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Study on Effects of Mechanical Properties of Aluminum Alloys on Residual Stresses Distribution in Cold Rolling Process on the Cylindrical Specimen Using FEM Simulation

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ABSTRACT

Through this paper the cold rolling process on cylindrical aluminum specimen with elastic-plastic material behavior simulated in ABAQUS FEM software. Then residual stresses distributions have been studied. This aluminum specimen uses in aviation industry in helicopters and hovercrafts to connect the propeller to rotor.

Study on this kind of specimen in aviation industry is so important because they are often exposed to dynamic loads and failure caused by fatigue life. If tensile dynamic stresses increase, the possibility of failure will increase and it causes loss of human life and money. Distribution of residual stresses has an effect on this kind of failure. Cold rolling operation were developed compressive residual stress in the surface of the specimen and improved the fatigue life endurance limit significantly. Study on effects of mechanical properties of aluminum alloys as one of the rolling process parameters on residual stresses distribution, will be so useful and helpful for selecting the best alloy in manufacturing process.

KEYWORDS: Cold Rolling, Residual Stress Distribution, Aluminum Alloys, FEM Simulation.

1. INTRODUCTION

Studying on fatigue life of some specimens is so important because it affects on human life. Study on the progression of the aviation industry is so helpful because the aviation industry has an important role to provide a good life for people. Producing some important specimen is required for repairing and maintenance of helicopters and hovercrafts because they are at risk of failure of fatigue life after passing some times of their lives. This can cause loss of human life and money. Researchers try to find ways for preventing from failure of these kinds of specimens. Fig.1 shows an important specimen that uses in helicopters and hovercrafts as a connector between propeller and rotor. This cylindrical aluminum specimen is always at risk of tensile stress and failure.

Fig. 1. Aluminum cylindrical specimen, the usage and measuring residual stress on its surface

The main reason of fatigue life failure is tensile residual stresses. Most of manufacturing process cause residual stresses in industrial parts. The effects of these residual stresses can be useful or harmful according to the type of stress, size and distribution of stresses. These are the effective parameters on mechanical behavior of parts such as fatigue life and resistance to corrosion. Residual stresses in a body are those which are not necessary to maintain equilibrium between the body and its environment. They may be categorized by cause (e.g. thermal or elastic mismatch), by the scale over which they self-equilibrate, or according to the method by which they are measured. The simplest definition of residual stresses is as follows: stresses that remain within a part after it has been deformed and all external forces have been removed. More specifically, the deformation must be non-uniform across the material cross-section in order to give rise to residual stresses. The deformation can result from cyclic loads or forming operations. It can be very detrimental to the performance of a material or the life of a component.

Tensile loading can cause tensile residual stresses that reduce fatigue life and help to crack growth and fracture. When there is residual stress in a specimen, mechanical resistance of the specimen will reduce and the surface of specimen will be brittle. Compressive residual stress is against tensile residual stress and it is so helpful for specimens.

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For example the specimen shows in fig.1 is always under tensile loads and these loads cause tensile residual stress and after passing times, tensile residual stress affects on fatigue life and it may cause sudden events and loss of human life or money.

Cold rolling operation were developed compressive residual stress in the surface of the specimen and improved the fatigue life endurance limit significantly. Distribution of residual stresses is affected by changes in cold rolling process parameters. This process improves fatigue life and mechanical properties and prevents from failure. The specimen material is one of the most important process parameters that affect on the final results.

An aluminum cylindrical specimen was studied in this paper. Aluminum is a chemical element in the boron group with symbol Al and atomic number 13. It is silvery white, and it is not soluble in water under normal circumstances. Aluminum is the third most abundant element (after oxygen and silicon), and the most abundant metal, in the Earth's crust. It makes up about 8% by weight of the Earth's solid surface. Aluminum is a relatively soft, durable, lightweight, ductile and malleable metal with appearance ranging from silvery to dull gray, depending on the surface roughness. It is nonmagnetic and does not easily ignite.

