# Simulation and Research on Deep Rolling Process Parameters

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**Abstract:** Deep rolling is a kind of mechanical surface treatments that can improve surface quality, dimensional accuracy and mechanical properties of the parts. Compressive residual stresses generated by the process reduce the tensile stresses during loading into the workpiece. The distribution of residual stress induced by deep rolling can be influenced by rolling parameters; such as overlap of the rolling tracks, friction coefficient between roller and target plate, deep rolling force and deep rolling mechanical tools. In the present research, the effects of these parameters are studied by finite-element simulations. The results indicate that: (I) increasing overlap results in increasing magnitude of the maximum residual stress. (II) Increase in the coefficient of friction results in decrease in the maximum residual stress. However, for coefficient of friction more than 0.1 the effect of friction may lead to contraction. (III) Increase in the force intensity results in increase in the maximum residual stress. (IV) The deep rolling with mechanical tools and spring force provides a higher residual stress than the roller with constant force mode.

**Keywords:** Deep Rolling, Finite Element Method, Residual Stress

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## 1 INTRODUCTION

It is well known that mechanical surface treatments, such as deep rolling, shot peening and laser shock peening, can significantly improve the fatigue behavior of highly-stressed metallic components. Deep rolling (DR) is particularly attractive since it is possible to generate, near the surface, deep compressive residual stresses and works hardened layers while retaining a relatively smooth surface finish. Previous research has shown that the best method to increase the damage tolerance is mechanical strain hardening of the surface layer. This can be achieved by deep rolling.
Deep rolling belongs to a group of manufacturing technologies, which are used for the mechanical strain hardening of the surface layer. With regards to the component requirements, deep rolling distinguishes itself by three substantial advantages from all the other mechanical strain hardening methods. The first advantage is that the highest and the deepest compressive residual state of stress can be induced to the component surface layer. The second advantage is a high strain hardening, especially deep inside the surface layer. The third major advantage of deep rolling is the improvement of the surface quality, especially in comparison to the shot-peening process.
Furthermore, in other examinations, a lifetime increase in comparison to shot-peened components could be observed. The results show that significant lifetime increase and decreased crack propagation can be achieved by the deep rolling process in both cases. In the present work, the application of the Finite Element Analysis (FEM) was proposed in order to determine model responses for different process parameters as an effective and cost reducing alternative to an experimental setup. The FEM enables the prediction of the material behaviour for the specified loading conditions, thus, the behavior of Ti-6Al-4V was modelled in ABAQUS.

## 2 LITERATURE REVIEW

The resistance of the material against fatigue can be increased by surface treatment techniques such as cold deep rolling (CDR) [1], water peening [2], shot peening [3], low plasticity burnishing (LPB) [4], laser shock peening (LSP) [5], ultrasonic shot peening (USP) [6], and ultrasonic impact treatment [7]. Fatigue cracking usually originates from the surface of parts undergoing cyclic loading. Surface roughness, residual stress, and near surface microstructure are believed to be the driving factors that control fatigue crack initiation and propagation and hence control the fatigue life of parts [8]. One of the most well known benefits of deep rolling as compared to other surface treatments is the great depth of the affected layer exhibiting alterations of the work hardening state (usually work hardening) and compressive residual stresses [1].
Another benefit is the generation of glossy surfaces with low roughness as compared to treatments like shot peening. These three effects can significantly enhance the mechanical behaviour of metallic materials, especially under cyclic fatigue loading.
Deep rolling is a surface treatment technique which is performed using roller type instruments to produce a surface compressive residual stress to improve the fatigue resistance of materials and engineering components [1]. The deep rolling technique is widely used in automobile industry, in turbo aircraft engine and turbine blades [1]. The effects of deep rolling on fatigue behaviour have been thoroughly investigated and the influence of notches and material hardness on fatigue strength enhancement of deep rolled components became clear [1]. Even deep rolling was already used in combination with thermal surface treatments such as induction hardening, especially in the automotive industry [1].
Nalla and Altenberger investigated effect of residual stress caused by deep rolling to suppress the crack formation [9]. Mader and Klocke investigated effect of residual stress of the deep rolling in compressor blades for turbo aircraft engines to suppress the crack formation resulting from alternating loads, as well as to stop or slow down crack growth [10]. Backer et. al. analyzed the deep rolling process on turbine blades using the FEM/BEM-Coupling and enables the computing of large scale models at low computational cost and high result accuracy and investigated effect of the deep rolling on suffer damages caused by the unavoidable impact of foreign objects.

