Name of the Student	S.Christopher Solomon
S.R.No.	6311-130-161-04456
Degree	Ph.D
Research Supervisor	Prof.S.V.Kailas, IISc Dr.M.R.Suresh, VSSC, ISRO
Affiliation	Department of Mechanical Engineering Indian Institute of Science, Bangalore
Research Title	Estimation and Control of Friction In Bulk Plastic Deformation Process

Synopsis

Friction plays a significant role in bulk plastic deformation processes in controlling the tool life, formability of the work piece material and the quality of the finished product such as, surface finish, microstructure and mechanical properties. Friction causes in-homogenous deformations, leading to defects in the finished products.Excessive friction leads to heat generation, wear, pick-up and galling of the tool surface, resulting in premature failure of the tools. Computer simulations based on Finite Element Methods are being extensively used for process planning and tool designin metal working industry for bulk plastic deformation process.Material and friction models used in simulation packages are very important to have accurate process simulations. Hence it is essential to estimate the friction and understand its role on deformation of the work piece to do realistic process simulations.

Friction in bulk plastic deformation processes is influenced by many factors such as velocity, temperature, contact pressure and tribological conditions such as surface roughness, lubrication etc. Among the above factors, Surface Roughness and Surface Topography (ST) of the die material are the important parameters that influence the friction between the dies and the work-piece. The abbreviation “ST” is used for surface topography. Transfer layer formation and the coefficient of friction along with its two components, namely, the adhesion and ploughing, are controlled by the ST. Ploughing component is mainly the frictional resistance caused by asperities of hard surface ploughing through soft material. The force required for plastic flow of softer material represents the ploughing friction component. Adhesion component of friction is due to the cold welding/adhesive bond occurring in the real contact area of asperities. The force required to shear the adhesionjunctions formed at the interface represents the adhesion component. Though surface characteristics such as roughness were dealt with by many researchers, the influence of surface topography on friction and microstructure evolution in bulk plastic deformation is still to be understood well.Though the work done by Menezeset al.has shown that friction is influenced by the surface roughness, ST and transfer layer, but does not link this ST to the microstructural evolution of the material.Friction influences the strain and strain rates imparted to the deforming material. The strain and strain rate (apart from the temperature) imposed on the deforming material would in turn influence the microstructural evolution of the work-piece. Thus,forapplication to industrial scale it is important that the influence of friction on the bulk deformation and microstructural evolution, if any, be understood.Further, the techniques used by Menezes et al. for generating the STs are very difficult to be adopted in industrial scale.

The present thesis addresses the following three issues on the possible influence of friction in metal forming.

- Use of surface generation techniques that can be easily adapted at the industrial scale.
- Role of ST on friction during room temperature and high temperature deformation.
- Role of this friction on the microstructural evolution during bulk plastic deformation of Aluminium alloys.

The die materialscommonly used in metal working processes namely H11 die steel & EN8 are used in the present study. STs on EN8 and H11 Die steel materials are generated using manufacturing processes adaptable to industrial scale. The methods used include conventional techniques like Grinding, Turning, EDM and advanced techniquesusing Laser.Different textures on the platens were generated using anNd-YAG solid-state pulsed laser by varying the pitch and feed rate of the laser. The surfaces are then characterized using a 3-D optical profilometer and 3-D contact profilometer. Scanning Electron Microscope (SEM) is also used to reveal the morphology of the platen surface.

The aluminium alloys AA7175 and AA2219 are chosen as they are extensively used in aerospace applications. Direct Chill cast and homogenized billets of these alloys are studied as they are generally used as input material for further conversion into wrought products through various metal working/ bulk plastic deformation processes.

To understand the role of strain, strain rate and temperature on the microstructural evolution, deformation studies were carried out on cylindrical compression testspecimens at sixdifferent strain rates and seven temperatures including room temperature.The flow stress, strain hardening behaviour and strain rate sensitivity of the AA7175 and AA2219 billets were evaluated from the flow stress data. Processing maps were then generated to determine the “safe workability” regime for these alloys so that friction can be evaluated at these temperatures and strain rates.Dynamic Recrystallisation regime (DRX), Dynamic Recovery and other “safe workability” regimesare characterised based on the efficiency of power dissipation of the material and microstructural analysis. The regions of “unstable flow” were also identified so that the same can be avoided during the processing.The optimal condition for hot working of AA7175 DC cast and homogenised billet is found to be in the temperature range of 300–400°C and strain rate in the range of 10^{-1}–$10^{-2}s^{-1}$ and that for AA2219 is found to be in the temperature range of 400–450°C and Strain rate in the range of 10^{-1}–$10^{-0.5}s^{-1}$.