Through this paper, the FEM simulation of cold rolling process on the surface of an aluminum cylindrical specimen in ABAQUS FEM software has been done to study on effects of changing the mechanical properties of aluminum alloys as one of the cold rolling process parameters on distribution and size of compressive residual stress and depth of it. The results can help to produce a high quality specimen. The mechanical properties of 3 aluminum alloys of series 2XXX such as 2024T4, 2014T4 and 2014T6 were studied. This series of aluminum alloys uses in aviation industry.

1-2: Literature review

A: Study on residual stress distribution and its effects on fatigue life:

In 1996, T. Yentzer [1] analyzed the cold rolling operation and studied on a cold rolled specimen. He found that, the cold rolling process can improve the mechanical properties, dimensional accuracy and surface quality in parts. Creation of compressive residual stresses reduces the tensile residual stresses and increase fatigue life.

In 2011, M. De Giorgi [2] presented an experimental analysis to assess the residual stress evolution in cold-rolled steels. His study aims to establish the influence of a yield strength gradient on the increase of residual stress in a hardened material when it is subject to a bending fatigue load. Rectangular specimens have been obtained from cold-rolled plates and having different hardening levels, were analyzed and the residual stress evolution, due to three-point bending load application, was evaluated with respect to the initial value. The comparison between tests on different specimens showed that the yield strength gradient plays an important role in the residual stress field evolution. He found that the residual stresses on the surface of a cold rolled specimen are compressive residual stresses. Cold rolled specimens are more hardened and have greater yield stress.

In 2008, M. Ranjbar et al. [3] found that if an operation decrease tensile residual stresses, improves fatigue life. These operations such as shot peening and cold rolling can create compressive residual stresses and improve fatigue life. He had been done an experimental analysis on a cylindrical specimen. The material was aluminum alloy 2024T4. They measured residual stresses on the surface of the specimen.

B: FEM simulation of cold rolling process in ABAQUS FEM software:

In 1998 B. Wang et al. [4] had been done a FEM simulation to investigate the influence of the roll speed on the rolling process. Using a commercial FEM code, ABAQUS, a number of cases had been studied. The angular velocity of the rigid rolls ranged from 30 to 480 revolutions per minute (r.p.m.) and the initial feeding speed of the plate was kept constant, thus causing a slipping between the plate and the roll surfaces. The results indicate that for an elastic-plastic hardening plate under the same thickness reduction, a higher rotating speed of rolls will help to reduce the roll separating force and the maximum value of the residual stress in the plate.

In 2012 K. Devarajan et al. [5] had been done a FEM simulation to investigate the influence of the rolling parameters on rolling process Using commercial FEM software, ABAQUS, a number of cases had been studied. A two-dimensional Elastic-plastic finite element model to simulate the cold rolling of thick strip with different roll angular velocity and roll diameter models has been described. this paper improves Wangs project. They studied on more process parameters such as roller diameters, velocity of rolling, friction coefficient and specimen dimension. They found that experimental results are similar to FEM simulation results.

2- FEM simulation of cold rolling process

A 2-dimensional analysis was carried out in this study on an aluminum cylindrical specimen with the physical parameters similar to the base specimen at first. Through this paper the cold rolling process on cylindrical aluminum specimen with elastic-plastic material behavior simulated in ABAQUS FEM software 6.10. The cold rolling process parameters such as roller diameter and specimen diameter were measured from the base specimen.

For the first simulation the diameter of roller is 60 mm and is modeled as rigid, the specimen diameter is 200 mm and quantity of involvement between roll and specimen is 0.08 mm. Fig.2 shows a FEM model of process in ABAQUS FEM software and fig.3 shows schematically the meshed model for specimen with 8955 CPE4R elements with plain strain property and is simulated using a four node quadrilateral and 2D deformed elements. The elements at the surface of the specimen are so smaller than the middle elements to increase the speed and accuracy of solving.

In this simulation, contacting between roller surface and specimen surface is surface to surface and solving method is dynamic explicit. Coulomb friction is assumed originally between the roller surface and the specimen surface, with a coefficient friction of 0.05. The important role of the frictional force in the rolling process has been extensively studied though not fully understood yet.

