the Residual Stresses of AL 2024 Alloy

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ABSTRACT

Cold forming processes are the common processes in sheet metal forming, especially in the final stages of production processes. In this work, cold rolling process was selected to study the effect of different reduction ratios on the residual stresses state in aluminum alloy (2024). Sheets of aluminum alloy (2024-T3) were prepared with dimensions (400 X 80 X 3.15 mm). The annealing process was conducted for these sheets to get the temper condition (2024-O). The cold rolling process was performed with different reduction ratios (10%, 20%, 30%, 40%, 50%, 60%) by a rolling machine composed of two rolls having (50 mm) diameter each. The residual stresses were measured using X-ray diffraction technique (XRD) in two directions (rolling direction RD, and transverse direction TD). The results of X-ray diffraction showed the presence of residual stresses at the surface of rolled specimens, and these were compressive stresses in the two tested directions (RD, and TD) at 10% reduction ratio. When the reduction ratio exceeded 10%, these stresses transformed to tensile stresses for specimens tested in rolling direction, while these stresses remained compressive type for all reduction ratios in transverse direction.Computer simulation was carried out using finite element method (FEM) by (ANSYS-LSDYNA 12.1) software to investigate the residual stresses behavior of AA 2024. The numerical results showed a good agreement with the experimental results especially for samples tested in the rolling direction.

Keywords: Cold rolling, Residual stress, X-ray diffraction, FEM.

دراسة تجريبية ومحاكاة تأثير نسب تخفيض مختلفة في عملية الدرفلة الباردة على الاجهادات المتبقية لسبيكة المنيوم 2024

الخلاصة

تعد عمليات التشكيل على البارد من العمليات الشائعة في تشكيل الالواح المعدنية وخصوصاً في المراحل النهائية من عمليات الانتاج. في هذا البحث تم اختيار عملية الدرفلة الباردة للتحقق من تأثير نسب التخفيض

المختلفة على حالة الاجهادات المتبقية لسبيكة المنيوم (2024). تم تهيئة الواح من سبيكة المنيوم (2024-T3) بأبعاد (3.15mm X 80 X 400). أجريت عملية التلدين لهذه الالواح للحصول على (2024-O temper). تم اجراء عملية الدرفلة على البارد بنسب تخفيض مختلفة (10%, 20%, 30%, 40%, 50%, 60%) بواسطة ماكنة درفلة متكونة من درفيلين قطر كل منها(50 mm). تم قياس الاجهادات المتبقية باستخدام تقنية حيود الأشعة السينية وباتجاهين (اتجاه الدرفلة, والاتجاه المستعرض). أظهرت نتائج حيود الاشعة السينية وجود أجهادات متبقية على سطح العينات المدرفلة وكانت هذه الاجهادات ضغطية بالاتجاهين (اتجاه الدرفلة, والاتجاه المستعرض) عند نسبة تخفيض 10 %.عندما تجاوزت نسبة التخفيض 10% هذه الاجهادات تحولت الى اجهادات شدية للعينات المختبرة باتجاه الدرفلة, في حين بقيت هذه الاجهادات ضغطية لجميع نسب التخفيض بالاتجاه المستعرض. تم أجراء محاكاة حاسوبية لعملية الدرفلة الباردة بأستخدام طريقة العناصر المحددة ببرنامج (ANSYS LS-DYNA 12.1) للتحقق من سلوك الاجهادات المتبقية لسبيكة الالمنيوم 2024. بينت النتائج العددية توافق جيد مع الجانب العملي, وخصوصاً للعينات المفحوصة بأتجاه الدرفلة.

INTRODUCTION

Residual stresses can be defined as the stresses that remain within a material or body after manufacture and material processing in the absence of external forces or thermal gradients. They can also be produced by service loading, leading to inhomogeneous plastic deformation in the part or specimen [1]. The most significant mechanical processes which induce surface residual stresses are those which involve plastic yielding and hence "cold-working" of the material, such as rolling, shot peening and forging. Practically, all other standard machining procedures, such as grinding, turning, polishing, etc., also involve local yielding (to a lesser extent perhaps) and also induce residual stresses [2].

During the manufacture of roll formed structural members, the production and storage of sheet materials as well as their subsequent forming cause plastic deformation in varying degrees around the resulting cross section. Plastic deformation causes both an increase in material strength in the section material through cold working and it also affects the residual or internal stress distribution present throughout the resulting structural section [3]. Due to the importance of residual stresses state, stress value and stress type (compression or tensile stress) on fatigue life ofsheet metal, many researches were done in the past to measure these stresses such as:

Imai and Yonetani [4] studied the residual stress in cold rolled aluminum sheets using X-ray method. They showed that the residual stress generated in the rolling direction (RD) is tension, while the stress in transverse direction (TD) is compressive, and the value of stress was varied from (20MPa to -20MPa) in the rolling and transverse direction. Nakayama et al. [5] investigated the surface residual stresses in cold rolled 5083 aluminum alloy by X-ray method. For (5mm) initial thickness, it was found that the compressive residual stress induced in RD at 20% reduction ratio and then changed to tensile stress with increasing reduction ratio, furthermore, the tensile stress decreased as the reduction ratio increased from 60% to 80%. The TD showed the nature of compressive residual stress that increased with increasing reduction ratio, furthermore, the compressive stress decreased as the reduction ratio increased from 60% to 80% showing a similar change to the stress measured in the RD. The influence of cold rolling and fatigue on the residual stress state of a metal matrix composite was investigated by Hanus et al. [6] who found that the cold rolling induces surface compressive stresses of about (-250 MPa), and the four point bending fatigue relaxes the surface residual stresses. Tadic and Misovic [7] studied the residual stresses in cold rolled narrow strips, experimental measurements and FEM simulation found that all tested samples with (15-50%) reduction ratio are in tensile residual stress of about (45-85 MPa), and the obtained results in FEM simulation confirm the proper selection of samples and the accuracy of presumptions in the experimental process. Parikin et al. [8] investigated the measurements of residual stresses in cold rolled 304 stainless steel plates using X-ray diffraction. It was found that the tensile residual stress was quite large reaching (442 MPa) for a sample reduced by 34% in thickness (containing of about 1% martensite phase), whereas the improvement in martensite volume fraction caused by reduction at room temperature decreased the residual stresses. In the present work, the effect of different reduction ratio by cold rolling process of AA 2024 sheet metal on the residual stresses state was studied using X-ray diffraction technique and numerical method for comparison purpose.