## 3 FINITE ELEMENT MODELING

The finite element package ABAQUS 6.10 is used to simulate the procedure corresponding to the experimental operation. Due to its capability, the explicit dynamic algorithm is used to simulate the numerous impacts. Then a General static algorithm is combined to provide the resulting deformed shape as a spring-back analysis. Deep rolling is performed using a roller and by reciprocating motion. Experimental results in [11], [12] show that the influence of deep rolling reaches up to 500 μm. At the same time, the residual stress gradient in this depth is very high. In order to resolve such high gradients at sufficient accuracy, it is necessary to provide a very fine mesh in the surface layer. Figure 1 shows mesh density of such model.

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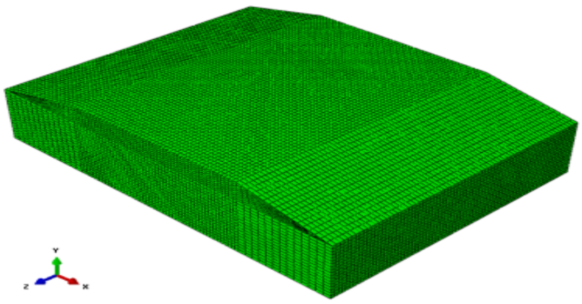

**Fig. 1** Model mesh requirements

The schematic model of deep rolling is illustrated in Fig. 5(b). The geometry of material target is assumed as deformable plate with 6mm width, 8mm length and 2 mm height dimensions. The boundary condition is fixed by encastre constraint. The meshes consist of 165888 Eight-node linear brick elements with reduced integration and hourglass control (C3D8R).
Simplicity roller is assumed to be a fully spherical discrete rigid with a mass positioned at its centre. Roller is meshed by using sweep technique and quad-dominated element shape. The mass scale factor was not used in this analysis. Several preliminary runs were conducted to establish the appropriate mesh design for Convergence test model. The presented results consist of two stages of model analysis. The first stage of analysis is the explicit dynamic of the model by using with the original mesh and configuration. The second stage is the analysis of static general, for considering spring back effect by importing part and original configuration from the output of the first stage.
The material used in this investigation is Ti-6Al-4V, where its chemical composition is listed in Table 1, and the material properties are given in Table 2. Also, the material model used in this study is Johnson-Cook model which is described by Eq. (1).

$$\sigma = (A + B\varepsilon^n)(1 + C \ln \dot{\varepsilon}^*)(1 - T^{*m}) \qquad (1)$$

where ε is the equivalent plastic strain, $\dot{\varepsilon}^* = \dot{\varepsilon} / \dot{\varepsilon}_0$ is the dimensionless plastic strain rate.
Moreover, $T^*$ is $T^* = (T - T_{room})/(T_{melt} - T_{room})$, '*A*', '*B*', '*C*', ''*n* and '*m*' are the material constants where '*A*' is the yield strength, '*B*' and '*n*' are the strain hardening coefficient and exponent, '*C*' is the strain rate coefficient and '*m*' is the thermal softening exponent. The material constants used in the Johnson-Cook equation are presented in Table 3.