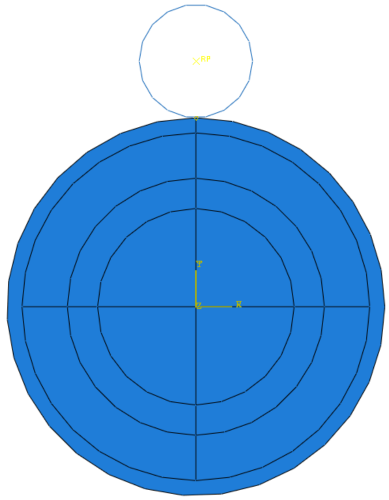

Fig. 2. FEM modeling of cold rolling process

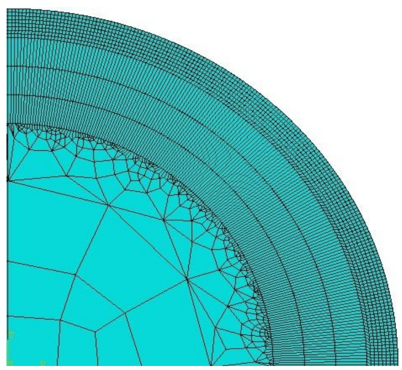

Fig. 3. Meshing the specimen

3- Material definition

Through this paper, aluminum alloys 2024T4, 2014T4 and 2014T6 have been used in order to study on effects of changing mechanical properties on the results of simulations. The mechanical properties of these alloys were obtained from tensile test in a laboratory.

True stress-strain curve was obtained for each alloy. The differences between these alloys are in yield stress and their plastic behavior. In this simulation an isotropic elastic-plastic linear hardening material modeling is used. This model is so similar to mechanical behavior of alloys. Fig.4, fig.5 and fig.6 show true and engineering stress-strain aluminum alloy material behavior. True stress-strain behavior can be approximated to linear elastic-plastic behavior. In figures, solid line curve is true stress-strain curve and dashed line curve is the elastic-plastic linear hardening curve. Fig.7 shows all 3 curves in one. The property of these alloys shows in table1, table2 and table3 that σ_y is yield stress, σ_u is ultimate stress and $\varepsilon_{p\text{-}y}$ is plastic strain in yield stress and $\varepsilon_{p\text{-}2}$ is plastic strain in ultimate stress. Young's modulus (E) is 70 GPa, Poisson ratio is 0.33 and density is 2700 $kg/_{m^3}$ for all alloys.

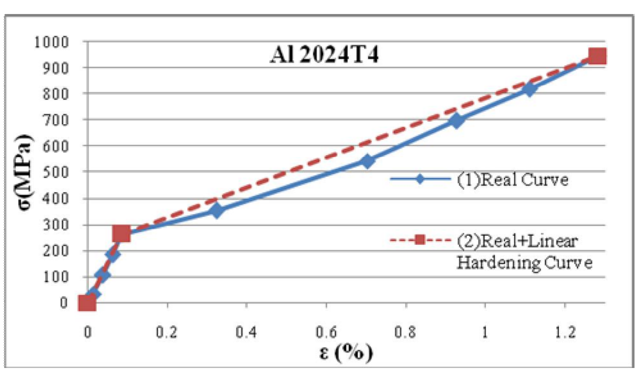

Fig. 4. True stress-strain curve for AL-2024T4 alloy

Table 1. Mechanical properties of AL-2024T4 alloy

Material	Aluminum 2024-T4
Elastic	
Density	$2700 kg/m^3$
E	70 Gpa
ν	0.33
Plastic	
σ_y	262.8 Mpa
ε_{p-y}	0
σ_u	945.2 Mpa
ε_{p-u}	1.28

