Effect of Friction Coefficient on Finite Element Modeling of the Deep Cold Rolling Process

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Abstract

This paper proposed a 3D finite element model for the deep cold rolling process, modeled using the commercially available Abaqus/Standard FE software, and uses the aforementioned model to study the effects of friction coefficient on the residual stress values predicted. It was shown that the friction coefficient had a minor impact on the surface residual stress values and a negligible effect beyond 0.4mm in depth.Another finite element model with different process parameters was run with the friction coefficient calculated from the earlier model. The results were then correlated to experimental data and it was concluded that

Keywords

Deep cold rolling, Finite element analysis, Simulation, Abaqus, Friction coefficient

Introduction

Mechanical surface treatment methods are able to induce a layer of surface and sub-surface compressive residual stress in components, thereby increasing fatigue life and foreign object damage tolerance. Shot peening is widely used in industry and is able to induce a layer of compressive residual stress about 200µm in depth. Deep cold rolling (DCR) is a relatively new process which is able to induce deeper stresses, up to 1mm in depth, and has the additional benefit of improving the surface finish. Deep cold rolling (DCR) as a mechanical surface treatment has its roots in roller burnishing, although its main objective is to induce deep compressive residual stresses in the surface and sub-surface layers of the component treated In contrast, roller burnishing's performance measure is usually related to surface finish. This results in much higher forces and applied pressures required in the DCR process [1].

While the high compressive stresses generated by DCR in the near surface layers can extend fatigue life, it is crucial that the location and magnitude of the corresponding balancing tensile residual stresses are carefully managed and understood, as they can negate the benefits of the near surface compressive residual stress and adversely affect the fatigue life of the component [2]. However, experimental determination of residual stress distributions by the hole drilling method [3] and the X-ray diffraction [4] tend to be time consuming, expensive and limited to discrete measurement points. Hence, finite element (FE) simulation is a crucial tool in the process optimization of the DCR method as FE simulation enables the user to analyze and predict the residual stress distribution of the component, even before a prototype is made, and make the necessary adjustments to ensure the component meets the requirements. Furthermore, FE is not geometrically limited, as complex geometries can be approximated using base mesh elements. In contrast, physical measurements are limited to discrete points of restricted geometry with a required degree of flatness.

Most of the previous work published on finite element modeling of deep cold rolling and/or roller burnishing utilized an assumed value for the friction coefficient [5]. The effect of the friction coefficient on the accuracy of the finite element model is unknown at this moment; hence, this paper aims to investigate the effect of the friction coefficient. The values studied will be μ=0.05, 0.1, 0.2, 0.3 and 0.4.

An assessment of literature showed that simulation work on DCR assumes the friction coefficient between the ball and the tool to be either 0, i.e. frictionless or μ= 0.2, which as expected, produces different residual stress distributions as friction causes less material to be pushed in the rolling direction [6]. Hence, this paper aims to study the effect of the friction coefficient on the FE model of deep cold rolling.

Methodology

Finite Element Model

The DCR model is a 3-dimensional rectangular test coupon with identical thickness to that used in the experimental work. Abaqus/Standard was used to model the test coupon. The 3-D deformable element type used is the C3D8R element, an 8-node linear brick, with reduced integration element and hourglass control. 32640 such elements were used to model the test coupon and 3338 four-node R3D4 rigid elements were used to model the ball tool. In order to reduce computational time, although it would have been ideal to model the entire process for the whole test coupon, a reduced burnished area was investigated. The treated area must be representative of the treatment of the entire coupon for the results from the reduced burnished area to be equivalent to the treatment of the entire area burnished. This can be achieved when steady state is reached in the treated area [5]. Through prior simulations conducted by the authors, it was determined that a treated area of 10mm x 5mm is sufficient to achieve this.