**Table 1** Chemical composition of the Ti-6Al-4V material

| Elements | Al | C | Fe | H |
|---|---|---|---|---|
| (Wt.%) | 5.8 | 0.03 | 0.21 | 0.004 |
| Elements | N | O | V | Ti |
| (Wt.%) | 0.01 | 0.17 | 4.08 | Bal. |

**Table 2** Material properties used for simulating Ti-6A1-4V

| Density (kg/m³) | Elastic Modulas (Gpa) | Poissions Ratio | Thermal Expansion ($10^{-6}$)/ºC | Specific Heat (j/kgK) | Inelastic Heat Fraction |
|---|---|---|---|---|---|
| 4428 | 110 | 0.31 | 9 | 580 | 0.9 |

**Table 3** Johnson-cook material parameters for Ti-6A1-4V

| | A (Mpa) | B (Mpa) | n | C | m | $T_{melt}$ (ºC) |
|---|---|---|---|---|---|---|
| Ti-6Al-4V | 862 | 331 | 0.34 | 0.012 | 0.8 | 1605 |

## 4 MODEL VALIDATION

In order to verify the accuracy of the finite element simulation of deep rolling, the residual stress profile was compared with the experimentally obtained data from the literature [13] and is shown in Fig. 2.

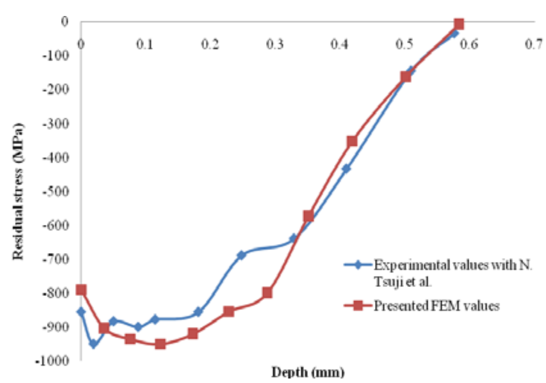


**Fig. 2** Modeling validation by comparison between the residual stress profiles and experimental by [1]

As the figure indicates, there is a satisfactory agreement between the experimental and numerical results, which provides some verification of the finite element model. The difference between the two graphs may be attributed to the lack of information in the experimental test conditions. Modeling conditions are given in Table 4 and Fig. 3.

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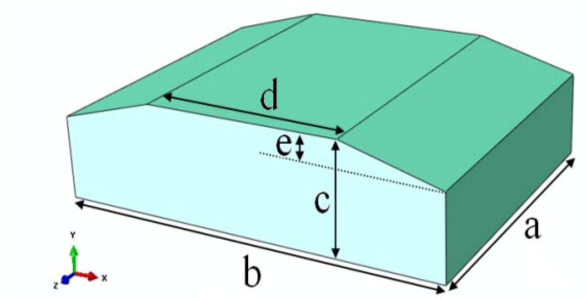



**Fig. 3** The model used for deep rolling

**Table 4** The dimensions of the roller and work piece shown in Fig. 3

| Roller | | Workpiece | |
|---|---|---|---|
| r | 0. 9 mm | a | 6 mm |
| h | 0.1 mm | b | 8 mm |
| V | 10 m/s | c | 2 mm |
| | | d | 4 mm |
| | | e | 0.5 mm |

## 5 NUMERICAL RESULTS

Four aspects of the deep rolling model are examined in the current work. The first is concerned with the effect of overlap, the second is effect of friction coefficient between the roller and target plate, the third is deep rolling with constant force, and the fourth is deep rolling with mechanical tools. All results are obtained from variation of residual stress along the path which is created by selecting nodes along the central axis in target plate as shown in Fig. 4.

