CFD analysis of hydrodynamic lubrication effects of micro textured surface

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Abstract. A great number of lubricated mechanical components everywhere in life. Improvement in efficiency would lead to greater cost savings in many engineering applications. In the present paper, an approach to increase the efficiency in hydrodynamic lubrication for applications in metal forming processes by surface texturing was studied using Computational Fluid Dynamics (CFD) simulation. A two-dimensional fluid domain containing a flat upper wall with a tangential velocity and a static lower wall containing an oblong groove of the same sizes was studied. This includes the effect of varying distances between grooves on lubrication. With an isothermal lubrication flow condition and parallel walls, the pressure in the lubricant domain produces largest load carrying capacity and wall shear force, indicating large contact area contributes to an increase of frictional force. The present study revealed that the positive influence on hydrodynamic lubrication performance can be achieved by introducing a textured surface. Larger distance between the grooves has effectively produced a pressure build-up in the lubricant domain introducing a larger load carrying capacity. It is seen that a load carrying capacity exists for a small distance between the grooves.

1. Introduction
Lubrication is important to reduce friction and to prevent wear of the sliding surfaces in many engineering applications. Poor lubrication has always been the reason to inferior surface finish and production stops in metal forming operations. The good boundary oils alone cannot solve tool wear problem. Combating tool wear with thin-film coatings, surface treatments and anti-seizure tool materials are common practices applied in industry to prolong the life of tooling. These are, however, depends on the type and cause of tool wear [1]. These days, the application of surface texturing to facilitate lubrication in engineering applications such as in stamping and forging is well known. While texturing of workpiece surfaces to promote lubrication in metal forming has been applied for several decades, tool surface texturing is rather new. Texturing workpiece surfaces by using large rolls roughened by Shot Blast Texturing (SBT) or Electro Discharge Texturing (EDT) [2] has become a state-of-the-art for several decades to promote mechanical lubricant entrainment, pressurization and possible escape by micro-hydrodynamic lubrication [3]. However, it is less feasible in large-scale, multi-stage sheet metal forming production, since the textured workpiece surface will flattened out after first forming operation [4]. A few tests of surface engineered deep drawing tools [5] have shown very promising results, indicating that textured tool surfaces may provide mechanical lubrication systems which can therefore substitute the chemical ones, and thereby replacing the environmentally hazardous lubricants with environmentally benign lubricants [6]. This positive result has shown that creating micro texturing patterns on tool surface would be economically feasible, since the textured
tool surface can be utilized to produce thousands of workpiece components [7]. In the present paper, the hydrodynamic performance of micro-textured surface with varying distances between grooves applied on metal forming tool surfaces, such as pressure distribution streamlines and wall forces, were studied.

2. Materials and method

2.1. Micro-textured surface

Three surface texture parameters were emphasized to promote micro-hydrodynamic lubrication mechanism [8] and to avoid mechanical interlocking in the groove valleys [9]: 1) oblong grooves oriented perpendicular to the drawing direction, 2) small groove angle $\gamma$ and 3) shallow groove depth $d$. Three different texture designs were chosen with a width of flat plateaus between the lubricant grooves $x = 0.23, 0.46$ and $0.92$ mm, respectively. Figure 1 shows the groove angle $\gamma$ and the groove depth $d$ were chosen to be $5^\circ$ and $0.01$ mm respectively. The groove angle was chosen according to recommendations by Sulaiman et al. [7], the depth was determined by the width, which was chosen small enough to ensure a sufficient number of grooves along the tool/workpiece interface. The length of the grooves were decided to be smaller than the workpiece width in order to ensure pressure build-up of the trapped lubricant. Figure 2 represents the resulting, measured grooves of nominal dimensions: length $y = 16$ mm, angle $\gamma = 3^\circ \pm 0.5^\circ$, width $w = 0.23$ mm $\pm 0.1$ mm, depth $d = 7 \mu$m $\pm 1$ $\mu$m and distance between grooves of $x = 0.23, 0.46$ and $0.92$ mm. It is noticed that the groove depths reached within the tolerance gap, whereas the groove angles turned out to be somewhat smaller than the aimed at. This is, however, only promoting the micro-hydrodynamic lubrication mechanism and preventing mechanical interlocking [9].

