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THE MODELLING OF RING TESTS AT ELEVATED TEMPERATURES FOR THE DETERMINATION OF FRICTION IN Ti-6Al-4V FORGINGS

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Abstract

Ring compression tests and finite element modelling were used to explore the friction conditions present in high temperature Ti-6Al-4V forgings where glass is used as the lubricant. The work explored the use of isothermal and non-isothermal simulations as a means of modelling non-isothermal test conditions. The friction factor is determined by comparison of the deformation of the internal diameter of the experimental compression rings and the simulated compression rings. It was determined that the heat transfer coefficients (HTCs) used in the simulations have a significant result on the friction factor predicted by the simulation results. It was found that it is possible to predict similar deformations through combinations of low HTC/high friction factor and high HTC/low friction factor. Consequently, it is considered critical that the heat transfer conditions for non-isothermal work where there is a high temperature gradient between workpiece and its surroundings be correctly modelled in order to determine the correct friction factor to be used in later simulations.

Key words: Ti-6Al-4V, friction, heat transfer, finite element modelling, thermomechanical processing

1. INTRODUCTION

The friction between the tool and workpiece in a hot metal forming process can have a significant influence on the applied loads required for shape change and on the strains, strain rates and stress distributions within the workpiece and thus its final microstructure and mechanical properties. For numerical simulations of metal forming a number of different friction models can be applied, for example the Coulomb friction law and the shear friction law. Regardless of which model is used it is necessary to identify the correct value for the relevant frictional values to accurately simulate the interaction at the workpiece/tool interface. A common method of experimentally determining these friction values is the ring compression test (Male & Cockroft, 1964). This method relies on comparison of the dimensions of experimentally deformed ring specimens with deformed dimensions of rings predicted by analytical techniques; traditionally this was accomplished via slip-line field theory, lower and upper boundary methods or slab theory however this has been superseded by finite element methods (FEM) as noted elsewhere (Wu et al., 2003; Zhu et al., 2011). In this work we examine one of the key issues that is often overlooked when performing FEM analysis of the ring compression test: the heat transfer between the

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tool and the workpiece, particularly when there is a significant temperature difference between them.

Investigations into the impact of the heat-transfer coefficient (HTC) on non-isothermal ring compression tests by Andersson et al. (1996) using aluminium alloys suggests HTC has a definite effect on metal flow and on the results of the compression test but the overall effect is small compared to inaccuracies in the calibration curves and the effects of varying friction. However, Zhu et al. (2011) using Ti-6Al-4V and glass lubricants with a sample temperature of 940°C and tooling at 220°C found that the friction calibration curves generated by FEM using DEFORM 3D varied significantly depending on the HTC values. The authors conclude that an increase in the HTC value produces an increased metal flow velocity and that the resulting deformation is similar to that produced by assuming an increased friction factor (Zhu et al., 2011). The work conducted in this paper has similarities to that done by Zhu et al. (2011) in terms of the use of Ti-6Al-4V at elevated temperatures in conjunction with tooling at lower temperatures, however the temperature is higher at 1100°C such that deformation is undertaken in the β phase field where the material is considerably softer and any cooling of the specimens during testing may result in a microstructural gradient due to phase changes.

2. METHODOLOGY OF EXPERIMENTAL WORK AND FE SIMULATIONS

2.1. Experimental Procedure

Rings of Ti-6Al-4V (β transus ~1005°C) were prepared with an outer diameter of 19.05 mm, inner diameter 9.525 mm and a height of 6.35 mm giving a ratio of 6:3:2. Two different glass lubricants were tested; one with a borosilicate chemistry and one with a silica based chemistry. The borosilicate glass was in powder form, the silica glass was tested as both a powder and in the form of glass fibres. The specimens were coated prior to testing by means of heating them to 1000°C for 90 seconds and then immersing them in a container of the appropriate glass powder, this resulted in the powders coating all surfaces of the rings. To apply the glass fibres, the fibres were teased out into flat mats and the heated rings were placed on top of one mat with a second mat placed on top of them; a ceramic heat tile was placed on top of the second mat to ensure there was contact between the surfaces of the rings and the fibres. Once cooled, the tile was removed and any excess fibres were trimmed from the edges of the rings. This method of applying the fibres produced coatings on the flat surfaces of the rings and left the inner and outer diameter surfaces uncoated, the results are shown in figure 1.