Experimental Work

Samples Preparation

In this work, the aluminum 2024 alloy was chosen to study the effect of reduction ratio by cold rolling process. To check up the chemical composition of the selected alloy, a chemical analysis was done by spectrometer testing device. This test was done in the State Company for Inspection and Engineering Rehabilitation/ Laboratories Department. Table (1) shows the chemical composition for used and standard 2024 AL alloy. A sheet of 2024-T3 aluminum alloy of (3.15 mm) thickness was cut in to rectangular samples with dimensions (400 mm X 80 mm). For high cold working operations, it is important to anneal the material. Hence, the samples were then full annealed to reduce the material hardness, to get the (2024-O) temper alloy (annealing temper), and to relieve any remaining stresses generated on the material as a result of previous cold work. The annealing process was carried out in University of Technology/Department of Materials Engineering Laboratories. The annealing process was restricted according to the American Society for Testing and Materials specifications (ASTM B 918 – 01). The annealing process was performed at (410 C°) for three hours followed by furnace cooling [9].

Table (1) Chemical compositions of standard and used 2024 AL alloy.

wt% / Material	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	AL
Standard [10]	≤0.5	≤0.5	3.8-4.9	0.3-0.9	1.2-1.8	≤0.1	≤0.25	≤0.15	Remainder
Experimental	0.101	0.175	4.55	0.65	1.25	0.003	0.117	0.061	Remainder

Cold Rolling Process

Six reduction ratios by cold rolling process were carried out at room temperature at (22 C°), as shown in table (2). The rolling machine used contains a pair of parallel rolls, see figure (1), each roll has (50 mm) diameter and (100 mm) length. The roll angular velocity was measured by using the photo contact tachometer (DT- 2268) shown in figure (2). The angular velocity of rolls is equal to (18 RPM) because the machine is originally designed with only one constant velocity which cannot be changed . Figure (3) shows the material sheets after rolling process, these sheets were cut to the same length after rolling process.

Table (2) Cold rolling reduction ratios, and number of pass through the roll.

Reduction ratio %	Inlet thickness h_0 (mm)	Calculated outlet thickness h_1(mm)	Experimental outlet thickness h_1(mm)	Number of pass through the rolls
10	3.15	2.835	2.82	1
20	2.82	2.52	2.54	2
30	2.54	2.2	2.25	3
40	2.25	1.89	1.86	4
50	1.86	1.575	1.6	5
60	1.6	1.26	1.3	6

Figure (1) Cold rolling machine.

Figure (2) Photo contact tachometer.

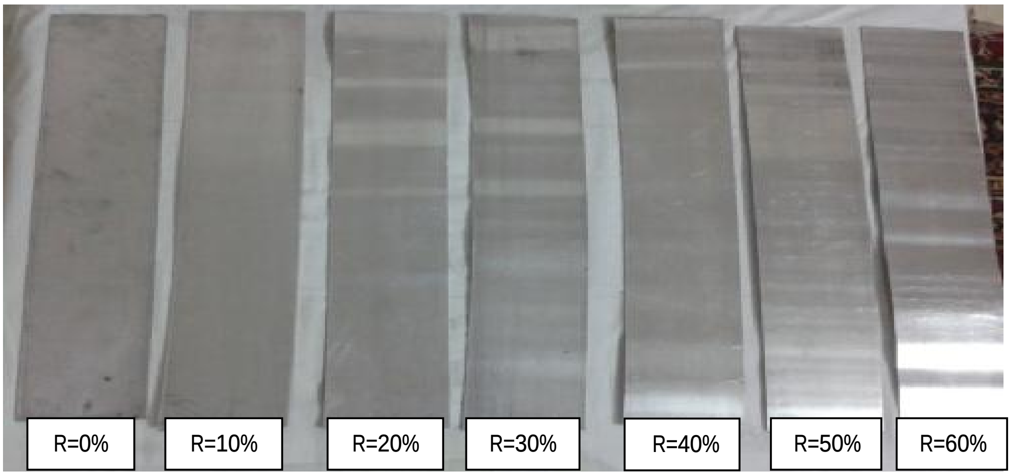


Figure (3) Material sheets after rolling process. The symbol (R) is the value of reduction ratio (%) in thickness.

Residual Stress Measurement

X-ray diffraction techniques exploit the fact that when a metal is under stress (applied or residual), the resulting elastic strains cause the atomic planes in the metallic crystal structure to change their spacing's. X-ray diffraction can directly measure this inter-planar atomic spacing, from this quantity, the total stress on the metal can then be obtained [11]. The most commonly used method for stress determination is the $\sin^2\psi$ method. A number of XRD measurements are made at different (ψ) tilts, see figure (4). The inter-planar spacing, or 2-theta peak position, is measured and plotted as a curve similar to that shown in figure (5). The stress can then be calculated from such a plot by calculating the gradient of the line and with basic knowledge of the elastic properties of the material. This assumes a zero stress at $d = dn$, where d is the intercept on the y-axis when $\sin^2\psi = 0$, as shown in figure (5) [12]. Then, by using Bragg's Law:

$$n\lambda = 2d\sin\theta \qquad \dots (1)$$

Because the measurement is made within the surface, then ($\sigma_3 = 0$). The strain (ε_z), however will not be equal to zero. The strain (ε_z) can be measured experimentally by measuring the peak position (2θ), and equation (1) solved for a value of (d_n). If we know the unstrained inter planar spacing (d_0), then:

$$\varepsilon_z = \frac{d_n - d_0}{d_0} \qquad \dots (2)$$

If we consider the strains in terms of inter-planar spacing, and using the strains to evaluate the stresses, then it can be shown that [12]:

$$\sigma_\phi = \frac{E}{(1+\upsilon)\sin^2\psi}\left(\frac{d_\psi - d_n}{d_n}\right) \qquad \dots (3)$$

Thus, the stress is given by:

$$\sigma_\phi = \left(\frac{E}{1+\upsilon}\right)\frac{m}{d_0} \qquad \dots (4)$$

Where:
σ_ϕ is the residual stress,
n is the number of wave lengths,
ψ is the specimen tilt angle,
d_ψ is the inter planar spacing at psi ψ angle,
m is the gradient of the d vs. $\sin^2\psi$ curve,
E is the modulus of elasticity,
υ is the Poisson's ratio (for AA2024 equal to 0.33) .