The DCR tool used in the experiments is modeled as a rigid body, with its center node as the main reference and control point. As the tool is hydrostatically controlled, it is hypothesized that the pressure can be substituted with equivalent concentrated force acting through the reference point of the ball in the direction normal to that of the component, taking into account some pressure losses (11% based on [7]) in the tool and tubing. The equivalent concentrated force can be estimated using the following formula [7],

$$F = (1-P_L)(\pi/4)(d_b^2)(P\cos\theta) \quad (1)$$

where P_L is the pressure loss, d_b is the ball diameter, P is the applied pressure and θ is the angle of the tool to the normal.

The movement of the ball is controlled via translating the center node of the ball, in the length and breadth direction. The rotational degrees of freedom of the ball were left free, ensuring that the ball is able to roll across the surface, influenced by the frictional forces between the tool and the component.

The boundary conditions were imposed such that the bottom surface of the test coupon is pinned. Since the test coupon is of sufficient thickness, it was assumed that the spring back of the coupon after treatment is negligible. Hence, this boundary condition is applied through all steps. The dimensions of the test coupon, the mesh, elements used and the boundary conditions are illustrated in Figure 1.

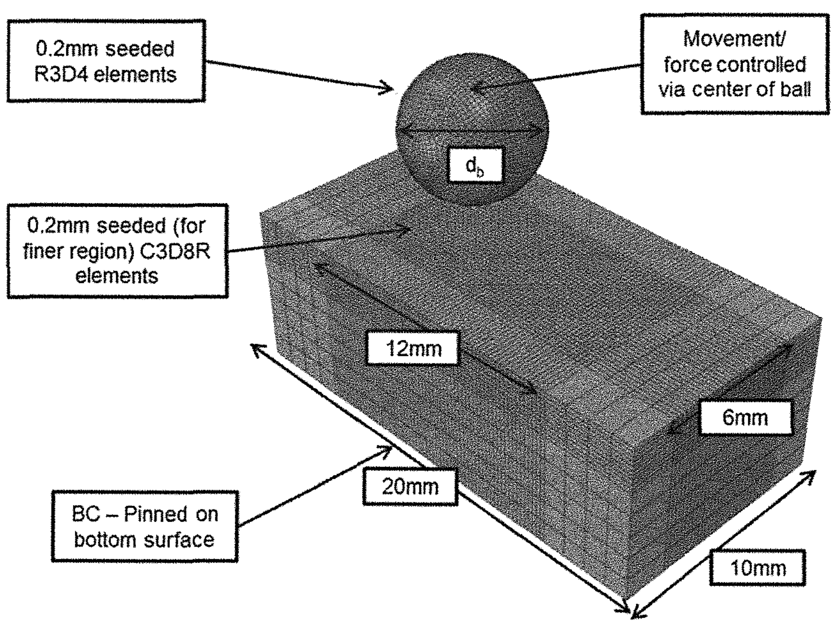

Figure 1: Finite element model and set-up

The various values of the friction coefficient used is this study are μ=0.05, 0.1, 0.2, 0.3 and 0.4. The variable used to correlate the model to experimental data is the residual stress profile in the steady state region of the burnished region (center of the burnished region).
Material Model
The material used is Ti-6Al-4V, and is modeled as an elastic-plastic material with strain hardening utilizing the power law – $\sigma = K\varepsilon^n$. The material data is determined via compression testing using test specimens with the Rastegaev geometry to ensure uni-axial compression [8]. The material data from 6 test specimens is averaged and tabulated in Table 1below.

	Yield Stress (MPa)	K (MPa)	n
Average	924.338	1361.4	0.1325
Standard Deviation	6.16449 (0.67%)	13.5972 (1.00%)	0.00264 (1.99%)

Table 1: Yield Stress and Power Law coefficients from compression test data.