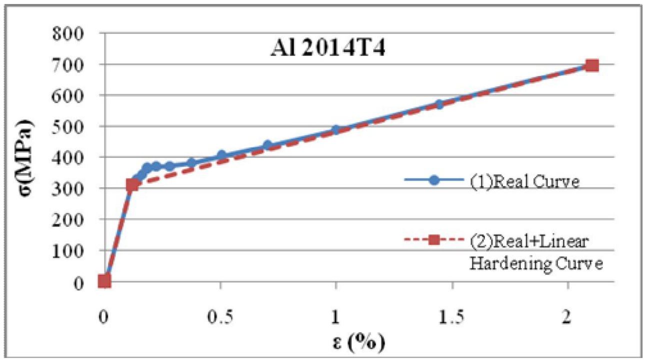

Fig. 5. True stress-strain curve for AL-2014T4 alloy

Table 2. Mechanical properties of AL-2014T4 alloy

Material	Aluminum 2014-T4
Elastic	
Density	$2700 kg/m^3$
E	70 Gpa
ν	0.33
Plastic	
σ_y	311 Mpa
ε_{p-y}	0
σ_u	696.8 Mpa
ε_{p-u}	2

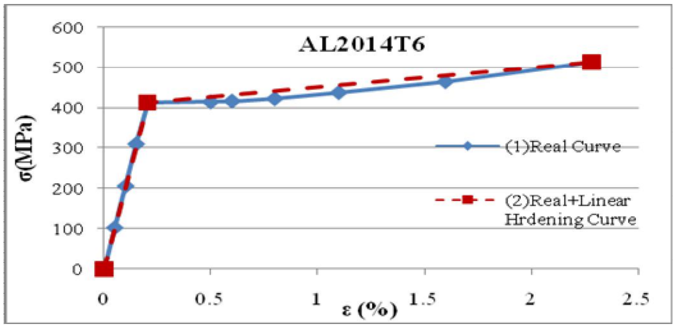

Table 3. Mechanical properties of AL-2014T6 alloy

Material	Aluminum 2014-T6
Elastic	
Density	$2700 kg/m^3$
E	70 Gpa
ν	0.33
Plastic	
σ_y	414 Mpa
ε_{p-y}	0
σ_u	514 Mpa
ε_{p-u}	2.08

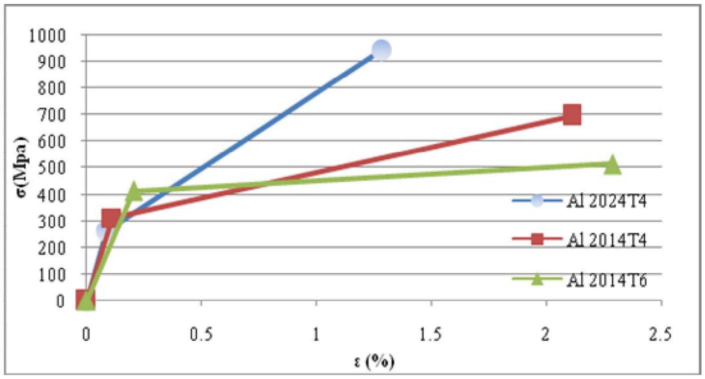

Fig. 7. True elastic-plastic linear hardening stress-strain curve for all alloys

4-Boundary conditions

There are 3 steps for analyzing the cylindrical cold rolling process:

Step 1:

The specimen rotates clockwise and it does not have any movement along the horizontal and vertical coordinate axes and it has predefined velocity to prevent from sudden impacts.

Roller rotates counter clockwise and it does not have any movement along the horizontal coordinate axes but it moves with constant speed of 0.08 mm/s for a second in (-y) axis.

Step 2:

The specimen and roller are constant in their places and only rotate. It will continue until a complete cycle would have been done.

Step 3:

This is similar to step 1, however the roller moves with constant speed of 0.08 mm/s for a second in (+y) axis to prevent from local stresses.

In this paper, all of process parameter such as roller diameter, specimen diameter, friction coefficient and quantity of involvement between roller and specimen are constant. The only variable is the material of specimen. The mechanical properties such as yield stress and ultimate stress is used in this paper. There are 3 aluminum alloys that the combination of them will make 9 different alloys.

According table 4, each yield stress can have 3 ultimate stresses that make 3 different alloys and 9 simulations is done. Table 4 shows the parameters of cold rolling process.