In this work, the surface residual stress was measured in the rolling and transverse direction using X-ray diffraction technique to estimate the effect of cold rolling reduction ratios on the surface residual stress state. All measurements were carried out in the National Center for Construction Laboratories and Research by the Shimadzu X-ray Diffractometer (XRD-6000) device, see figure (6). The (Cr K-α) X-ray tube was used, this tube runs at (40 mA), and (30 kV) with a wavelength equals to (λ = 2.2897 A°). For the aluminum and its alloys, higher intensity will appear approximately at (2θ = 156.7°). The range of scan is selected between (154 -160°) at a scan rate of (0.2°). While, the (ψ) is always selected in the range (0-50°). However, four angles (0°, 15°, 30°, and 45°) were chosen in the measurement operation.

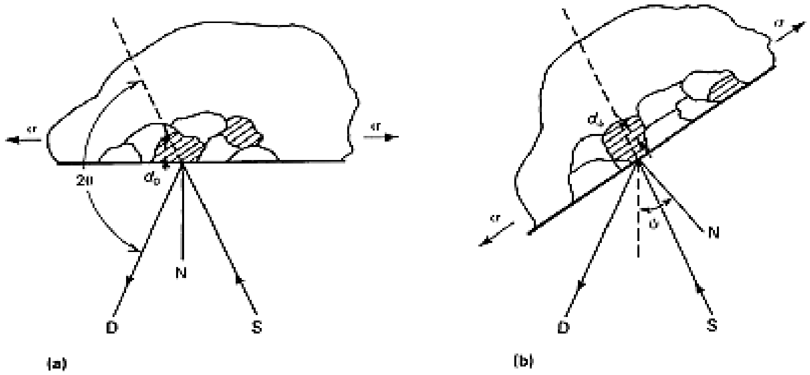
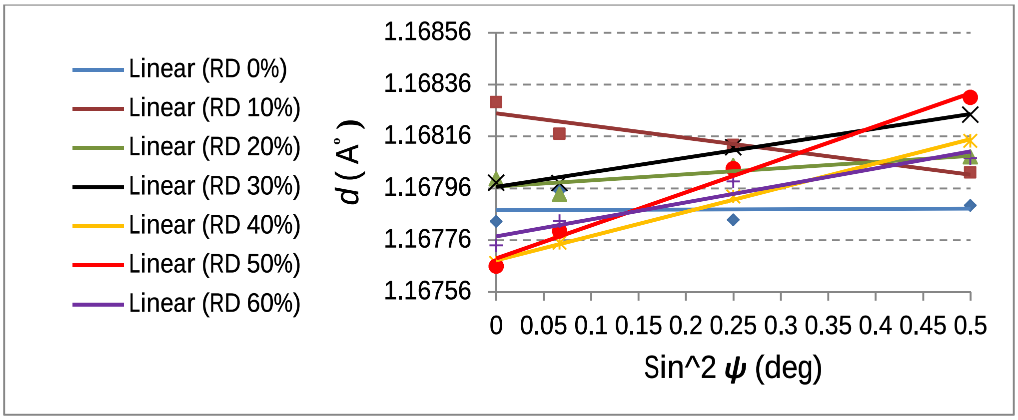
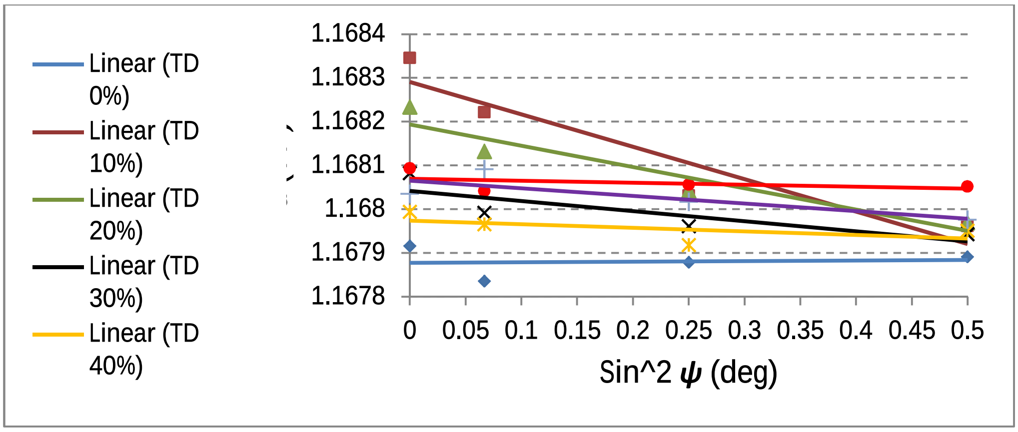


Figure (4) Principles of X-ray diffraction stress measurement.(a) ψ =0. (b) $\psi = \psi$ (sample rotated through some known angle ψ). D, X-ray detector; S, X-ray source; N, normal to the surface.[13]



(A)



(B)

Figure (5) Linear dependence of d (A°) upon $\sin^2\psi$ for cold rolled aluminum 2024 alloy, (A) rolling direction, (B) transverse direction.

