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ESTIMATION OF INTERFACE FRICTION DURING RADIAL ULTRASONIC COMPRESSION USING FINITE ELEMENT MODELLING

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3.0 INTRODUCTION

The main reason for using lubricants in metal forming processes is to reduce the interfacial friction between the tool and workpiece. The reduction of interface friction provides many benefits to the fabrication process and end product. For example, the process forming load can be lowered, tool life can be extended, and final product defects can be minimised. In current manufacturing processes involving metal forming, it is necessary to use lubricants that avoid or reduce environmental pollution. Dry and low viscosity lubricants have been used in metal working processes which contain reactive or non-reactive chemical additives that contribute to environmental pollution. Accordingly, some studies have been conducted to investigate the use of ultrasonic vibration as a non-chemical lubrication medium [1].

Since Blaha and Langenecker [2] reported that the yield strength reduction was due to superimposed ultrasonic vibration in tensile testing of zinc crystals, many other similar studies have been carried out and several theories have been developed to explain the observed phenomena, including energy absorption due to moving dislocations, superposition effects of oscillating stress, reduction in internal friction, reduced material properties, dynamic effects of vibrated tools [3], and reduction of interface friction [4, 5].

A large number of investigations have observed that vibratory energy can reduce frictional forces. One publication [6] postulated five possible mechanisms that could improve the frictional condition under the influence of a vibratory load: (1) separation of surfaces and cyclic re-establishment of the lubricant film on the contacting surface, (2) friction force vector reversal due to movement of the tool, (3) heating of asperities possibly reducing the shear strength, (4) pumping of lubricants to provide better lubrication conditions, and (5) cleaning effect which permits efficient bonding of the lubricant to the metals being deformed.

The effects of ultrasonic vibration on friction during upsetting tests have been studied [4] and it has been suggested that under an applied longitudinal ultrasonic load there is a reduction in interface friction. This effect has also been observed for applied radial mode ultrasonic vibrations. A recent study [7] of longitudinal and radial ultrasonic upsetting of plasticine reported that ultrasonic vibration significantly reduced the interface friction and the upsetting force due to a thermal reduction in the coefficient of friction.

This chapter aims to investigate the numerical stress-strain relationship when radial oscillatory stress is superimposed on a static stress during ultrasonic compression tests of aluminium specimens under different coefficient of friction, μ. A series of finite element (FE) models are developed to investigate the effects of changes in friction in the simulations of ultrasonic compression tests. The change of friction during static and ultrasonic compression can be estimated by comparing the stress-strain relationships derived from the previous experimental study [8].

3.1 FINITE ELEMENT SIMULATION

Aluminium is used as the material model in this simulation. The properties of aluminium, derived from the previous static tension test [9], were: Young modulus 69 GPa, yield stress 60 MPa and Poisson's ratio 0.33. Classical metal plasticity was used to define the plastic strain by using the following equation [10],

$$\varepsilon^{pl} = \varepsilon^{t} - \varepsilon^{el} = \varepsilon^{t} - \frac{\sigma}{E}$$

where, ε^{pl} is true plastic stress, ε^{t} is true total strain, ε^{el} is true elastic strain, σ is true stress, and E is Young's Modulus. The material is initially isotropic, homogeneous and incompressible such that the volume of each element of the model remains constant. The behaviour of aluminium is treated as elastic-plastic with low strain hardening. The material was deformed under steady-state conditions at room temperature and no temperature effects were induced.

The compression simulation was carried out using a commercial finite element code, ABAQUS, with implicit solution. Half of the specimen was meshed using 2D axis-symmetric 4-node elements. The upper and lower platens were assumed to be rigid bodies, modelled as an analytically rigid surface. Figure 3.1 shows the problem description of static and ultrasonic compression. To allow for manageable computational time, whilst ensuring that the effects of ultrasonic oscillation could be evaluated, the ultrasonic excitation was applied for very short time intervals in the FE models.