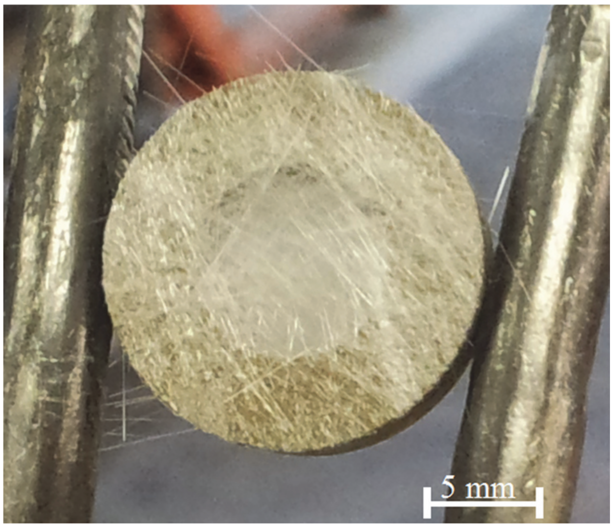

Fig. 1. *Ring specimen with glass fibres applied.*

Compression testing was performed using the University of Sheffield's Thermo-Mechanical Treatment Simulator (TMTS). This set up allowed a programmed sequence to control the entire experiment from heating to compression to post-compression quenching. The coated rings were placed in the machine's sample holding apparatus, an induction furnace was used to heat the specimens to 1100°C and hold them at temperature for approximately 30 s; temperature was monitored throughout testing by the use of thermocouples embedded in each specimen. Once the temperature of the specimens was stable they were inserted directly into the test furnace (held at 200°C) and compressed at a strain-rate of 1 s^{-1}. The height reductions for each batch of specimens are given in table 1. Initial tests were conducted using specimens coated with a boron nitride aerosol; these tests served to verify experimental procedure prior to testing with the glass coated specimens. At the end of each test the specimen was removed from the test furnace and water quenched. The final dimensions of the deformed ring specimens were measured at 12 locations around the diameter of the ring and the average results plotted as the percentage reduction in height against the percentage reduction in internal diameter.

Table 1. *Height reduction of the test specimens given as true strain values.*

Lubricant	True Strain Values				
Boron Nitride	0.2	-	0.5	0.7	0.8
Glass Fibre	0.2	0.36	0.5	0.7	0.8
Powdered Glass Fibre	0.2	0.36	0.5	0.7	0.8
Borosilicate Powder	0.2	0.36	0.5	0.7	0.8

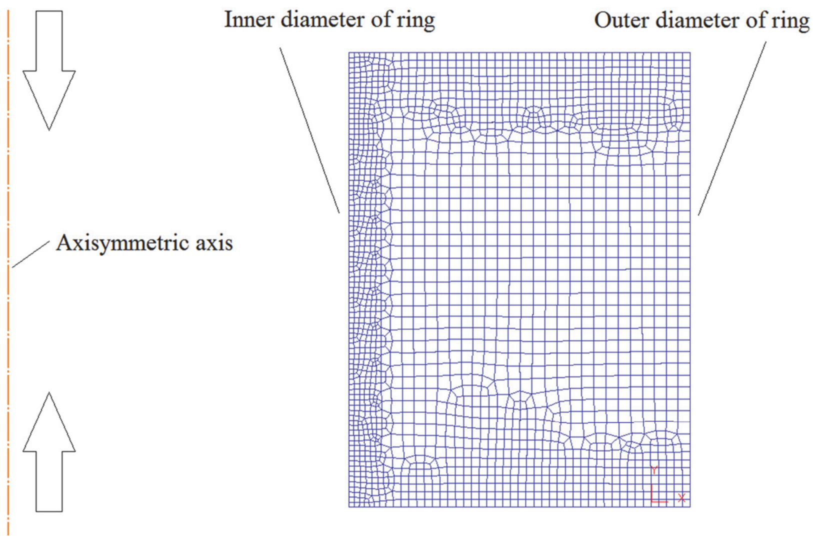

Fig. 2. *The starting mesh and setup for all simulations performed, the arrows indicated the direction of compression.*