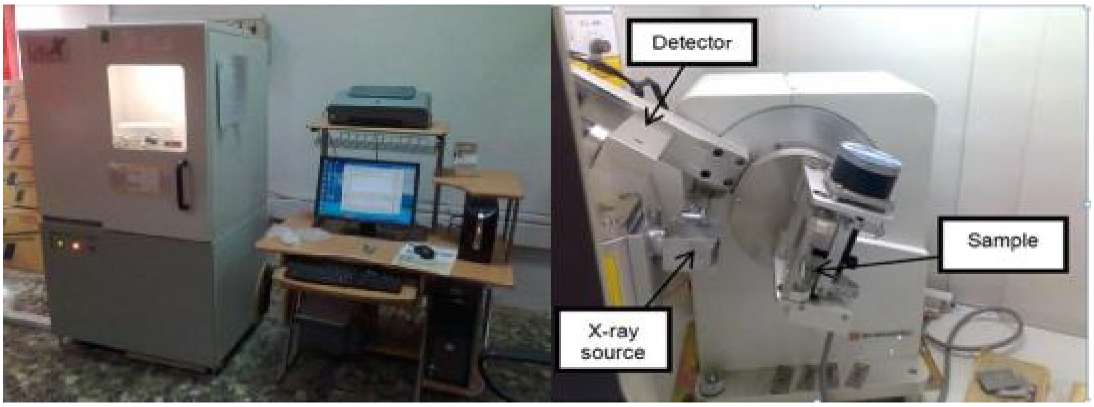


Figure (6) Shimadzu X-ray Diffractometer (XRD-6000).

Numerical Simulation of Cold Rolling Process

ANSYS LS-DYNA 12.1 software was used as a numerical tool to simulate the cold rolling process of AL2024 alloy sheet, and to illustrate the effect of the reduction ratio in thickness of material on the surface residual stress state. Six models of three-dimensional were created by ANSYS LS-DYNA 12.1 software. Each pass through the roll gap is represented by one reduction ratio in experimental work, and was simulated by two parallel rolls during building of the models, see figure (7A, B, C, D, E, F). The roll diameter and sheet dimensions used in simulating models are (50 mm) and (80 L X 80 W X 3.15 t) mm, respectively. The SOLID164 element, which is an 8-node brick element with nine degrees of freedom at each node, translations, velocities, and accelerations (UX, UY, UZ, VX, VY, VZ, AX, AY, AZ), was used. The Bilinear Kinematic material model has been used for the sheet material to be rolled. While, the rolls are modeled as rigid bodies.The bilinear kinematic hardening model uses two slopes (elastic and plastic) to represent the stress- strain behavior of a material [14]. In ANSYS LS-DYNA, a rigid body that remains rigid for the duration of the analysis is designated as a material model [14].

Results and Discussion

The experimental measurement of surface residual stress was taken for an unrolled and rolled material in each reduction ratio. The measurement was done in two directions (rolling, and transverse direction) for each specimen. The amount of residual stresses taken directly after being calculated by computer software was provided inside the system device (XRD-6000), using the equation (4).The values of residual stresses and all required calculations are illustrated in tables (3), and (4).The variation between the inter-planar spacing d (A°) and $\sin^2\psi$ for all measured specimens is illustrated in figure (5). The gradients of these lines (slope of line, m) are calculated by the computer software of (XRD-6000) device to determine the value and type of residual stress. When the inter-planar spacing d (A°) increases with increased ($\sin^2\psi$), then the specimen has a tensile residual stress. The decrease of inter- planar spacing d (A°) with the change of the ($\sin^2\psi$), means that the specimen has a compressive residual stresses with respect to the direction of test.

The behavior of the surface residual stress in rolling, and transverse direction due to the increase of cold rolling reduction ratio is depicted in figure (8). It was found that at 10 % reduction in thickness, a compressive residual stress is generated in both (rolling, and transverse) direction due to small amount of cold work. In rolling direction, the type of residual stress transfers from compressive to tensile stresses, when the amount of reduction ratio exceeds 10 % by cold rolling process for 2024 aluminum alloy. The value of tensile residual stress increases with increased reduction percentage until 50 % cold work. When exceeding the (50%) reduction in thickness, the residual stress decreases by about (48%) at 60% reduction ratio.

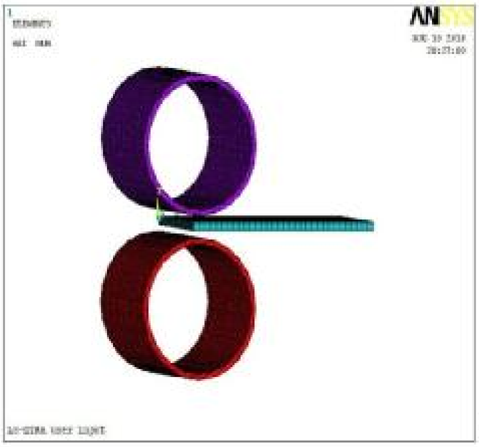
A compressive residual stress was observed in transverse direction, and the value of this residual stress increases until 50 % reduction ratio. There is a slight decrease in residual stress when the amount of reduction ratio increases from 50 to 60 %. From this behavior, it is noted that the increase of tensile residual stress in rolling direction led to decrease the value of compressive residual stress in transverse direction. Also, the increase of percentage reduction ratio by cold rolling process up to 50 % leads to decreased residual stress due to the increase of the plastic deformation.

The behaviors mentioned above are due to the small amount of reduction, the strain in material thickness is greater than strain in longitudinal direction, i.e., the compressive stresses dominated over the tensile stresses during metal deformation by cold rolling. But, when the reduction ratio increases, the tensile stresses become dominant (the material thickness decreases, whereas the material length increases with rolling direction.

The cold rolling process was successfully simulated using ANSYS LS-DYNA software, see figures (9), and (10). Figures (11), and (12) indicate the numerical results of stress state on the workpiece surface in both rolling and transverse direction. The residual stresses can be determined by knowing the amount of stresses remained after removing all rolling load in each reduction ratio.

