Design and characterization of textured surfaces for metal forming applications

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Abstract. Surface texture has been the state-of-the-art in many tribological engineering applications to enhance lubrication as well as to improve wear resistivity. The present work focuses on textured surfaces manufactured by micro-milling and excimer laser texturing techniques on flat, hard tool steel surfaces. In order to promote lubrication entrapment and possible escape by micro-hydrodynamic lubrication mechanism, shallow, longitudinal grooves oriented perpendicular to sliding direction were designed and manufactured on the tool steel surfaces. The morphological characterization of the textured surfaces was performed using a tactile roughness profilometer, Light Optical Microscope (LOM), Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) measurements. It is found out that both surface texturing techniques are feasible for the surface texturing purposes. Assessment of resulting textured surface topographies by means of LOM, SEM and AFM analysis has revealed that the positive result regarding the desired textured surface profile by the excimer laser technique was obtained, owing to its ability to produce shallow groove depth and smaller groove angle than the micro-milled textured surface. This has been confirmed by observation on the laser textured surface topographies by using LOM, SEM and AFM measurements.

1. Introduction

In many mechanical engineering applications, improper lubrication is not desirable that would results in poor tribological performance and thereby, shortens the lifetime of two metal sliding surfaces. Often, large amount of efficient but hazardous lubricants like chlorinated paraffin oils are seen as the effective solution and able to produce instant result. This is favourable by industry that sees instant profit and high productivity as their priority. The good boundary oils alone cannot solve tool wear problem. Correct tribological contact design and manufacture are critically important in reducing wear. Besides, combating the wear with thin-film coatings, surface treatments and anti-seizure steel materials are common practices applied in industry to prolong the life of the sliding surfaces. These are, however, depends on the type and cause of the wear [1]. These days, the application of surface texturing to facilitate lubrication in mechanical engineering applications such as in metal forming, bearings and internal combustion engines is well known.

Texturing of workpiece surfaces to promote lubrication in metal forming has been applied for several decades, while the 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 been applied to promote mechanical lubricant entrainment, pressurization and possible escape by micro-hydrodynamic lubrication [3,4]. However, it is less feasible in large-scale, multi-stage sheet metal forming production, since the textured workpiece surfaces will flattened out after first forming operation.
[5]. A few tests of surface engineered deep drawing tools [6] have shown very promising results, indicating that textured tool surfaces may provide mechanical lubrication systems which can substitute the chemical ones, and thereby replacing the environmentally hazardous lubricants with environmentally benign ones. This positive result has shown that creating micro texturing patterns on tool surfaces would be economically feasible, since the textured tool surfaces can be utilized to produce thousands of workpiece components.

The present paper studies textured tool surfaces for metal forming applications with a focus on a small groove angle, shallow groove depth, and oblong grooves oriented perpendicular to the sliding direction, with varying distances between the grooves. The manufacturing of the textured tool surfaces by using laser micro-machining and conventional micro-milling were studied comprehensively. The resulting textured tool surface topographies were evaluated by means of LOM, SEM and AFM analysis.

2. Materials and method

2.1. Tool material

The tool steel material is a cold work tool steel SKD11 with high C and Cr contents that was alloyed with Mn, Mo, P, S, Si, and V. The tool steels were through-hardened, tempered to 62 HRC, and subsequently polished to a surface roughness $R_a$ of 0.1 µm before the surface texturing was applied. Table 1 presents the mechanical properties and the compositions of the tool steel used in the experiments.

| Components | Composition | Density $\rho$ (g/cm$^3$) | Poisson ratio $\nu$ | Elastic modulus $E$ (GPa) |
|------------|-------------|---------------------------|---------------------|---------------------------|
| Tool steel (AISI D2) | 1.4% C, 0.6% Mn, 11% Cr, 0.03% P, 0.03% S, 0.04% Si, 0.8% Mo, 0.2% V | 7.58 | 0.3 | 210 |

![Figure 1](image1.png) **Figure 1:** Schematics of laser texturing of oblong shaped grooves on tool surfaces.