3.2 STATIC AND RADIAL ULTRASONIC (RU) COMPRESSION SIMULATIONS

The static-ultrasonic compression simulations were performed using the following procedure. Initially, the specimen was deformed under static loading by applying a constant velocity of 5 mm/min to the upper platen. By controlling the total time step, at post-yield or 22 % reduction of the specimen height, ultrasonic excitation was superimposed on the lower platen during plastic deformation at a frequency of 20 kHz and radial vibration amplitude, A_0 of 4 μm. Two coefficients of friction were set throughout each compression, first at μ=0.25 and second at μ=0 or frictionless. To allow for manageable computational time, the ultrasonic excitation was applied for 0.8 seconds in the FE models. Subsequently the model returned to its static loading condition before the simulation was stopped when the specimen was compressed to approximately 50 % of its original height. Figure 3.2 shows the original and deformed meshes of the compression model.

For the second series of FE models, the effect of a change in the numerical value of the coefficient of friction during the interval of ultrasonic excitation was investigated. In this case, during static compression the coefficient of friction was set at 0.25 and, during ultrasonic excitation, the coefficient of friction was changed. Two different values were used; $\mu = 0$ for frictionless and $\mu = 0.15$. A friction value of 0.15 was chosen because it is consistent with reductions reported in previous studies. Maximum reductions in the coefficient of friction of 35 % and 40 % have typically been reported previously and the reduction to a value of 0.15 represents a 40 % reduction in coefficient of friction which was reported in a study of ultrasonic strip drawing [11].

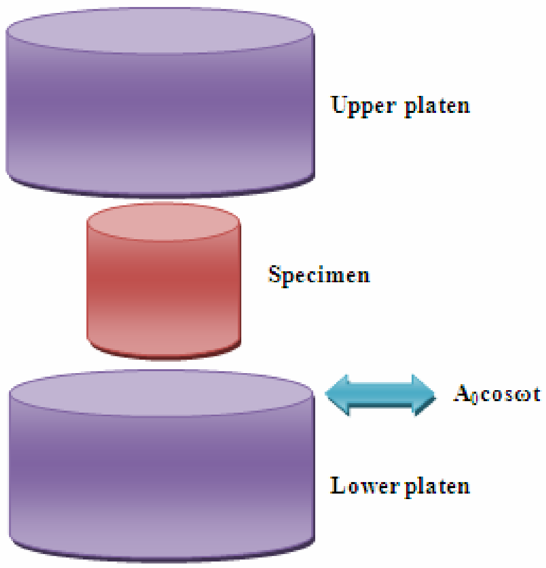

Figure 3.1: Problem description of the static and ultrasonic compression

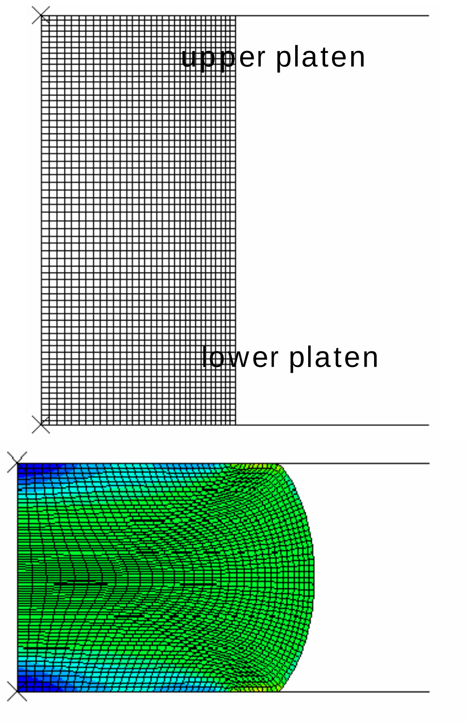

Figure 3.2: Original and deformed mesh profile of a cylindrical specimen for compression FE model.

3.3 DISCUSSION OF FE MODEL RESULTS

In some previous investigations, radial ultrasonic excitation has been applied in the study of a wire drawing process. In most cases, the application of ultrasonic excitation onto the drawing die, giving a tangential oscillation relative to the specimen motion, reduced the drawing force and it was suggested that this reduction was caused by a reduction in interface friction [12]. Since the oscillatory stress was not measured, there were conflicting interpretations of the measured data and of the possible factors that could reduce the mean stress. It was not known whether a change in friction or stress superposition effects or both caused the reduction in mean stress.