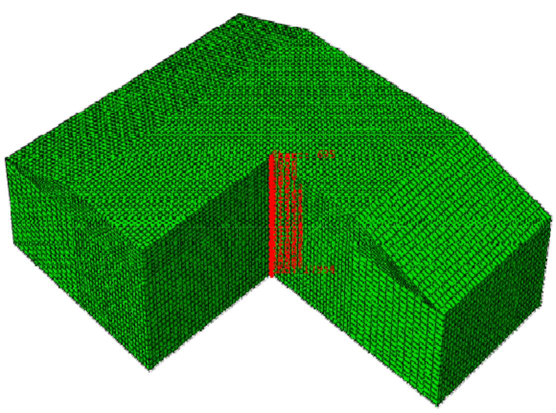
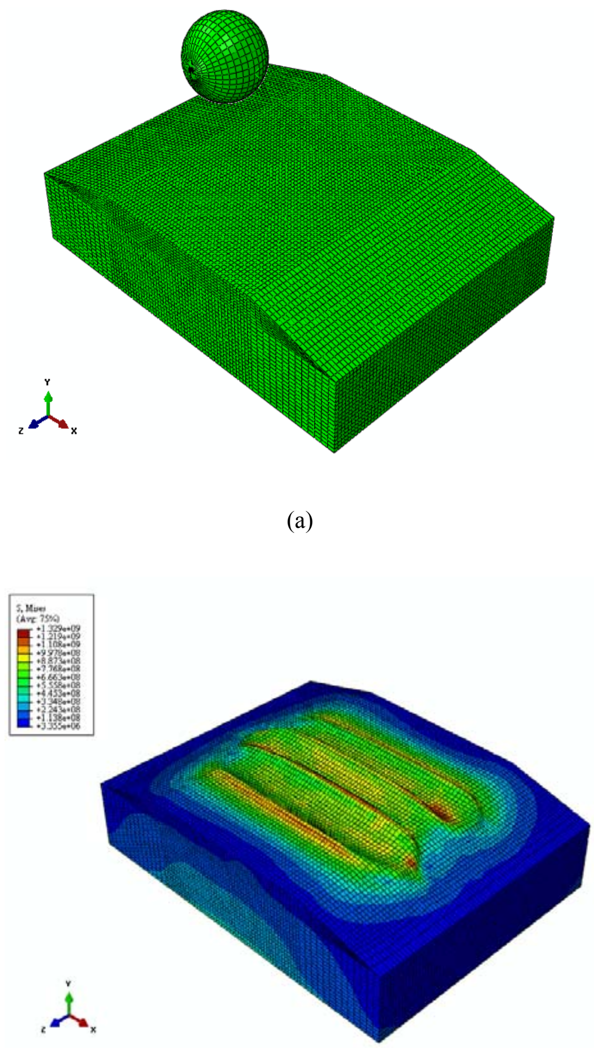


**Fig. 4** Path along Y-direction in target plate

The stress distribution in x, y and z directions, indicated in Fig. 5, are typically shown in Fig 6. As the figure indicates, the stress component in *Y*-direction ($\sigma_{yy}$) is not so significant and may be considered negligible.
However, the stress component in *x*-direction ($\sigma_{xx}$), which coincides with rolling direction is considerable but still is significantly lower than the stress component in Z-direction ($\sigma_{zz}$), which is perpendicular to the direction of rolling. However, only the stress component $\sigma_{xx}$ is considered for evaluation of the effects of the rolling parameters on residual stress distribution, induced by deep rolling in this work.



(a)

(b)

**Fig. 5** (a) Finite element model of the work piece (up), (b) a deep rolling model (down)

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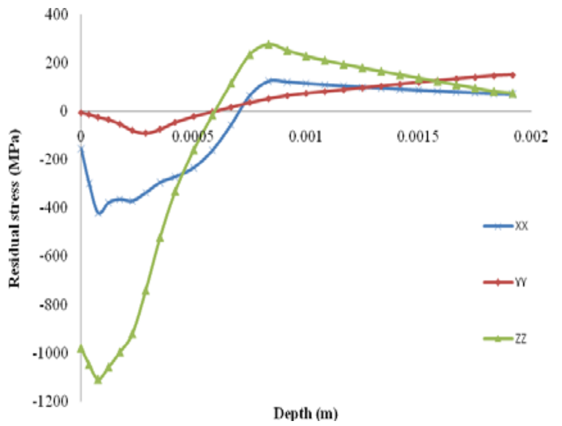