Figure (8) illustrates the experimental and numerical surface residual stresses behavior. It is found that a good agreement results for the residual stresses state in rolling direction, in terms of the comparison based on the aggregate behavior for these stresses or the values range, and types of these stresses.In transverse direction, the 10 %, and 20 % reduction ratios achieved a good agreement behavior with the experimental results, while the reduction ratios from 30 % to 60 % showed tensile residual stresses in contrast to the measured values in practice that exhibited compressive residual stresses. However, a good agreement was found in terms of the overall behavior during all reduction ratios.

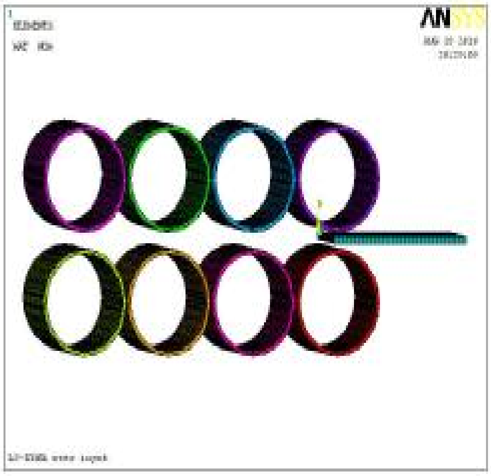
It is likely that the reason for this discrepancy between the experimental and numerical values is due to the residual stresses that affect the crystal structure of the material atoms (the deformation in the inter-planar spacing *d* (Å)). Thus, the measurement of these stresses depends on the amount of change of these distances and the direction of change. In computer simulation, the residual stresses are measured at a node on the workpiece surface, while the affected node by stresses cannot be compared with influenced atom by such stresses in real materials.



(A) R=10%

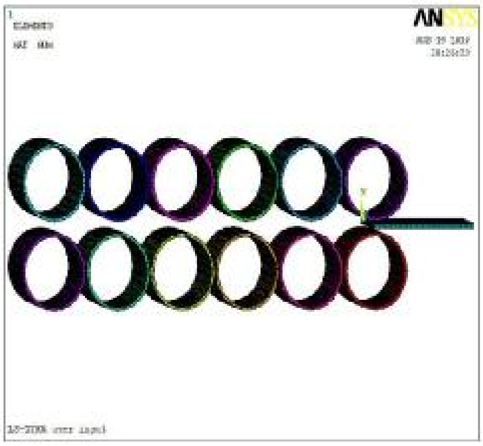
(B) R=20%

(C) R=30%



(D) R=40%

(E) R=50%



(F) R=60%

Figure (7) A, B, C, D, E, F, Simulation of cold rolling process, % reduction of thickness.

Table (3) Results of XRD for specimens measured in rolling direction.

Reduction Percentage R %	Modulus of Elasticity *E* (GPa)	Tilt angle (ψ) degrees	Diffraction angle (2θ), degrees	Inter-Planar Spacing *d* (A°)	Gradient of the *d* vs. $\sin^2\psi$, X 10^{-10}	Residual Stress σ_ϕ(MPa)
0	72.8	0	157.229	1.167831565	0.0000139	0.654
		15	157.171	1.167950756		
		30	157.226	1.167837722		
		45	157.199	1.167893175		
10	73.4	0	157.006	1.168291605	-0.00045	-21.041
		15	157.065	1.168169425		
		30	157.086	1.168126018		
		45	157.137	1.168020777		
20	73.8	0	157.149	1.167996051	0.00022	10.504
		15	157.178	1.167936354		
		30	157.124	1.168047579		
		45	157.108	1.168080589		
30	74	0	157.156	1.167981634	0.00054	25.083
		15	157.157	1.167979575		
		30	157.090	1.168117754		
		45	157.029	1.168243935		
40	74	0	157.307	1.167671783	0.0009	41.952
		15	157.269	1.167749552		
		30	157.182	1.167928126		
		45	157.078	1.168142549		
50	74.2	0	157.313	1.167659516	0.00121	56.841
		15	157.247	1.167794640		
		30	157.130	1.168035207		
		45	156.997	1.168310272		
60	74.4	0	157.274	1.167739312	0.00063	29.292
		15	157.228	1.167833617		
		30	157.154	1.167985753		
		45	157.110	1.168076462		

Table (4) Results of XRD for specimens measured in transverse direction.

Reduction Percentage R %	Modulus of Elasticity E (GPa)	Tilt angle (ψ) degrees	Diffraction angle (2θ), degrees	Inter- Planar Spacing d (A°)	Gradient of the d vs. $\sin^2\psi$, X 10^{-10}	Residual Stress σ_ϕ (MPa)
0	72.8	0	157.188	1.167915787	0.0000153	0.717
		15	157.227	1.167835669		
		30	157.206	1.167878792		
		45	157.200	1.167891120		
10	73.4	0	156.980	1.168345554	-0.0007	-32.920
		15	157.040	1.168221155		
		30	157.132	1.168031084		
		45	157.166	1.167961046		
20	73.8	0	157.034	1.168233579	-0.00046	-21.796
		15	157.083	1.168132216		
		30	157.127	1.168041393		
		45	157.162	1.167969280		
30	74	0	157.107	1.168082653	-0.00022	-10.372
		15	157.151	1.167991932		
		30	157.166	1.167961046		
		45	157.175	1.167942526		
40	74	0	157.150	1.167993991	-0.00008	-3.534
		15	157.164	1.167965163		
		30	157.187	1.167917843		
		45	157.171	1.167950756		
50	74.2	0	157.102	1.168092974	-0.00005	-2.064
		15	157.127	1.168041393		
		30	157.120	1.168055830		
		45	157.122	1.168051704		
60	74.4	0	157.130	1.168035207	-0.00016	-7.692
		15	157.103	1.168090910		
		30	157.139	1.168016655		
		45	157.159	1.167975457		