2.2. FE Simulation Work and Experimental Results

The ring compression tests were initially modelled as an isothermal 2D axisymmetric process using DEFORM 2D V11 in order to determine if isothermal modelling would be sufficient to identify friction values. Simulations were performed using the shear friction law and friction factors $0 \leq m \leq 1$ in increments of 0.1 at the contact surfaces between the rings and the compression platens; a plastic flow model was used taking the Sellars-Tegart flow stress rule with constants generated from previous in house work (Sellars & Tegart, 1972). All simulations were performed using the same base simulation file and mesh (figure 2). The mesh was comprised of 2087 elements with an average element size of 0.168 mm. Mesh refinement was performed at the contact surfaces and the inner diameter to accurately capture heat transfer contact behaviour and the internal deformation of the ring, the element size in these regions varied between 0.06 and 0.09 mm. The temperature of the isothermal simulations was set to 1100°C and strain rates were kept the same as in the experimental work. The isothermal friction factor calibration curves generated using DEFORM 2D are presented in figure 3 and figure 4 shows the experimental calibration curves on the same plot as the calibration curves.

Figure 4 indicates that several of the lubricants tested would have a friction factor of $m > 1$, this is not a possible value for m and indicates a problem with the simulation curves. The key difference between experimental and simulation work was non-isothermal testing compared to isothermal simulations. Analysis of temperature data logged during the compression test indicated that significant heat was lost during the compression of the specimen with temperature losses of up to 200°C recorded in some tests. The simulations were repeated with a contact HTC of 2.188 N/mm/s/°C (as used in Ti-6Al-4V extrusion simulation work using glass lubricant previously performed by Li et al. (2002)) in an attempt to account for the heat transfer effects observed. These simulation results gave temperature decreases of approximately 70°C. Performing simulations with higher HTC values (20 N/s/mm/°C) produced additional increases in the deformation of the internal diameter of the rings and temperature losses similar to those recorded experimentally (225°C). A comparison of calibration curves for isothermal simulations and simulations with HTC values of 2.188 N/s/mm/°C and 20 N/mm/s/°C is given in figure 5.

The results indicate that modelling heat transfer will result in an increased reduction of the internal diameter of the rings and produce significantly higher friction factor curves. For the high HTC simulations the curve corresponding to a friction factor value of $m = 0.5$ is above the curve for $m = 1$ that was generated with an HTC of 2.188 N/s/mm/°C. The assertion that heat transfer is the cause of discrepancies between isothermal simulation results and experimental measurements is reinforced by comparison of the shape of simulation specimens with experimental specimens as shown in figure 6, figure 7 and figure 8.