To study the influence of ST on friction at room temperature, Uni-directional pin-on-plate tests were done. In this test, a pin made of the test material is slid against an inclined plate made of the die material. On this plate, various STs are incorporated. This test helps in evaluating friction under varying axial loads in a single experiment. Tests were done with AA7175 pins and EN8 flats which were textured using conventional grit polishing, grinding and advanced laser texturing techniques.Five different types of laser textured surfaces were studied using pin-on-plate tests. Lubricated sliding experiments, which is idealised to give the ploughing component of friction, were done on various laser textured surfaces. It is found that the ploughing component of friction is controlled by ST of die material and it is the major factor contributing to about 60-85% of the total friction for the range of surface textures tested. Ploughing component of friction is almost same for all the laser textured surfaces (0.2-0.27) having unidirectional lay and is marginally higher (0.38) for laser textured surface with random surface texture.The laser texture surface 1 is found to have lowest adhesion and ploughing components of friction and uniform surface topography.Hence the laser parameters for surface 1 is taken as basis for generating textures on platens for further studies by changing the feed and pitch of the laser head.

In a pin-on-plate test, the output is only the friction and does not involve bulk plastic deformation of the work-piece material (pin material). Bulk plastic deformation in the work-piece material is required to understand the influence of friction on the microstructural evolution.A test that can be used to study the effect of friction and its influence on microstructural evolution in a work-piece material is the ring compression test. Hence ring compression tests are done at room temperature.The dies used in the ring-compression tests are made of EN8 and H11, the commonly used die materials. These tests enable the study of variousfactors such as surface texture, platen velocity and the influence of friction on microstructureevolution together. EN8 platens were textured using turning, grinding and laser texturing techniques. Six different textures were obtained using the laser texturing by changing the pitch and feed rate of the laser head and retaining the basic laser parameters as that of laser surface 1 used for pin-on-plate testing. For H11 platens, in addition to the above textures done for the EN8 platens, EDM and MoS_2 coatings were also done. Lubricated ring compression tests were done at room temperature to estimate the ploughing component of friction for various textured surfaces. Ring compression tests were done with velocities in the range of 0.6mms^{-1}–0.006mms^{-1}to simulate strain rates in the range of $10^{-1}s^{-1}$ to $10^{-3}s^{-1}$. The results at room temperature indicate that friction is independent of velocity or strain rate. Surface texture of the platen influences the friction factor to a great extent in bulk plastic deformation process. The turned surface texture has an unidirectional perpendicular texture for the radial flow of material during ring compression testing, providing a plain strain condition of deformation near the surface region, which increases the ploughing component of friction. For the room temperature tests, EDM surface and turned surface exhibited high friction factors. Friction factor is found to besimilar for all laser textured platens. Further, the friction factor is found to be lowest for MoS_2 coated platens, which would act as a solid lubricant.It is also found that the friction factor did not vary much between H11 and EN8 plates at room temperature. However, friction factor for H11 platens were found to be marginally lower compared to EN8 platens. This can be attributed to the differences in the average surface roughness and hardness of H11 (50 HRC)and EN8 (45 HRC) platens. Similarly AA7175 rings are found to exhibit marginally higher friction than AA2219 rings at room temperature tests. This is primarily due to the difference in the flow stress at room temperature. Room temperature ring compression tests with lubricated platens were done to evaluate the adhesion and ploughing components of friction. The adhesion component of friction is in the range of 0.05-0.15 for various textured surfaces. For lubricated contacts, friction at low velocity (0.006mms^{-1}) is marginally higher. Lower friction at higher velocity (0.6mms^{-1}) is possibly due to a mixed lubrication regime operating at interface between the die and work piece. Even for lubricated contacts, EN8 platens are found to exhibit marginally higher friction than H11 platens. This is attributed to the higher variations in "bearing area ratio" for EN8 platens compared to H11 platens. AA7175 ring is observed to exhibit marginally higher friction compared to AA2219 in lubricated contacts. This is due to the ploughing components of friction being predominant and the flow stress values of AA7175 material is higher than AA2219 at room temperature. Pin-on-plate test results are correlated with the room temperature ring compression tests so that ring compression tests can be used for characterising the friction at high temperatures.