**Fig. 6** The stress distribution in *x*, *y* and *z* directions

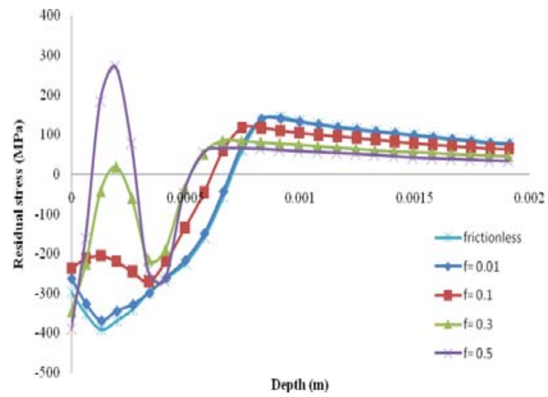


**Fig. 8** Effect of coefficient friction on residual stress

### A. Effect of overlap

The deep rolling finite element analysis is performed to investigate the influence of overlap. Six different overlaps are considered: 0%, 8.3%, 16.6%, 25%, 33% and 42%. In this analysis a rigid roller with radius of R=0.9 mm is used. The variation of residual stress $\sigma_{xx}$ along the selected path for five different cases of overlap is shown in Fig. 7. Furthermore, this indicates that increase in overlap results in increase in the magnitude of the maximum residual stress. However, an overlap of 42% has led to surface burr and contraction; hence a complete analysis was not possible.

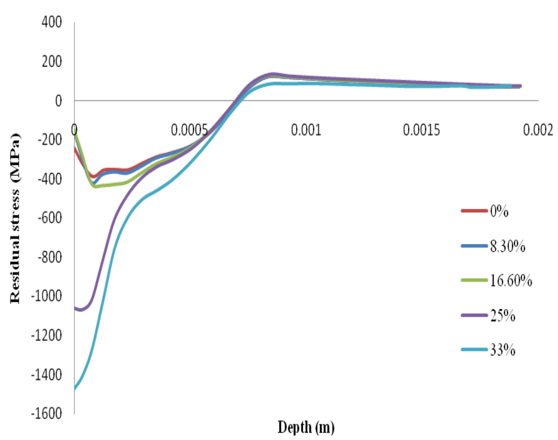


**Fig. 7** Effect of different overlaps on deep rolling

### B. Effect of friction coefficient

The residual stress profile along the mentioned path against the varied friction coefficient is plotted in Fig. 8.
The figure clearly shows that increase in the coefficient of friction, results in decrease of magnitude of the maximum residual stress in x direction $(\sigma_{xx})$ and for coefficient of friction μ ≥0.1 the effect of friction may cause instability in residual stress. Increased coefficient of friction between the workpiece and the roller will cause contraction.

### C. Deep rolling with constant force

The residual stress profile along the mentioned path shown in Fig. 4, against the varied force is plotted in Fig. 9. The figure clearly shows that increase in the force intensity results in increase of magnitude of the maximum residual stress.
There are two important issues regarding this diagram. First, the residual stress is nearly identical at the depth above 0.5mm, for different applied forces. This indicates that the effect of surface rolling process is negligible and parameters alterations have effect only on the surface residual stress.
The second is that there is an error in the results at a depth less than 0.1 mm because of the coarse mesh in this area. However due to the large processing time a smaller mesh size is not possible. For this reason, the results of the depth below 0.1mm are not considered at the conclusion.