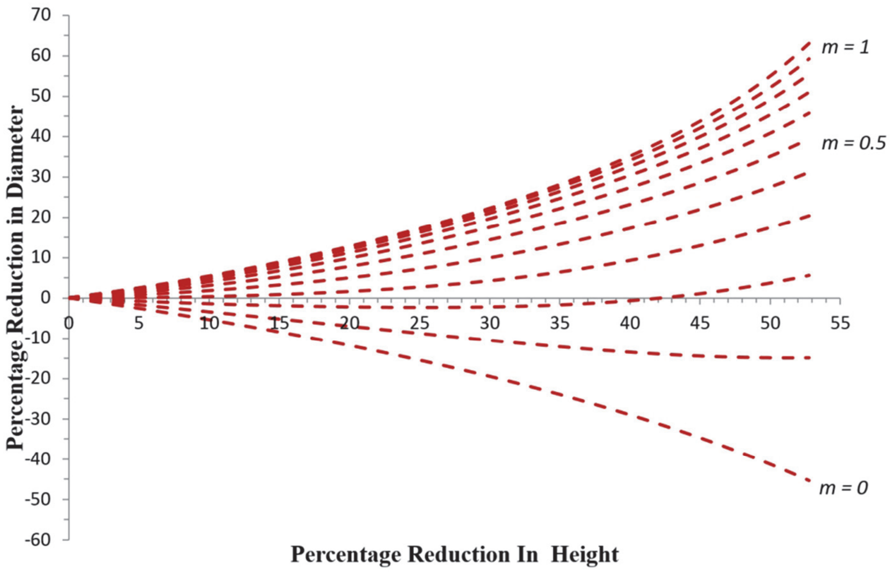

Fig. 3. Friction factor calibration curves generated via isothermal simulations.

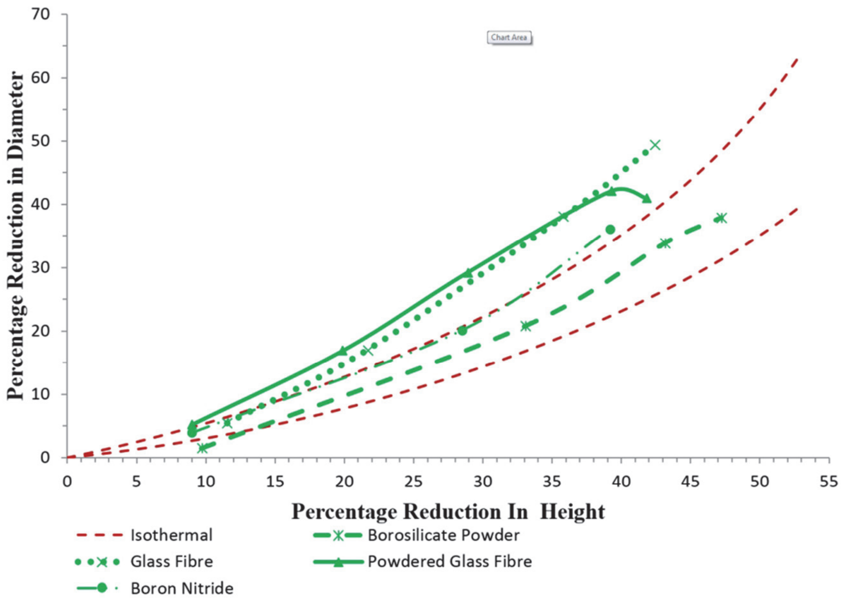

Fig. 4. Experimental results are presented alongside the isothermal simulation calibration curves.

The shape of the workpiece from low HTC simulation results and that of the compressed specimen are noticeably different (figure 6 and figure 8). The use of a higher HTC value provides greater heat transfer from the specimen to the platens; this results in rapid chilling of the ring at the contact surfaces and consequently an increase in flow stress in this region. Deformation then becomes concentrated in the hotter regions of the compression specimen and there is a localised increase in flow velocity; the results can be seen in figure 7 where the shape produced has a deformation pattern closer to that of the experimental specimen than that produced by the low HTC simulations.

3. DISCUSSION

– The results obtained from experimental work produced calibration curves that varied significantly from what was expected. When plotted against the calibration curves generated via isothermal simulation work, the apparent friction factor values for some of the glass lubricants exceeded the sticking condition with values of $m > 1$. It was determined that the use of isothermal simulations to generate the calibration curves was not suitable for the testing conditions modelled. Non-isothermal simulations performed using HTC values found in literature