The numerical effects on stress-strain behaviour were examined when a constant dry interface friction coefficient, $\mu = 0.25$, was applied during static and ultrasonic excitation intervals. Figure 3.3 shows the calculated stress-strain curve for static and radial ultrasonic (RU) intervals for $\mu = 0.25$. At the onset of RU excitation, the mean oscillatory stress reduced by approximately 4 MPa from the static stress. However the measured stress reduction of the ultrasonic interval in the previous work [8] as can be shown in Figure 3.4 seems to be higher at 9 MPa. Also, at a strain of 0.2188, the peak-peak oscillatory stress amplitude is 3 MPa which agrees quite well with the 4 MPa peak-peak stress amplitude measured as reported in the previous experiment [8]. It can be observed in the FE data in Figure 3.3 that RU simulations calculate a drop in the maximum oscillatory stress from the static stress for a constant coefficient of friction for static and RU compressions and this does not fit with the classic oscillatory stress superposition definition as described by Kirchner [13]. For radial mode ultrasonic excitation, the friction force and excitation force are co-axial and the ultrasonic excitation force modifies the friction force vector cyclically. It is therefore expected that the friction force is modified even though the coefficient of friction is constant and that this accounts for the drop in maximum oscillatory stress from the static stress in RU compression simulations under a constant interface friction coefficient.

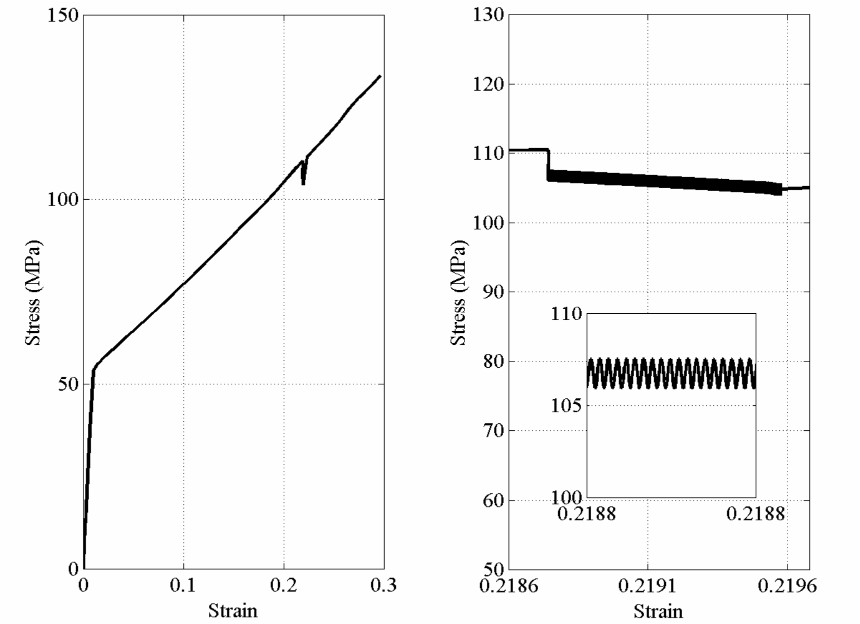

Figure 3.3: FE model showing an interval of RU excitation for a constant coefficient of friction $\mu = 0.25$, inset shows zoomed view of oscillatory stress amplitude.

