Surface Texture Design for Sheet Metal Forming Applications

Meghshyam Shisode, Ton van den Boogaard, and Javad Hazrati

Abstract Sheet metal surfaces are generally textured to improve tribological performance in deep drawing applications. Variations in coefficient of friction in forming processes is one of the major causes of defective products. The major reasons for an unstable friction condition are the tool wear and inhomogeneity in lubricant amount. Textured surfaces can offer enhanced and stable friction condition. However, there is no clear design guidelines available for texturing sheet metal surfaces for a robust friction condition. Various types of texturing methods are available. In this study, the friction sensitivity of surface texture made by laser-texturing method to variations in tool wear and inhomogeneity in lubricant distribution is investigated. The laser-textured surface parameters such as crater diameter and texture density are chosen within the physically attainable range such that a robust friction behavior during forming process is achieved. A multi-scale friction model is used to determine coefficient of friction for textured surfaces in boundary and mixed lubrication conditions. The friction model in combination with surface generating algorithm is used to optimize individual crater geometry and their spacing. The objective is to determine the surface texture which is least sensitive to the potential variations in the tool roughness and lubricant amount in sheet metal forming applications.

Keywords Friction · Sheet metal forming · Texture · Optimization

Introduction

The laser-textured surfaces are gaining increased attention in industry to obtain a stable friction condition and better paint appearance in automotive and packaging applications. Though there are no mass production techniques yet available which can compete with the electro-discharged textured (EDT) sheet metals but the improved performance by the laser-textured surfaces have triggered motivation to develop mass production techniques. The sheet metal components manufactured by deep drawing

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process have number of uncertainties or variations between the product batches or even two consecutive components which may lead to defective products. The major sources of variations are evolving tool topography due to wear, lubricant migration on sheet surface, change in ambient condition, and material properties of the sheet metal. Controlling the tribological system is one of the important factors to improve the productivity. The tribological system is defined by the tool-sheet metal contact condition, their surface topographies and the lubricant. The tool wear is a major reason which results in unstable friction condition at tool-sheet metal leading to product deviations and failures.

Friction between the contacting surfaces is a local phenomenon which depends on the local surface interactions [1, 2] often referred as the real area of contact. The real area of contact depends on the contact loads, materials, and surface topographies of the contacting surfaces [3]. It is very well understood that the surface texture plays a significant role in determining the coefficient of friction. For instance, the surface pockets of the laser-textured surface can act as lubricant reservoir where a hydrodynamic pressure can build up leading to a lower coefficient of friction.

The main goal of this study is to design a laser-textured surface for a robust friction behavior in boundary and mixed lubrication regimes. The robust friction behavior allows the minimum variation in the coefficient of friction for the uncertainties in the tribological system. In this study, surface texture is designed to achieve least variation in friction coefficient due to variations in the tool topography because of wear and uneven lubricant distribution in the blank. For this purpose, laser-textured surfaces are generated for a range of laser texture parameters such as crater depth, diameter, and density. The coefficient of friction is determined using a multi-scale friction model [2, 3] by varying tool topography and lubricant amount within a realistic range as expected in industrial forming tools.

Approach: Robust Friction Behavior

The current study is limited to laser-textured surfaces under boundary and mixed lubrication friction regimes. The tool surface topography and lubricant amount are used as the uncertainty parameters. The tool is assumed to be rigid and the untextured sheet surface used for laser-texturing to be zinc coated steel (GI) sheet with coating thickness of 7μm and substrate material of DX54. The material properties of zinc coating and steel substrate are required in the friction model and can be found in [2]. A set of laser-textured surfaces are artificially generated based on the physically attainable range of crater parameters [4]. A validated multi-scale friction model for zinc coated steel sheets is used to determine coefficient of friction at a range of contact loads and different surface topographies of the tool surface [1, 2]. Variation in the coefficient of friction due to change in tool topography is determined for all the surfaces. The optimum surface is selected such that it results in minimum variation in coefficient of friction.

Laser-Textured Surfaces

Figure 1 shows the surface topography of the laser-textured surface manufactured by pico-second pulse laser. The untextured GI sheet manufactured in steel industry has a low surface roughness (Sq) $\leq$ 0.5 µm [3] with a gaussian surface height distribution. However, the surface roughness of the untextured sheet can vary based on the process setting and roughness of the underlying steel substrate. The surface roughness of the untextured sheet can also be changed by further treatment such as sand blasting [3]. The surface is textured with a spherical crater of predefined size and area density.