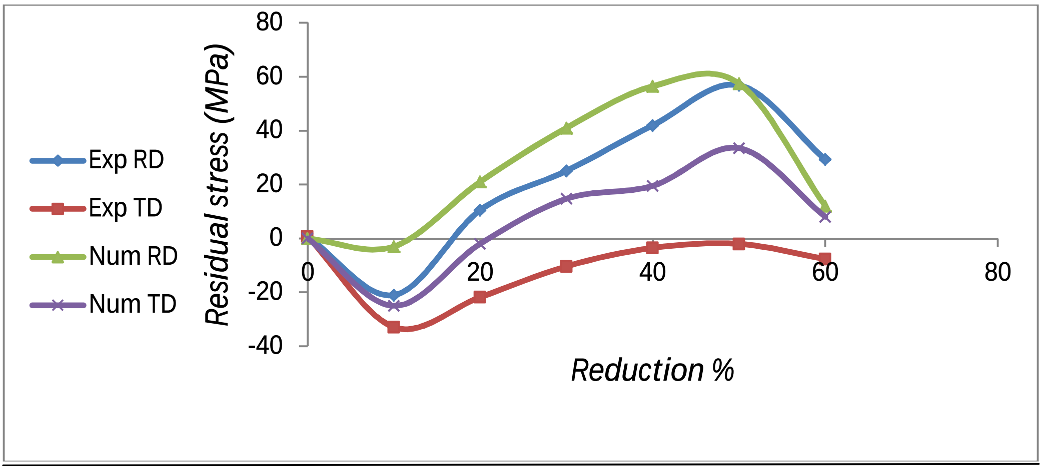


Figure (8) Numerical and experimental behavior of the effect of different reduction ratios on the residual stresses state during cold rolling process.

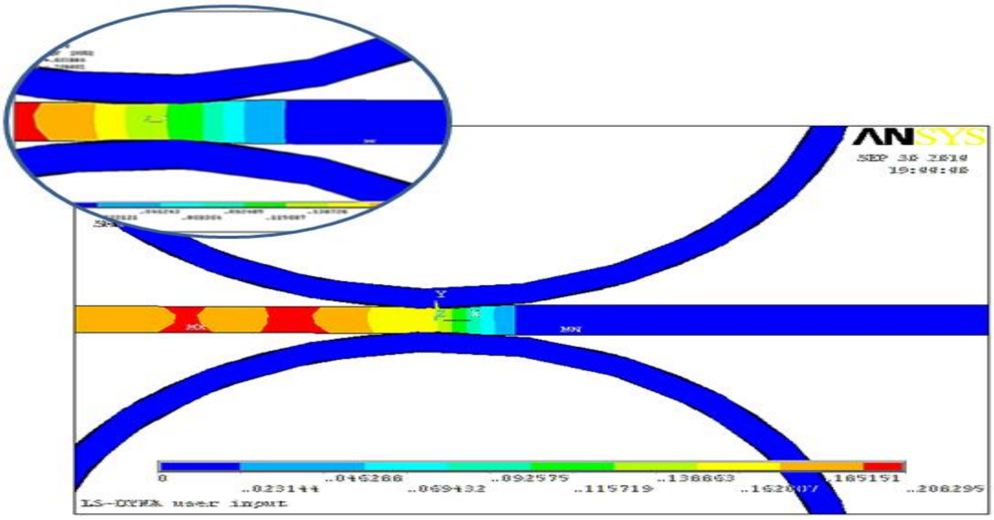
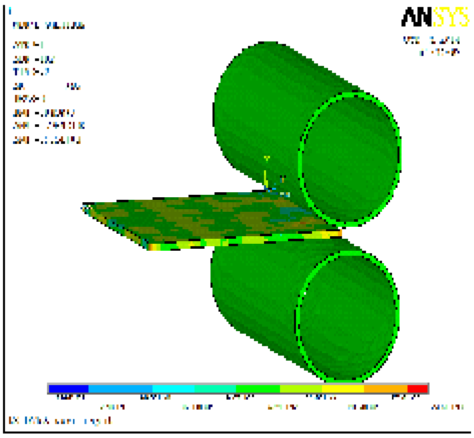
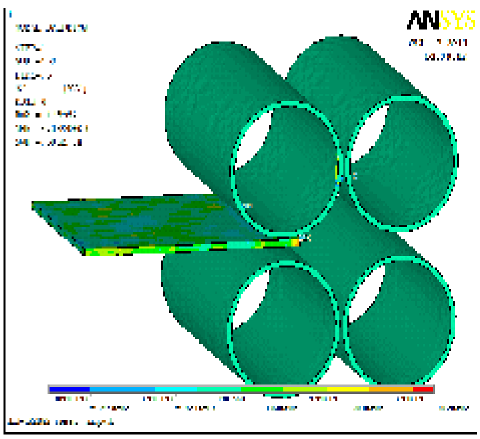


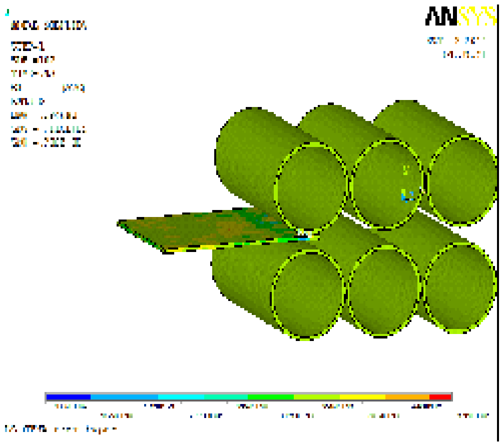
Figure (9) Reduction zone in simulation of cold rolling process.