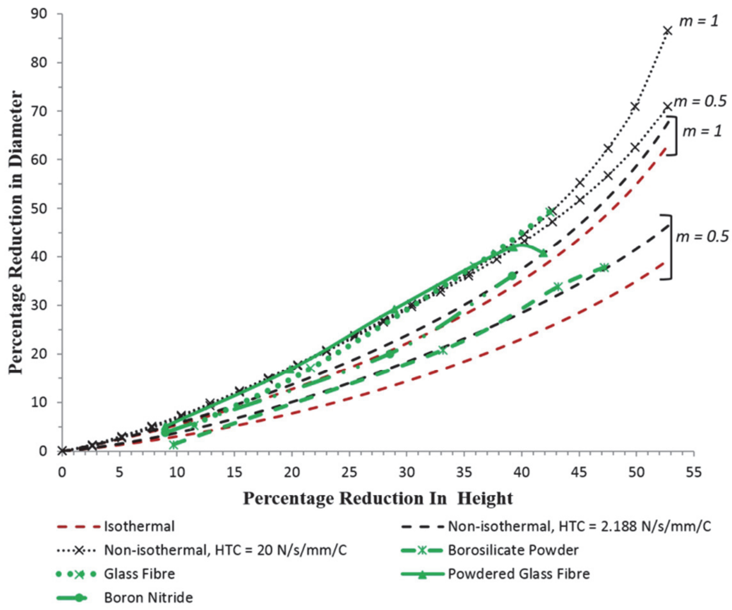

Fig. 5. *Isothermal calibration curves and non-isothermal calibration curves with a HTC at contact surfaces of 2.188 N/mm/s/°C.*

produced calibration curves with an increased degree of reduction of the internal diameter of the compression rings. The result was an increase in the gradient of the calibration curves compared to the isothermal curves at the same height reduction; increasing the HTC used in the simulations further moves the curves changing the position of the experimental results in relation to them such that experimentally determined values of *m* no longer exceed 1. Comparison of images of the cross-sections of the experimental specimens to the simulations revealed that simulations with high HTC values produced a similar cross-sectional shape to that of the experimental results. The areas where deformation was concentrated in the experimental specimens was observed in macrographs; these areas of deformation show similarities to strain maps produced by high HTC simulations. However, these results indicate that different values of friction factor could be assigned to the experimental data by adjusting the HTC used in the simulation. As the friction factors and the HTCs present at various interfaces in the experiment are unknown it is impossible to estimate the HTCs by fixing the friction factor in the simulation and varying the HTC value until the curves become aligned with the experimental data as the same deformation may be produced by:

– Low friction paired with a high HTC
– High friction paired with a low HTC

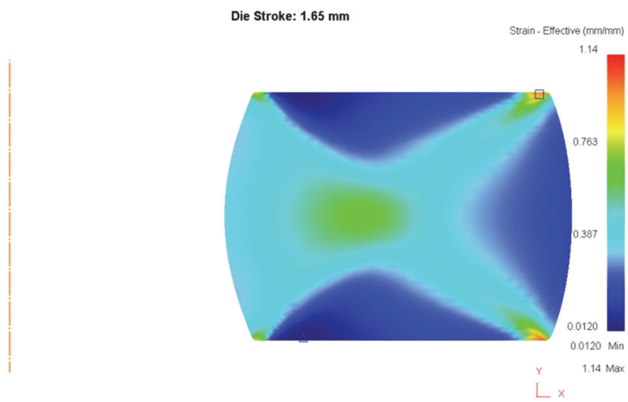

Fig. 6. *Simulation image of the strain distribution and shape at* $\varepsilon_T = 0.5$ *with friction 0.5 and HTC=2.188 N/s/mm/°C.*

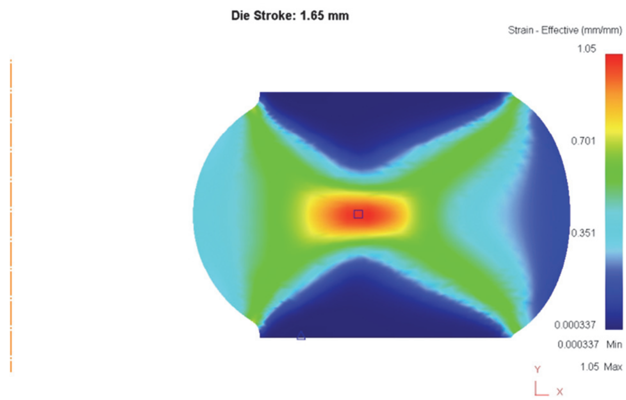

Fig. 7. *Simulation image of the strain distribution and shape at* $\varepsilon_T = 0.5$ *with friction 0.5 and HTC=20 N/s/mm/°C.*

In addition to this it is possible for the heat transfer of the system to be relatively complex as it may involve combinations of heat transfer through lubricants to the test platens, from bare metal to the environment on the sides of the rings as well through lubricant to the environment for specimens that were entirely covered by lubricant.