![Figure 2](image2.png) **Figure 2:** Mechanical micro-milling to manufacture shallow, oblong shaped grooves on tool surfaces.
2.2. Preparation of textured surfaces by excimer laser and mechanical milling

RapidX-250 KrF excimer laser micromachining and manual-operated conventional milling machine were used to manufacture textured surfaces on tool steels SKD11 with a roughness Ra of approximately \( \sim 0.1 \) \( \mu \)m, see Figure 1 for laser surface texturing technique and Figure 2 shows conventional manual-control micro-milling texturing technique. In the case of laser surface texturing, semi-automatic laser machine was controlled by a highly flexible Computer Numerical Control (CNC) A3200 program. AutoCAD technical details of the desired textured surfaces were first drawn and transferred to BobCAD software before the A3200 program started the laser texturing on the hard steel SKD11. In this study, three surface texture parameters are emphasized to promote micro-hydrodynamic lubrication mechanism [7] and to avoid mechanical interlocking of the workpiece sliding into and out of the groove valleys of the textured tool surfaces [8], which are 1) oblong grooves oriented perpendicular to the drawing direction, 2) small groove angle \( \gamma \) and 3) shallow groove depth \( d \). Four different texture designs were chosen with a width of flat plateaus between the lubricant grooves \( x = 0.23, 0.46, 0.92 \) mm and 1.61 mm, respectively. Figure 3 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 Popp and Engel [9], 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. Table 2 lists the surface texture parameters as calculated by Equation 1 and 2.

![Figure 3: Design of groove geometry.](image1)

\[
\tan \gamma = \frac{d}{a}
\]  
\[
R^2 = a^2 + H^2 = a^2 + (R - d)^2
\]

Table 2. Surface texture parameters.

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

2.3. Surface topography measurements

Roughness profiles of the textured surfaces were evaluated using Mitutoyo Formtracer CS-3100 profilometer, see Figure 4. To further evaluate resulting grooves of the textured surfaces, Light Optical Microscope (LOM), Scanning Electron Microscope (SEM) and Atomic Force Microscopy (AFM) were used to evaluate surface topography of the textured surfaces. The samples were cleaned in acetone for 10 minutes before analysis.

![Figure 4: Measured roughness profiles of the resulting textured surface topographies.](image2)
3. Results and discussion

Figure 5 represents the resulting, measured grooves of nominal dimensions: length \( y = 20 \text{ mm} \), angle \( \gamma = 3^\circ \pm 0.5^\circ \), width \( w = 0.23 \text{ mm} \pm 0.1 \text{ mm} \), depth \( d = 7 \mu\text{m} \pm 1 \mu\text{m} \) and distance between grooves of \( x = 0.23, 0.46, 0.92 \) and \( 1.61 \text{ mm} \). It is noticed that the groove depths were reached within the tolerance gap, whereas the groove angles turned out to be somewhat smaller than aimed at. This is, however, only promoting the micro-hydrodynamic lubrication mechanism and preventing mechanical interlocking.

As seen in Figure 6, roughness profile measurements showed that the mechanical micro-milling texturing technique is feasible for creating desired depth and width of the grooves, however, shallower grooves is best to be manufactured by excimer laser. Interestingly, smooth bottom groove valleys were observed when manufactures of grooves using excimer laser technique, see AFM result shown in Figure 6 to the bottom right image. This smooth groove valleys would be beneficial in reducing stress concentration that leading to localized crack initiation. Additionally, the resulting textured surfaces made by the laser will be cost savings since this would eliminate the problems of polishing the textured surfaces after the texturing operation due to the edge burr present on both groove ends near to the plateau when manufacturing the grooves using micro-milling, see SEM images shown in Figure 6 to the bottom left. It has been realized that, in case of time consumption when it comes to manufacturing the grooves, the excimer laser technique required more times in comparison to the manual operated micro-milling technique. This would probably adding to the manufacturing costs.

![Figure 5: Laser textured tool surfaces concentrating on varying distances between the grooves (x = 0.23, 0.46, 0.92, and 1.61 mm) of the similar sizes of groove depth d and groove angle γ.](image)

![Figure 6: Resulting textured surfaces by means of LOM, SEM and AFM analysis, for as-received tool steel SKD11 condition (left), and the tool steels manufactured by mechanical micro-milling (middle) and excimer laser techniques (right).](image)

4. Conclusion

Applying textured surface on tool steel surfaces is feasible to improve the tribological performance. Implementing laser texturing technique as a method to generate micro-texturing on a hard tool material with desired groove angle, groove depth, groove width and distance between grooves was successfully performed. With the aim to evaluate the resulting textured surface made by the excimer laser technique, the evaluation on surface roughness profiles of each textured tool surface was carried out and comparison was made to the conventional micro-milling technique. Positive result regarding the desired
textured surface profile by the excimer laser technique was obtained, owing to its ability to produce shallow groove depth and smaller groove angle than the micro-milled textured surface. This has been confirmed by observation on the laser textured surface topographies by using LOM, SEM and AFM measurements. Further assessments of resulting textured surfaces by advanced surface profilometer is deemed necessary to address the contribution of constituent spatial components with varied amplitudes and wavelengths. This could give more meaningful measured textured surface parameters in developing a functional correlation between a manufacturing process and its corresponding surface profile.

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