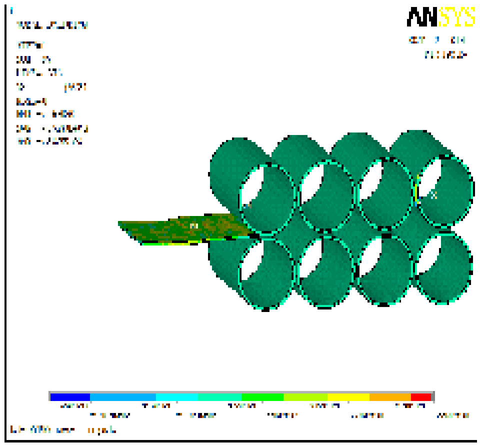
(A) R=10%



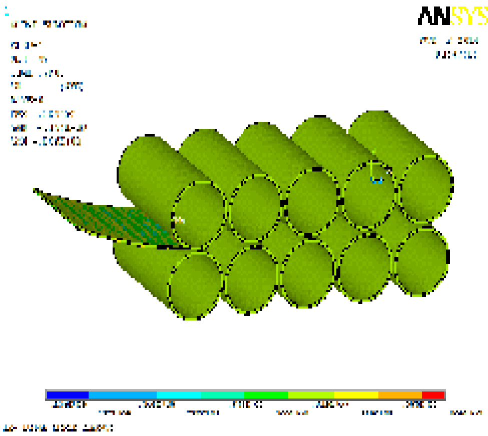
(B) R=20%



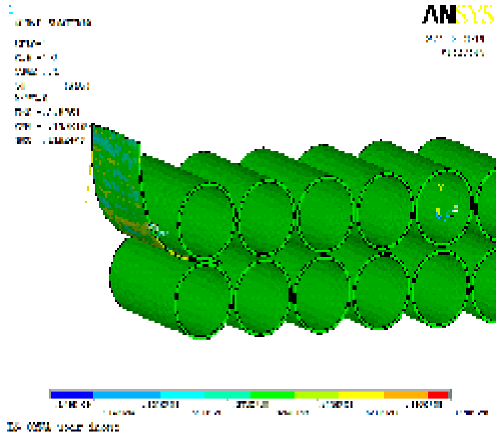
(C) R=30%



(D) R=40%

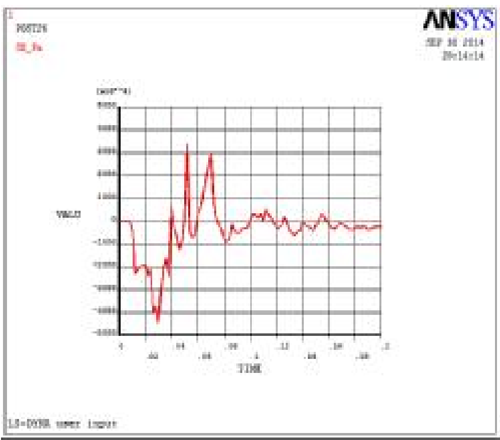


(E) R=50%

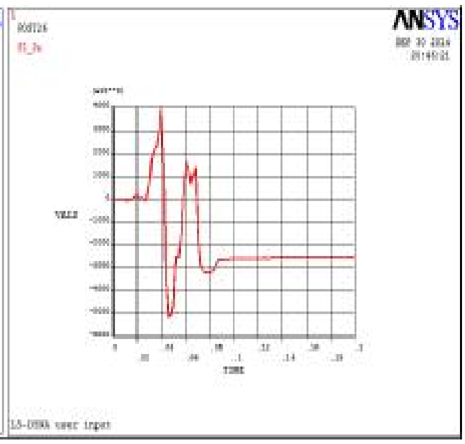


(F) R=60%

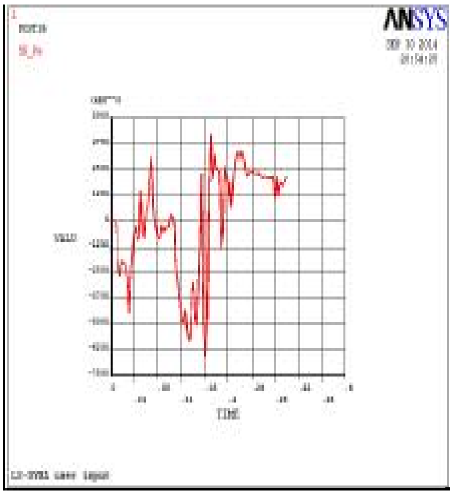
Figure (10) A, B, C, D, E, F, Simulation results of cold rolling process, % reduction of thickness.