### Table 1. Surface texture parameters.

| Parameters               | Value |
|--------------------------|-------|
| Groove angle $\gamma$ (°) | 5     |
| Groove width $w = 2a$ (mm) | 0.23  |
| Groove depth $d$ (mm)     | 0.01  |
| Groove ratio $d/w$        | 0.05  |

\[
\tan \gamma = \frac{d}{a}
\]

\[
R^2 = a^2 + H^2 = a^2 + (R - d)^2
\]

Figure 1: Design of groove geometry.

Figure 2: Micro-textured of tool surfaces concentrating on varying distances between the grooves ($x = 0.23, 0.46, 0.92, \text{and } 1.61$ mm) of the same sizes of groove depth $d$ and groove angle $\gamma$.

2.2. CFD analysis of textured surfaces

The present work was carried out using Computational Fluid Dynamics (CFD) FLUENT v6.3. Simulation of a fully wetted smooth upper wall with two different tangential velocities over a static lower wall containing an oblong groove of the same sizes separated by a 40 $\mu$m of lubricating film was performed for 2D steady-state flow of viscous incompressible fluid (density of 940 kg/m³ and dynamic viscosity of 1.06 kg/ms). The two different drawing speeds $u = 240$ mm/s and 65 mm/s were
applied with micro-textured tool features. The high and low speeds were intended to identify possible influence of micro-hydrodynamic lubrication mechanism. The convergence criteria was set to $\varepsilon 10^{-4}$.

3. Results and discussion

3.1. Effects of distance between grooves

Figure 3 shows comparisons of pressure distributions as a function of the sliding distance along the walls in the $y$-direction for the two flat parallel walls separated by a thin lubricating film. The smooth, non-textured lower static surface produces the highest pressure and the highest shear force between all surfaces investigated. This is in fact due to the greater contact area, which in turn gives rise to a larger frictional force. As seen in Figure 3, grooves can be beneficial in reducing the large contact area, thereby reducing the pressure distribution in order to reduce the friction between two sliding surfaces, meanwhile, the lubricant pressures reached its high values on smooth, flat parallel surfaces when no grooves are present, indicating that the grooves influencing the hydrodynamic performance. The benefits of applying grooves is especially pronounced when the distance between the grooves are larger, in which allows lubricant entrapment in the groove and subsequently the lubricant escape out of the groove, as experimentally and analytically proved in ref. [8]. This implies that the larger the distance between the grooves, the lower the lubricant pressure, see Figure 4(a). Same effects can also be observed on the shear force as shown in Figure 4(b). The results explained that the hydrodynamic lubrication efficiency depends on pressure (representing the load carrying capacity) and shear force in the $y$- and $x$-direction, respectively.

Figure 3: Pressure distributions in the fluid domain of the smooth, non-textured and textured surfaces.

Figure 4: Distributions of a) pressure and b) shear force in varying distances between the grooves $x$.

3.2. Effects of sliding speed

The influence of high and slow sliding speeds on hydrodynamic performance in the case of small and large difference between the grooves were studied. Figure 5 shows the load carrying capacity and shear force increases tremendously when the high sliding speed is applied. This is may be due to the relationship between viscosity and micro-hydrodynamic lubrication mechanism [9]. The positive influence of high sliding speed on hydrodynamic performance is as expected, owing to the frictional force produced by the lubricating film. This simulation is in agreement with the experimental results.
[10] and the CFD simulation results [11] from the previous studies on textured surface and their influence on frictional behaviour.

![Graph](image)

**Figure 5:** Effects of high and slow sliding speeds on distributions of a) pressure and b) shear force along the sliding surfaces for small and large distances between the grooves $x$.

4. Conclusion

CFD analysis on the effects of micro-textured surfaces of hydrodynamic lubrication performance was performed. The CFD simulation discussed on the effects of the varying distances between the grooves on the load carrying capacity and the shear force. Introduction of micro-textured grooves to the lower static surface affects the lubricant flow, wall shear force and pressure distributions. The smaller the distance between the grooves, the lower the load carrying capacity as well as the shear force, indicating the grooves influencing the hydrodynamic performance. Larger sliding speed contributes to a larger load carrying capacity and shear force in the lubricant domain. It was found out that an optimum amount of textured tool surface area exists which reduces frictional wall force and pressure between the lubricant and the two sliding surfaces. The textured surfaces were advantageous at greater sliding speeds which facilitate the possible escape of trapped lubricants by micro-hydrodynamic lubrication mechanism.

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