Experimental Tests
Flat rectangular test coupons of Ti-6Al-4V measuring 60mm x 30mm x 7mm were mounted on a work piece holding fixture and deep cold rolled with an industrial robot using a DCR tool with hydrostatic pressure, P, predetermined overlap, o, (co-determined with the step-over), tool diameter, d_b, and fixed feed-rate, f, to be used as reference data for the initial simulation. The cross validation of the model once the friction coefficient was determined was done against the trial with a larger diameter DCR tool, 2.16 d_b, with lower hydrostatic pressure, 0.5 P, identical percentage overlap, o, (larger step-over due to the tool size) and identical feed-rate, f, as its parameters.

Results and Discussion
The initial model for this work only comprised of a treated region of about 10mm x 1.2mm. This was deemed as insufficient as the steady state of the model in the transverse direction was not achieved. Hence, a larger region of the model, measuring 10mm x 5mm was treated instead, in order to ensure that steady state was achieved for the entire model, as seen in Figure 2, enabling the model to be equivalent to the experimental work.

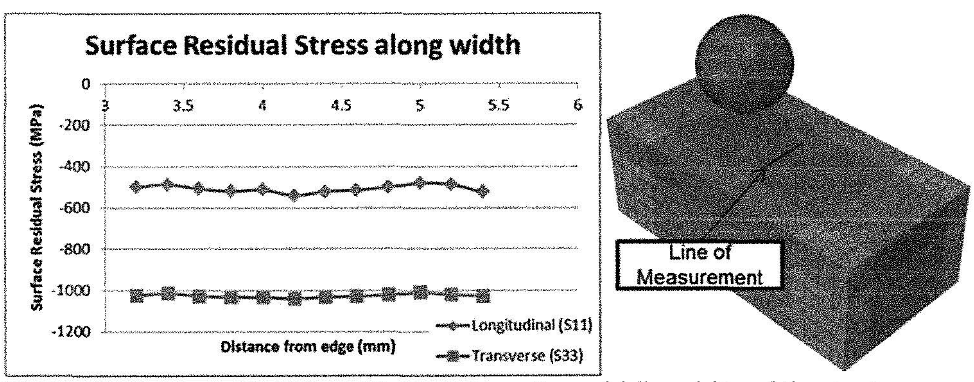

Figure 2: Surface Residual Stress along the middle width of the test coupon

In the first simulation, the first DCR tool, with tool diameter d_b, was modeled at hydrostatic pressure P, yielding a force of 1131N based on equation (1). The results are illustrated in Figure 3. The longitudinal direction is defined as the direction parallel to the tool path and the transverse direction is perpendicular to the tool path.