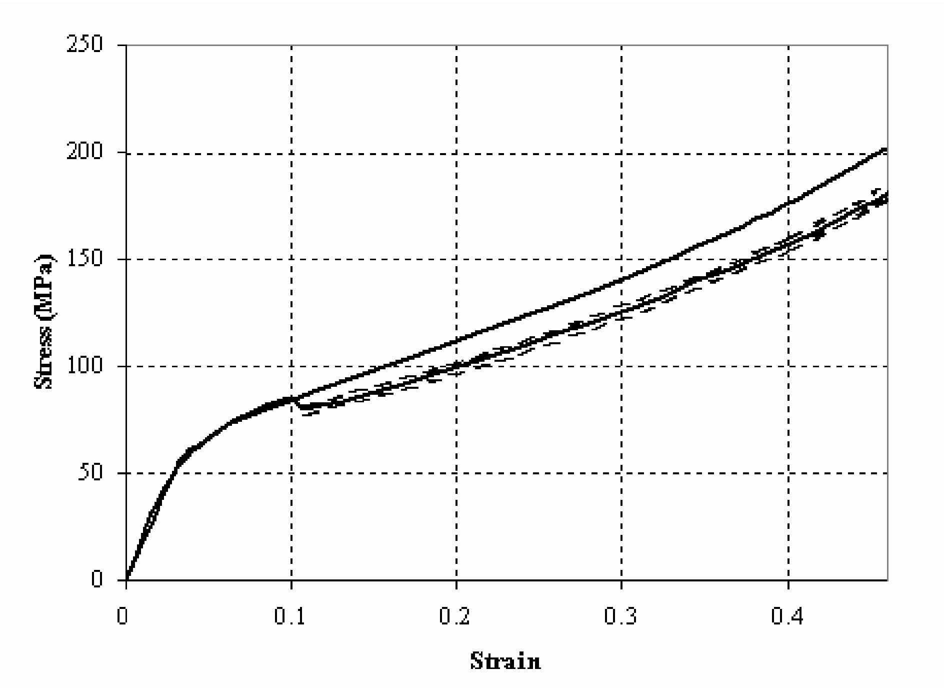

Figure 3.4: Measured static and RU compression test for dry surface showing: — static and mean stress, --- path of max. and min. oscillatory stress [8].

The investigation using the FE model continued by changing the interface friction coefficient from dry to a friction free condition, $\mu = 0$. Figure 3.5 plots a compression test simulation with $\mu = 0$ throughout, and with an interval of ultrasonic excitation (which cannot be seen in the main figure but it is visible in the zoomed inset). During the interval of RU excitation there is no measurable change in the mean stress and no significant peak-peak stress amplitude was calculated. Figure 3.6 compares the two previous figures, illustrating how the oscillatory stress amplitude for $\mu = 0$ is extremely small and therefore not visible in the figure. Figure 3.6 also shows that the difference between the static stress and mean oscillatory stress at a strain of 0.219 for $\mu = 0.0$ is 6 MPa, which is less than the measured mean reduction of 9 MPa [8] when RU was superimposed on the static load during compression.

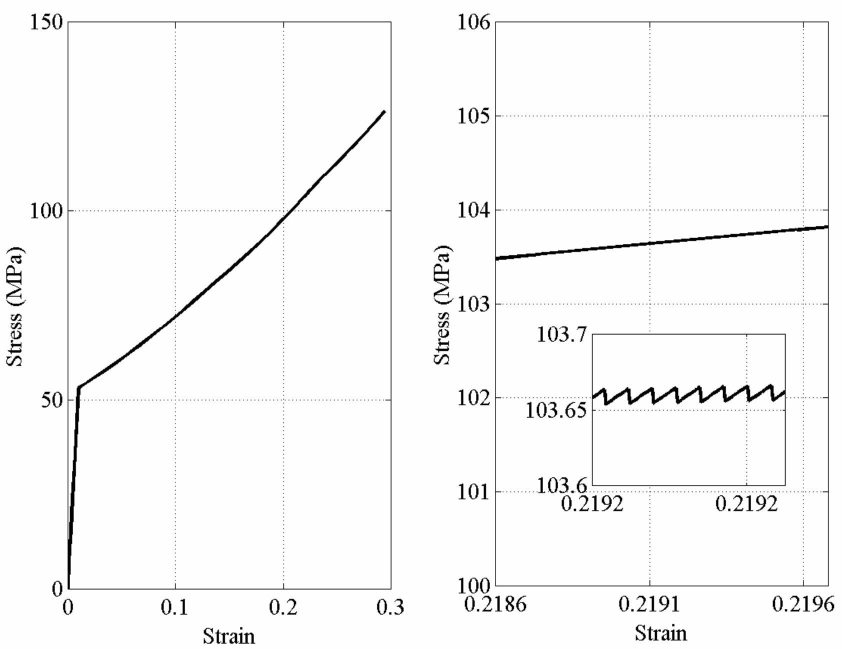

Figure 3.5: FE model showing an interval of RU excitation for zero friction, $\mu = 0$, inset shows zoomed in view of oscillatory stress amplitude.