Table 4. Parameters that used in simulation

Process parameters	**No. of variables**		
	1	**2**	**3**
Roller diameter(mm)	60	60	60
Specimen diameter(mm)	200	200	200
Quantity of involvement(mm)	0.08	0.08	0.08
Yield stress (MPa)	262.8	311	414
Ultimate stress (MPa)	945.2	696.8	514
Plastic strain (mm)	1.19	2	2.08

5- Analysis of results

According to column 2 of table 4, simulation was done. Then a cylindrical coordinate system was defined to see S_{22} stress contour (In cylindrical coordinate system, R is S_{11} or stress along the radios, ϴ is S_{22} or stress along the surface). Fig.8 shows surface residual stress distribution after analyzing by ABAQUS FEM software.

The residual stresses in the surface of specimen are compressive and these compressive residual stresses continue along the path to the specific depth. Then residual stresses become tensile and in the center of specimen the value of residual stress is zero. Fig.9 shows the changes of residual stresses along the path.

According to fig.9, the maximum surface compressive residual stress (a) and the value of depth of residual stress (b), are 2 values as the results of simulation that changing the process parameters cause changing in these values.

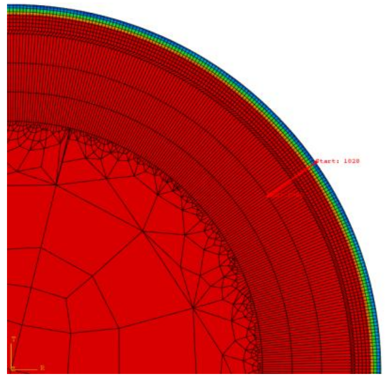

Fig. 8. Surface residual stress contour and definition a path in order to draw a curve to shows the changes of residual stress along that path

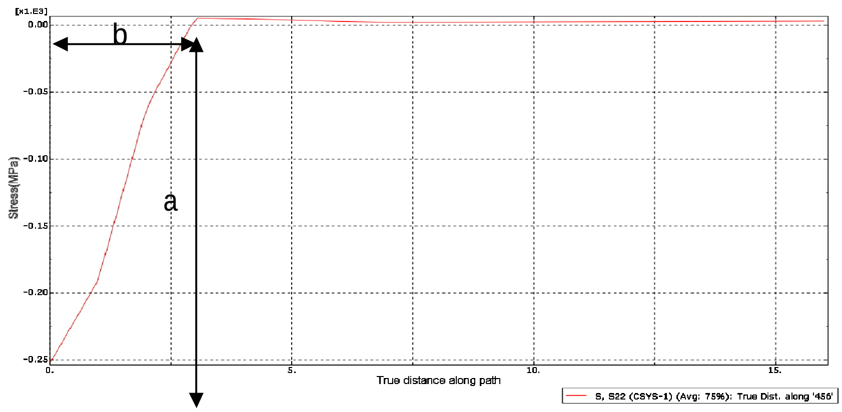

Fig. 9. Changes in residual stresses along the path that showed in fig.8

There are 3 paths like the path in fig.8 to prevent from localized stresses and the effects of start and end of contact. The ultimate (a) and (b) values are the average of values of these paths. For example in the first simulation the average of (a) and (b) are equal to: a=-258 MPa and b=2.88 mm from the surface of specimen.

The result of this paper compares with a result of an experimental project [3] to verify the results of simulation. Table 5 shows this comparison. Ranjbar uses the rolling parameters as shown in table 5. The average error for Ranjbars experimental test and this simulation is equal to 2.8%. It is an ideal result for this simulation.

Table 5. Comparison between results of an experimental test and results of this paper

	Parameters	**NO.1**
Rolling parameters	Roller Diameter(mm)	50
	Specimen Diameter (mm)	122
	Quantity of Involvement (mm)	0.075
	Yield Stress (MPa)	414
	Ultimate Stress (MPa)	514
Ranjbar Experimental test result	Residual Stress (MPa)	-348.48
Simulation result	Residual Stress (MPa)	-358.26

Table 6 shows the final results of simulation. According table 6, 9 simulations have been done and the values (a) and (b) were obtained from these simulations. Table 6 shows 9 simulations, that the values of residual stress (a) and depth of it (b) have been shown in this table. These values have so effects on fatigue life. According to table 6, some results have been extracted.