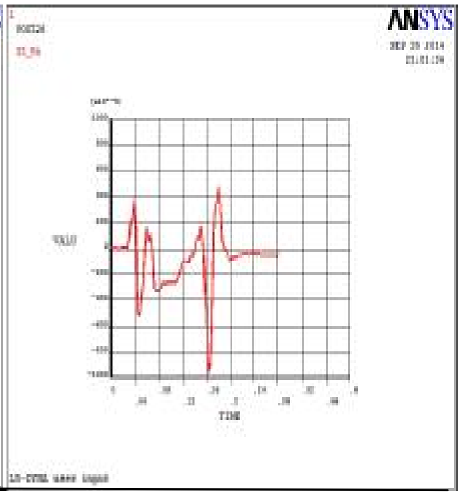
RD 10%



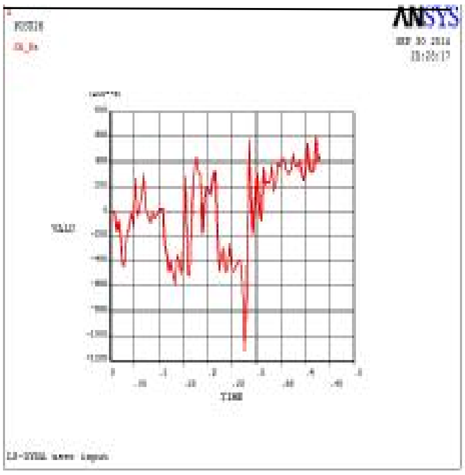
TD 10 %



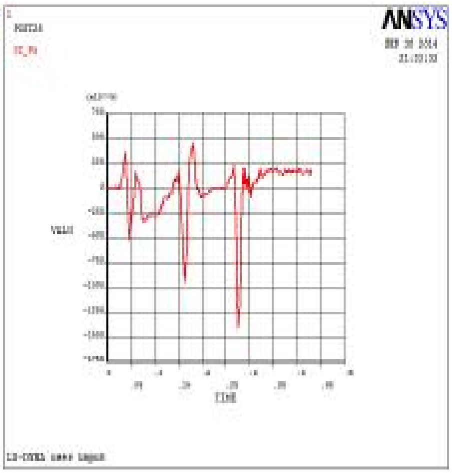
RD 20%



TD 20%

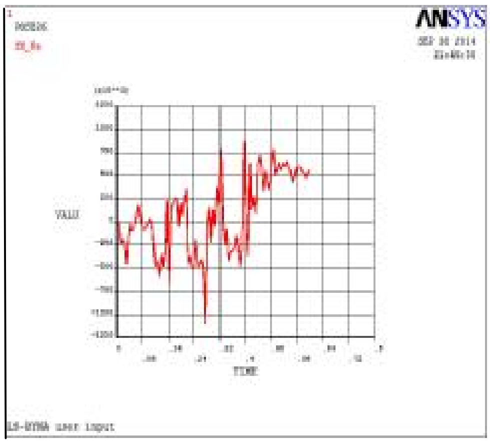


RD 30%

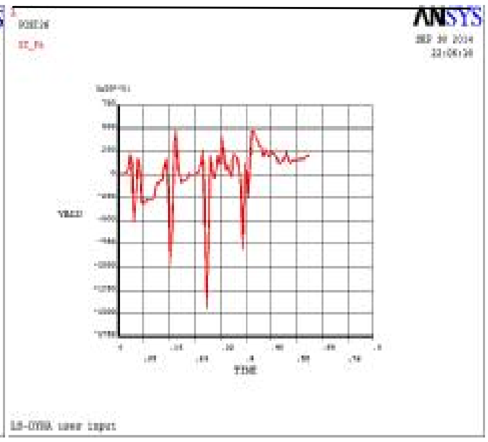


TD 30 %

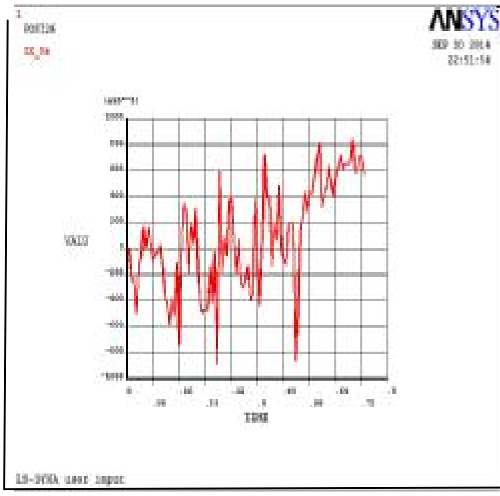
Figure (11) Numerical surface residual stress (Pa) results at 10, 20, and 30 % reduction ratios.



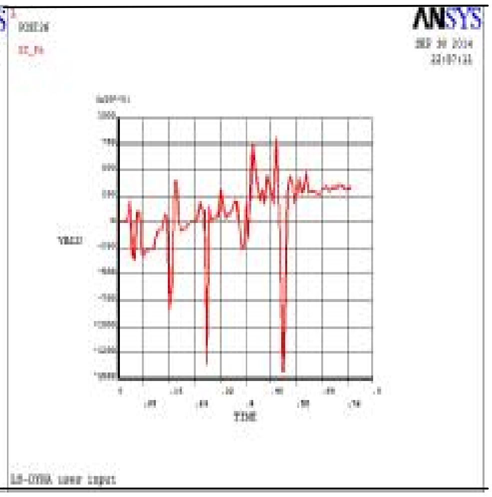
RD 40%



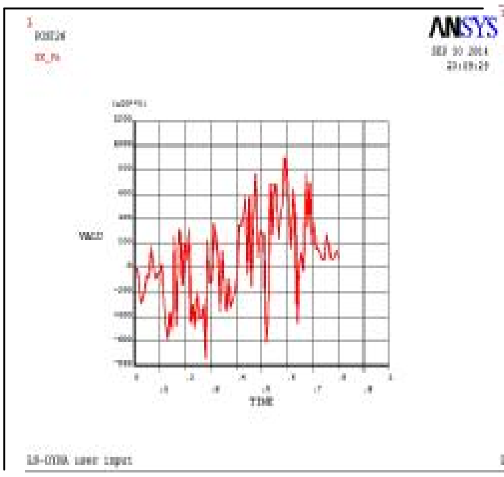
TD 40 %



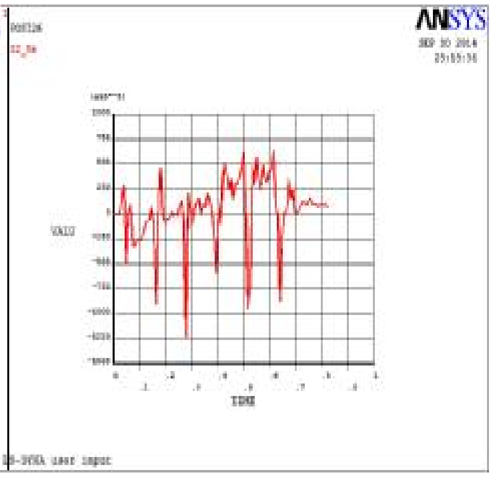
RD 50%



TD 50 %



RD 60%



TD 60 %

Figure (12) Numerical surface residual stress (Pa) results at 40, 50, and 60 % reduction ratios.

CONCLUSIONS

i) The XRD results showed that the reduction over the range (10-50%) induced compressive surface residual stress, which increases with the amount of cold work in the transverse direction. A slight decrease in the residual stresses was observed at 60 % reduction.

ii) Only 10 % reduction resulted in compressive surface residual stress in the rolling direction, while reduction of over 20 % until 60 % caused transferring this stress to tensile residual stresses.

iii) A good agreement was found between the experimental and numerical results using ANSYS LS-DYNA software for surface residual stresses behavior.

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