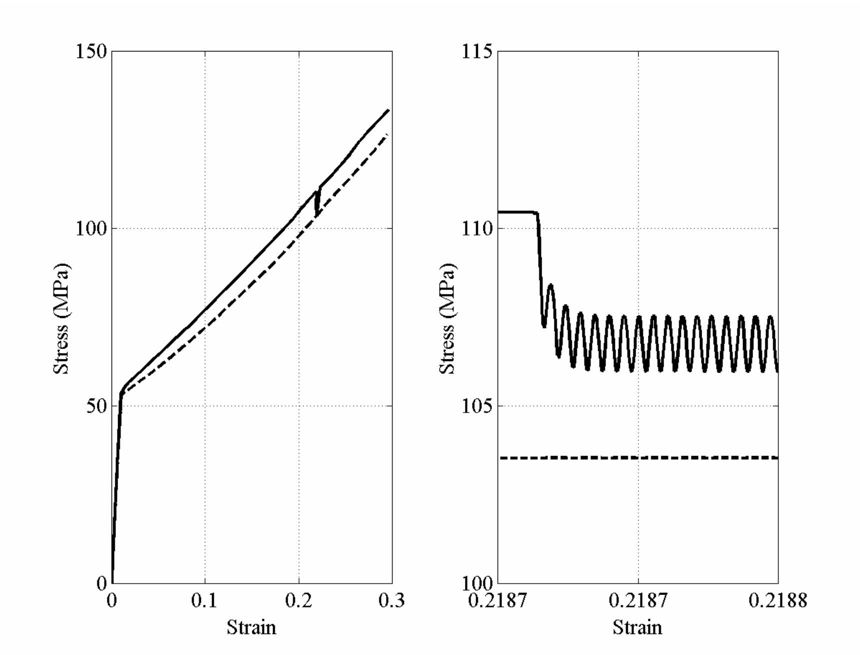

Figure 3.6: Combining Figure 3.3 and 3.5 for RU excitation, showing — for $\mu = 0.25$, ---- for $\mu = 0$, left shows zoomed in view of oscillatory stress amplitude (which is too small to be visible for $\mu = 0$).

The above models do not satisfactorily represent the experimental results of the mean flow stress reduction under applied RU excitation during compression tests. The FE model was therefore developed by adjusting the coefficient of friction from a value which represents a dry surface to a friction free surface during RU excitation. Figure 3.7 illustrates the numerical effects on the stress-strain relationship. By changing the numerical friction coefficient from $\mu = 0.25$ for a dry surface to a frictionless surface, $\mu = 0$, during applied RU excitation, the mean oscillatory stress is now significantly reduced from the static stress. For applying ultrasonic excitation at a strain of 0.219, the mean stress is reduced by 15 MPa from the static stress but there is no measurable peak-peak oscillatory stress amplitude. For a friction free contact there is no resistance to sliding and no friction force, and the force in the radial direction at the contact surface is only due to the ultrasonic excitation force. The calculated oscillatory force response is therefore of very low amplitude, leading to a low oscillatory stress amplitude in the calculated stress-strain relationship.

There are dissimilarities between the FE model data and the experimental results. Firstly, the measured reduction in the mean stress from static to RU excitation is 9 MPa [8], for all surface conditions, however the FE model predicted 15 MPa. The peak-peak stress amplitude from the RU compression experiments was consistently 4 MPa [8], for all surface conditions, whereas the FE model predicts a peak-peak oscillatory stress amplitude of only 0.01 MPa.

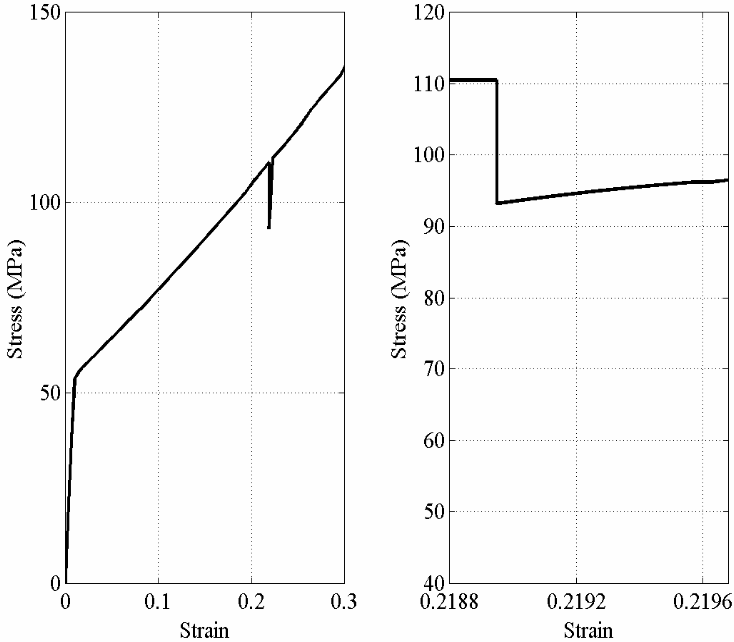

Figure 3.7 FE model showing an interval of RU excitation for friction coefficient μ = 0.25 for static compression and change to friction free, μ = 0 for ultrasonic compression, left expanded scale of ultrasonic stress interval.