A further complication is that die chilling produces not only a localised increase in flow stress but may also result in phase changes in the material. In the case of Ti-6Al-4V this would result in a transformation from the BCC β phase where flow stresses are typically low to the α+β phase (HCP+BCC) where flow stresses are significantly higher. These two phases are usually modelled in FE simulations using different flow stress formulations, so it is necessary to ensure that the material model used to simulate the process is robust enough to account for this possibility.

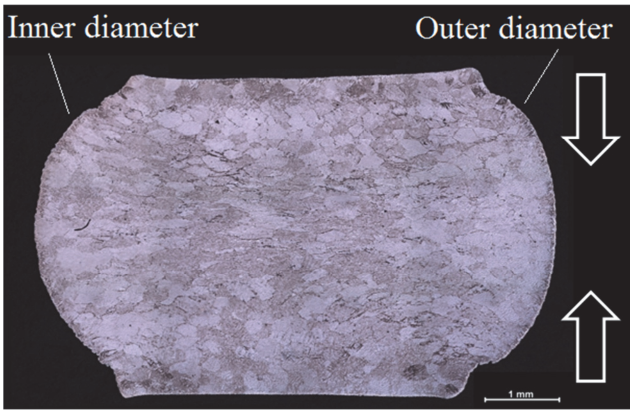

Fig. 8. *Composite micrograph of the cross-section of a compression ring deformed to ε_T = 0.5 (actual ε_T = 0.46).*

4. CONCLUSIONS

In order to accurately determine the friction factor via a combination of ring compression tests and simulation work it is necessary to correctly model the full experimental conditions in the simulation. For non-isothermal conditions where there is a large temperature gradient between the specimen and the test environment the heat transfer will significantly alter the deformation behaviour of the ring compression specimens compared to isothermal conditions. The impact of correctly modelling thermal conditions may vary with the magnitude of the thermal gradient between the workpiece and the environment. The extent of the heat loss recorded during experimental testing implies that a robust flow stress model is required to model the test in order to reflect any phase changes that may occur during the process and accurately predict the flow of material as a result of phase changes and temperature variations.

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MODELOWANIE PRÓBY SPĘCZANIA PIERŚCIENI W WYSOKICH TEMPERATURACH DLA WYZNACZENIA WSPÓŁCZYNNIKA TARCIA ODKUWEK ZE STOPU TI-6AL-4V

Streszczenie

W pracy badano warunki tarcia w wysokich temperaturach pomiędzy odkuwkami ze stopu Ti-6Al-4V i szkłem, będącym smarem, w próbie spęczania pierścieni przy wykorzystaniu modelowania metodą elementów skończonych. Sprawdzono możliwość zastosowania symulacji zarówno przy zachowaniu warunków izotermicznych, jak i nieizotermicznych, do modelowania nieizotermicznych warunków prób doświadczalnych. Czynnik tarcia oszacowano porównując zmiany wewnętrznej średnicy pierścienia w eksperymencie i symulacji numerycznej. W trakcie badań zaobserwowano, że wartość współczynnika wymiany ciepła (HTCs) przyjęta w modelowaniu ma istotny wpływ na wyznaczony w oparciu o symulacje czynnik tarcia. Zauważono, że możliwe jest otrzymanie zbliżonych wyników dla kombinacji: mały HTCs/duża wartość czynnika tarcia oraz duża wartość HTCs/mały czynnik tarcia. W związku z powyższym stwierdzono, że warunki wymiany ciepła w procesie nieizotermicznym, charakteryzującym się znacznym gradientem temperatury pomiędzy próbką a otoczeniem, powinny być prawidłowo uwzględnione dla poprawnego wyznaczenia czynnika tarcia stosowanego w kolejnych symulacjach.

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