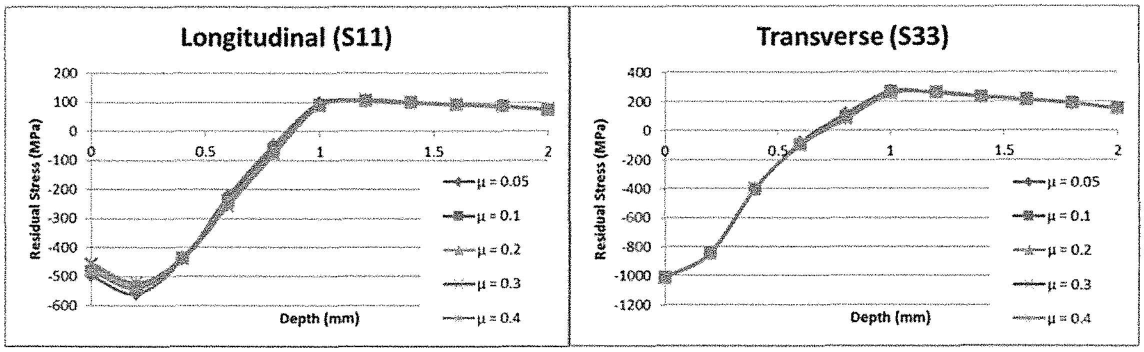

Figure 3: Predicated residual stress results for first set of parameters

It is observed that while the friction coefficient has a minor effect in the near surface region of the component, up to 0.4mm, when measured in the longitudinal direction. However, with increasing depth, the effect becomes negligible. Furthermore, in the transverse direction, all the residual stress plots are effectively identical, for the various values of μ. This suggests that the friction only has an effect on the near surface region and only on the stresses in the direction of rolling. This observation can be attributed to the ridge of material, which can be as high as about half the indentation developed by the tool as it moves across the surface of the material to be treated [5]. The frictional force between the component and the ball contributes shear forces acting on the component, through the ball slipping across the surface. However, as the ball is free to rotate, it is hypothesized that the lower levels of friction causes slightly more slip, accounting for the 10% increase in longitudinal stress at the surface level between μ=0.5 and μ=0.4. From Figure 4, it is clear that the difference at the surface is the largest deviation between all the curves. Since the largest difference is only about 10%, taking into account variation in FEM, it can be concluded that the value of the friction coefficient does not have a significant influence on the results.
Furthermore, the difference it may cause is within experimental error and would be hard to observe in actual experiments. Henceforth, for the verifying trial run, the value of μ=0.2 will be used to model the process. For the verifying trial run, the second set of parameters where used, which yielded a force of 2363N based using equation (1). The results of the validation run are illustrated in Figure 4 below.

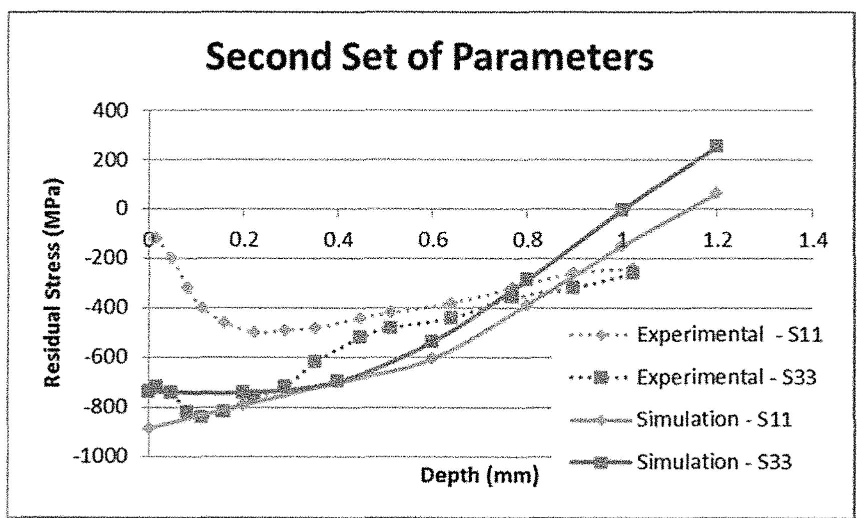

Figure 4: Validation run with second set of parameters, compared to experimental results

It is clear that there is a good correlation between the experimental data and the simulation results in the transverse direction, where the dashed and solid lines with square shaped markers, representing the experimental and simulation data respectively, show similar trends. However, there is significant difference between the data in the longitudinal direction, especially in the near surface region. It is hypothesized that the deviation was due mainly to the material model parameters used, as the compression test coupons and experimental test pieces were manufactured from different test blocks and is unlikely to be due to the friction coefficient used.

Conclusion and Future Work

It can be seen that the friction coefficient does not have a significant impact on the overall results in DCR simulation, although it has already been previously established that there will be a difference in the frictionless case compared to the cases with friction [5]. Future work will be focused on improving the correlation between the experimental and simulation data, especially ensuring that test coupons used for the experiments and the determination of the test coupons are from the same stock, to eliminate material differences as a possible source of error. With advances in simulation and computational power, finite element process modeling of the DCR process will be able to be applied to larger and more complex components, especially in cases where physical residual stress measurements are difficult or even impossible, giving stress engineers a crucial tool in residual stress design.

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