Table 6. The results of simulations

NO.	**Roller diameter (mm)**	**Specimen diameter (mm)**	**quantity of involvement(mm)**	**Yield stress (MPa)**	**Ultimate stress (MPa)**	**Residual stress (MPa)**	**Depth of it (mm)**
1	200	60	0.08	262	945.22	-258.43	3.53
2	200	60	0.08	262	696.8	-259.96	3.00
3	200	60	0.08	262	514	-262.80	2.96
4	200	60	0.08	311	945.22	-226.17	2.80
5	200	60	0.08	311	696.8	-231.276	2.66
6	200	60	0.08	311	514	-246.81	2.85
7	200	60	0.08	414	945.22	-128.50	2.40
8	200	60	0.08	414	696.8	-153.68	2.25
9	200	60	0.08	414	514	-142.04	2.26

- According to sections 1, 4, 7 in table 6, in constant condition, if the yield stress decreases, the value of compressive residual stress and depth of it will increase. The results have been shown in fig.10 for residual stress and fig.11 for depth of residual stress. Sections 2, 5, 8 and sections 3, 6, 9 in table 6 also show this result.
- According to results of simulations and sections 1, 2, 3 or sections 4, 5, 6 or sections 7, 8, 9, the ultimate stress has no constant effect on residual stress and depth of it. This parameter is so dependent to the geometry of the modeling.

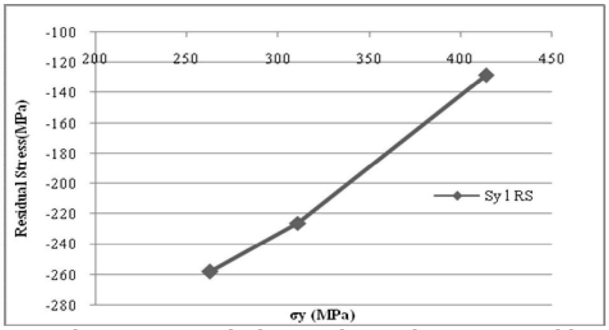

Fig. 10. Changing in residual stress due to changing in yield stress

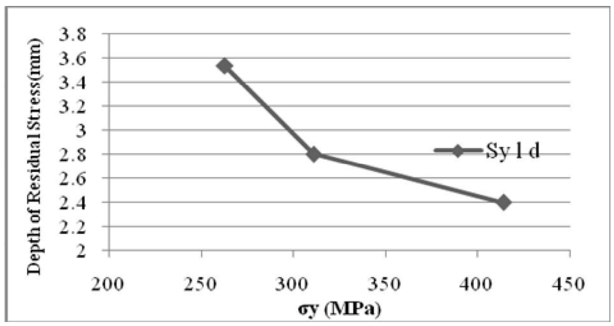

Fig. 11. Changing in depth of residual stress due to changing in yield stress

6- Conclusions and discussion

In this paper, the FEM simulations of cold rolling on aluminum cylindrical specimen were done. This specimen is so important and study on this specimen can reduce the failure that helps to reduce loss of human life and money. Simulations show that the residual stresses in the surface of specimen are compressive and these compressive residual stresses continue along the path to the specific depth. Then residual stresses become tensile and in the center of specimen the value of residual stress is zero. These compressive residual stresses are useful and decrease tensile stresses in order to increase fatigue life. Some experimental residual stresses were done and results of FEM analysis were compared to experimental data and good agreements were found.

In this paper the effects of mechanical properties of aluminum alloys as the process parameters on residual stress and depth of it were studied and these results were obtained:

1: If the yield stress decreases, the value of compressive residual stress and depth of it will increase.

2: Increasing or decreasing the ultimate stress has no constant effect on residual stress and depth of it.

According to the results of this paper, for producing this specimen, the material properties can be found from FEM simulation. Comparison between simulations results and the real residual stresses that have gotten from experimental tests help us to find the material properties of specimen.

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