Another FE model was developed, where the coefficient of friction was maintained at μ = 0.25 during static compression, and was changed to μ = 0.15 during the ultrasonic compression interval. From the calculated stress-strain relationship, as illustrated in Figure 3.8, a close agreement is now achieved with the previous measured stress-strain data under dry condition [8] as shown in Figure 3.4. The reduction in mean stress which was measured from the experiments is identical to the reduction which is predicted by the FE model. At a strain of approximately 0.22 the mean stress is reduced by 9 MPa from the static stress. The measured peak-peak stress amplitude at the same strain value is 4 MPa from experimental results and predicted at 3 MPa from simulation data. This result agrees with previous studies [2, 9] which claim that the interface friction can be reduced if the specimen is subjected to a radial ultrasonic excitation during a static deformation process. Table 3.1 show the summary of the stress reduction calculated using numerical analysis compared to the previous experimental data. It is clear the FE model estimates that the interface friction is reduced from the static compression of μ=0.25 to μ=0.15 during radial ultrasonic compression which represent 40% of friction reduction.

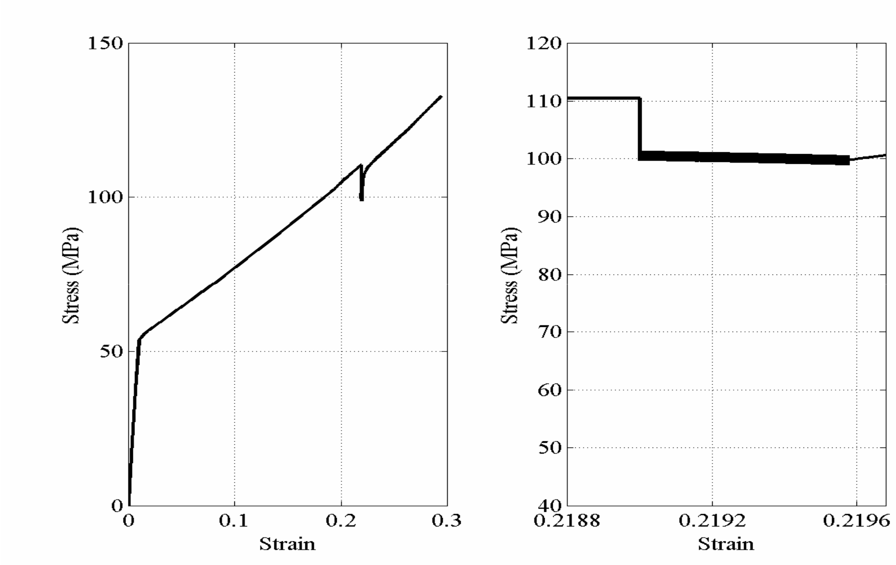

Figure 3.8 FE model showing an interval of RU excitation for friction coefficient μ = 0.25 for static compression and μ = 0.15 for ultrasonic compression.

Table 3.1: Stress reduction and peak-peak stress amplitude during static and radial ultrasonic compression.

Compression procedure	Stress reduction from static stress	Peak-peak stress amplitude
Experiment [8] – dry surface throughout static and ultrasonic	9 MPa	4 MPa
Simulation - μ=0.15 throughout static and ultrasonic	4 MPa	3 MPa
Simulation - μ=0 throughout static and ultrasonic	6 MPa	0
Simulation - μ=0.25 during static, changed to μ=0 during ultrasonic	15 MPa	0
Simulation - μ=0.25 during static, changed to μ=0.15 during ultrasonic	9 MPa	3 MPa

3.4 CONCLUSION

A numerical investigation into RU compression was carried out under different interface friction conditions. The numerical data has been compared to the data of the previous similar experimental study. The experimental data solely is unable to determine the value of the coefficient of friction. By comparing the stress-strain simulation data with the previous experimental stress-strain curve, it can be concluded that the application of radial ultrasonic during compression has reduced the interface friction at approximately 40% compared to the static compression test.

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