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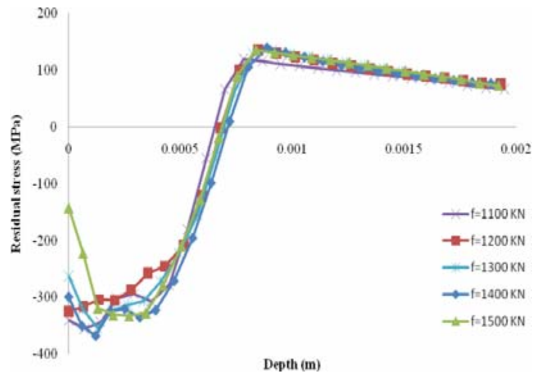


**Fig. 9** Effect of the roller's force intensity on deep rolling

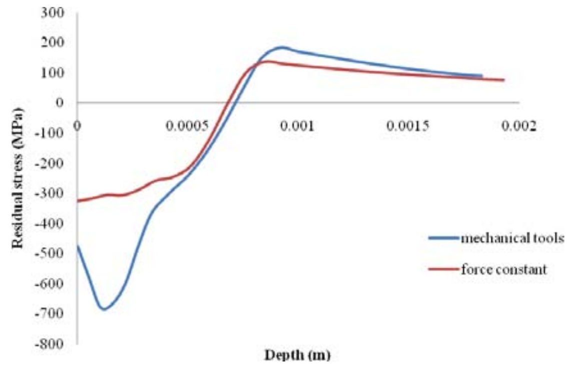


**Fig. 11** Comparison between two methods of force constant and mechanical tools

### D. Deep rolling with mechanical tools

In this case, the pressure required for deep rolling is supplied by the spring force. The processed forces are regulated by changing in the amount of spring compression. Fig. 10 shows the variation of residual stress, $\sigma_{xx}$ , along the mentioned path shown in Fig. 4 for five situations. Fig. 10 shows that increase in the spring compression results in a substantial increase of magnitude of the residual stress created in the work piece.

Moreover, the result of this test was compared with the situation where the applied force is constant, as shown in Fig. 11. To make a right comparison, the two charts were prepared at identical forces. Regarding the mechanical method, the roller displacement chart versus the processing time, has tiny amplitude.

Therefore, it is possible to get the spring force by multiplying the initial compression with the spring constant. Figure 11 clearly shows that the case of surface rolling with mechanical tool and spring force with respect to the case of constant force is better, and it results in additional residual stress; moreover maximum residual stress would penetrate deeper.

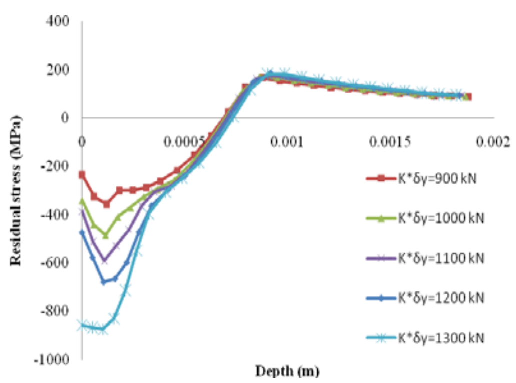


**Fig. 10** Deep rolling with mechanical tools and spring force

## 6 CONCLUSION

A comprehensive 3D finite element dynamic analysis by considering spring back effect was conducted to simulate the deep rolling process. The model was validated by comparison between the residual stress profiles obtained by simulation and the result of X-Ray diffraction technique proposed by [13]. The effect of overlap of the rolling tracks, friction coefficient between roller and target plate, deep rolling with constant force, and deep rolling with mechanical tools of residual stress $\sigma_{xx}$ after spring back have been examined and discussed.

The results revealed that increase in overlap of the rolling tracks largely increases the magnitude of the residual stress created in target plate. Moreover, increase in the friction coefficient between roller and target plate results in decrease of magnitude of the residual stress. For high coefficient of friction the effect of friction can cause instability in residual stress. Increased coefficient of friction between the workpiece and the roller will cause contraction. Next, surface rolling was done in two different conditions. The first was at constant force where the results indicated that increase in force intensity followed by increase in the maximum residual stress. In the second condition, the surface rolling was performed using mechanical tool with spring force.

Results showed that increase in the spring compression results in increase magnitude of the residual stress created in workpiece.

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