ABSTRACT
Surface texture of the die plays an important role on friction during metal forming. In the present study, unidirectional and random surface finishes were produced on hardened steel plate surfaces. To understand the influence of surface texture on the friction, experiments were conducted using Al-Mg alloy pins that slid against steel plates of different surface texture. In the sliding experiments, a high value of coefficient of friction was observed when the pins slid perpendicular to the sliding direction and a low value of friction occurred when the pins slid on the random surfaces. FE simulations were performed using the measured friction values to understand the stress and strain evolutions of various surface textures. The numerical results showed that the states of stress and strain rates are strongly influenced by friction at the interface, and hence would influence the final material microstructure. To substantiate the numerical results, laboratory compression tests were conducted. Surface textures on the die were attained so as to experience different friction values at different locations. A large variation in the microstructure at these locations was observed during experiments, verifying the hypothesis that surface texture and friction influence fundamental material behavior.

INTRODUCTION
Friction has an important influence in metal forming operations. By controlling the surface texture of the die, the interfacial friction can influence the net shape of the finished work-piece. The die surface can also affect the strain-rate distribution in the work-piece, which is believed to ultimately determine the microstructure evolution of the deforming material. Thus, the die surface finish can be manipulated to obtain desired microstructure within the finished work-piece.

Efforts have been made to study the influence of die surface texture on friction during metal forming processes using experiments [1, 2]. In addition, attempts have been made to study the influence of friction on the deformation in metal forming operations using numerical analyses [3, 4]. In the present study, experimental and numerical simulations were performed to investigate the influence of surface texture and friction on the strain-rate response and microstructural evolution of the deforming materials.

EXPERIMENTAL DETAILS
To prepare the experiments, two different surface textures – unidirectional and random - were produced on EN8 steel plates. The unidirectional surface was created by dry grinding the plates with emery paper of 600 grit size. The random surface was generated under wet grinding conditions using a polishing wheel and SiC powder (600 grit). The surface roughness parameters of the steel plates were measured using an optical profilometer. Experiments were then conducted using a pin-on-plate sliding tester. The details of the apparatus have been described previously [5]. In the sliding experiments, the pin and plate were made of Al-4Mg alloy and EN8 steel plate, respectively. For the unidirectional surface, the pin was slid perpendicular to the unidirectional grinding marks on the steel plate. Experiments were conducted under both dry and lubricated conditions in ambient environment.

During the sliding tests, the friction values were obtained for the different surface textures. These friction values were subsequently used directly at the die – workpiece interfaces in finite element compression simulations to ascertain the state of stress, strain rate distribution and the deformed shape in the workpiece. All of the finite element simulations were performed using commercially available finite element code, DEFORM 3D. The finite element code is based on the flow formulation...
approach and uses an updated Lagrangian procedure. In the simulation, the dies (upper and lower) were modeled as a rigid body, while the cylindrical workpiece was modeled as a rigid-plastic body. Material properties typical for an Al-Mg alloy were assigned to the work-piece [E = 74 GPa, σ = 70 MPa, γ = 0.35]. The experimental friction values were assigned at two different locations (each halves of the lower die) between the lower die and the workpiece. A constant coefficient of friction was employed between upper die and work-piece interface for all simulations. Similar to finite element analysis, laboratory uni-axial compression tests were done on cylindrical Al-4Mg alloy at constant true strain rates of 4 s⁻¹ at room temperature. Instead of different friction values (taken from pin-on-plate sliding experiment), different surface textures (unidirectional and random) were generated at each halves on the lower die surface so that the workpiece would experience variable friction at the interface. After the experiment, the deformed workpiece was sectioned along the compression axis and the microstructure evolved was studied using conventional methods.

RESULTS AND DISCUSSION

It was observed that the surface roughness (Rₐ) values measured for different textured surfaces were found to be 0.15 μm and are comparable to one another even though they were prepared using different grinding or polishing techniques. In the pin-on-plate experiments, the coefficient of friction values for the pins slid perpendicular to the unidirectional grinding marks were found to be 0.65 and 0.35 under dry and lubricated conditions, respectively. For the random surface texture, it was 0.35 and 0.20 under dry and lubricated conditions, respectively. This clearly points to the fact that similar Rₐ, the coefficient of friction values changes owing to texture. Thus, it can be inferred that the coefficient of friction considerably depends on surface texture under both dry and lubricated conditions. The influence of surface texture on coefficient of friction is also reported previously [6-8].

To study the influence of friction in metal forming, simulation of compression tests were conducted. In the simulation, the coefficient of friction values, obtained for the unidirectional and random surfaces under dry conditions, namely 0.65 and 0.35, were considered. Figure 1 depicts the distribution of the strain rate for the simulation when the workpiece was compressed to 50%. Here, the coefficient of friction values were same (0.65) between all contacting surfaces. It can be observed that the strain rate distribution, as expected, is the same (i.e., the side view after sectioning perpendicular to the axes along the major diameter) for both the left hand and right hand sides near to the lower interface. In these regions the friction values were assigned to the same in both halves of the die - workpiece interface. Another simulation was carried out by assigning different friction values at different locations at the lower die – workpiece interface. In these simulations, the friction values assigned for the left and right halves of the die – workpiece interface were 0.65 and 0.35, respectively. The friction value was 0.65 between upper die and work-piece interface. Figure 2 shows that the distribution of strain rate is significantly different for the left hand and right hand sides near to the lower interface when the friction is different. Low effective strain rate is observed at the left half and near to lower die – workpiece interface when high friction value is assigned. However, high effective strain rate is observed at the right side and near to the lower die – workpiece interface when low friction value is assigned. In addition, it can be seen that the high strain rate region in the core of the work-piece in the first simulation (Fig. 1) shifts towards the region of higher die - workpiece friction in the second simulation (Fig. 2). Furthermore, the shape at the periphery of the work-piece is the same for the first simulation (Fig. 1) and different for the second variable friction simulation (Fig. 2).

![Fig. 1 Variation of strain rates when same friction values were assigned at the lower die - workpiece interface.](image1)

![Fig. 2 Variation of strain rates when different friction values were assigned at the lower die - workpiece interface.](image2)
of strain rate and temperature various kinds of microstructural mechanisms will operate leading to different microstructural evolution [9]. Thus, similar to finite element analysis, laboratory compression tests were conducted with unidirectional and random textures on the left and right halves of the lower die surfaces, respectively. Figure 3 (a) shows the photograph of the cross section of compressed work-piece. The arrows indicate the type of texture generated on the low die surfaces. It can be observed that the material flow was found to be greater at the right hand side of the work-piece that experiences low friction coefficient due to random surface texture. The optical micrographs taken near the interface is also presented in the figure (figures (b) and (c)). It can be seen that microstructural features are different in both sides of the work-piece. Thus, in this study, it can be inferred that the surface texture of the die plays an important role in controlling the friction which intern controls the stresses and strain rates and thus microstructural evaluation in the deforming materials.

**REFERENCES**