High temperature ring compression tests are done in the hot workability regime (350-400^{o}C and strain rates of 10^{-3}s^{-1} to 10^{-1}s^{-1}) for both AA7175 and AA2219 using textured H11 platens.As the temperature of the material increases, the flow stress of both the work-piece and die material reduces. The reduction in the flow stress of the work-piece is higher when compared to that of the die material because of the lower melting point of the work-piece. Thus the work-piece material will plastically deform more at higher temperatures making it flow more easily, making it conform more closely to the ST of the die. This will increase both the ploughing and adhesion component of friction thus increasing the coefficient of friction with temperature.

Friction factor is found to increase with temperature for both AA2219 and AA7175 rings for all textured platens except EDM surface which is found to have marginal reduction in friction. Increase in friction at high temperature is mainly due to the increase in real contact area and adhesion,and due to decrease in flow stress. Ring compression tests done with platens having turned surface textures exhibited marginal increase in friction with temperature. EDM surfaceis found to have higher friction at room temperatures due to higher ploughing component of friction as these surfaces were having higher average slope for the asperities. Hence at high temperature, the increase in real contact area is not very appreciable and the decrease in friction for the EDM surface is attributed to the reduction in shear strength of the material at high temperature.

Friction is found to be high at very low velocitiesin the temperature range of 200-400^{o}C. However at higher temperaturei.e. 450^{o}C and above, friction is very high reaching sticking condition and is independent of velocity.All textured surfaces exhibited similar friction at high temperature (200-400^{o}C). AA2219 is found to exhibit marginally higher friction factor than AA7175 at high temperature tests. This is primarily due to the strain rate sensitivity of the material. AA2219 has higher strain rate sensitivity, resulting in relatively higher flow stress at higher temperature compared to AA7175. Hence AA2219 has marginally higher friction at high temperatures and higher strain rates. The variations in microstructure across the section for ring compression test samples are compared with those obtained from the cylindrical compression tests to study the influence of friction on microstructural evolution in work-piece material.

Influence of transfer layer on friction is very significant in bulk plastic deformation process. In order to characterize the influence of transfer layer on friction, pin-on-disc testing is done to characterize the friction at high temperature by repeated sliding on the same track. Pin-on-Disc testing is done with AA7175 pins and EN8 ground disc in the temperature range of 25^{o}C to 500^{o}C.The width of wear track increases with increase in temperature. The transfer layer is found to be continuous and cover almost the full surface of steel at high temperatures. The increase in friction at high temperature is mainly due to the decrease in flow stress, resulting in increased transfer layer formation. The adhesive forces are found to increase with increase in temperature. The quantum of material transfer with temperature is a qualitative measure of intensity of adhesive forces.The high temperature ring compression test results are correlated with pin-on-disc test results and it is found that very good correlation exists between pin-on-disc test and ring compression test.

Various friction measurement techniques, such as pin-on-plate test, ring compression test and pin-on-disc test, were used to determine friction and the results were found to be similar for all three tests. This indicates that friction values obtained from any of these tests could be used for simulation studies.Finite element simulations were done for ring compression tests and friction calibration curves were generated. The material properties for the FE analysis is obtained from the true stress strain curves of the cylindrical compression tests. Elastic-plastic analysis has been carried out by varying the friction factor between the platen and ring interface. The analytical solutions developed by

Avitzur,DePierre& Gurney were used for experimental computation of the friction factor and the results are compared with the ring calibration curves generated using finite element analysis.The trend observed in the FEM results matched well with the experimental results. Thus a methodology can be evolved for texture design and analysis of complex metal working processes.

Finally a case study was done for forging a conical shapewith AA2219 where the die surface was prepared by turning. The forging simulations were done using the true stress strain data obtained from cylindrical compression tests and friction factor obtained from ring compression tests. The actual deformed shape was close to that obtained by simulation. This clearly indicated that the friction factors obtained from ring compression tests were found to be closely matching with the actual process. Hence accurate process simulation for complex bulk plastic deformation process of aluminium alloyscould be done using the material data and friction factors characterised for various surface textures from any of the tests mentioned above.