In this study, the texture pattern is generated on the actual untextured surface of GI sheet obtained right after galvanization process. Figure 2a shows a typical untextured surface with Gaussian height distribution and Fig. 2b shows the textured surface and its resulting height distribution.

Multi-scale Friction Model

A reliable friction model is required to determine the coefficient of friction accounting for different surface textures. Traditionally, a constant Coulomb friction behavior is assumed between the contacting surfaces in the boundary and mixed lubrication regimes. However, the experiments [1, 2, 5] show that the coefficient of friction varies depending on contact pressure, strain, and amount of lubrication in the sheet metal. Local surface texture evolves due to the asperity deformation which consequently changes the local surface interaction between the contacting surfaces. The roughness of the surface decreases due to asperity flattening resulting in a decrease in coefficient of friction.

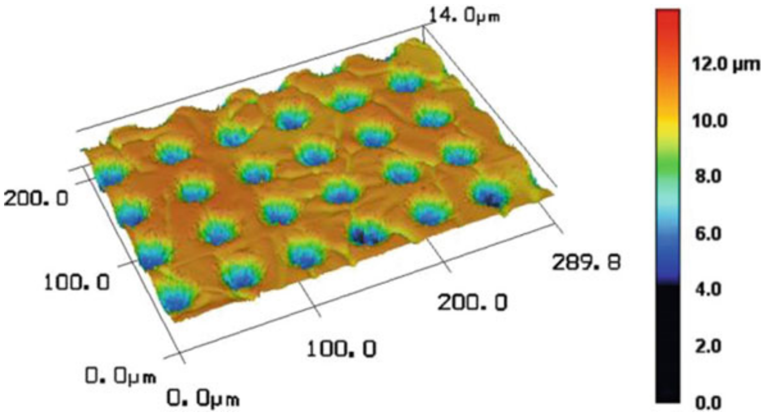


Fig. 1 Laser-textured surface manufactured using pico-second laser [4]

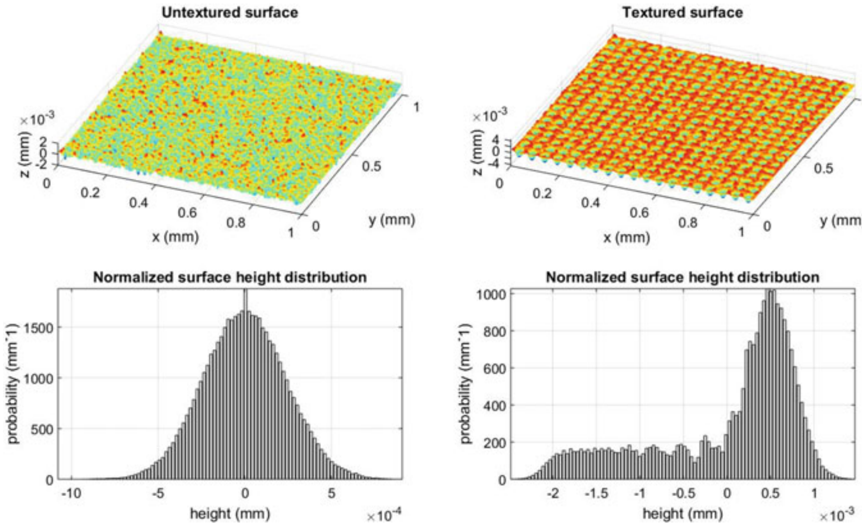
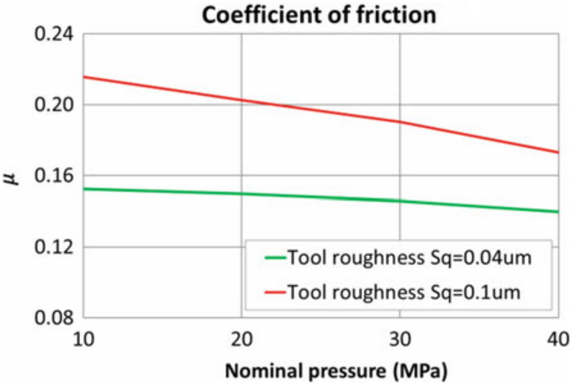


Fig. 2 Left: modeled untextured surface ($Sq_{wp} = 0.3$ μm), and right: textured surface (texture density: 50%, crater diameter: 40 μm, crater depth: 2.5 μm)

Recently, Shisode et al. [1] proposed a multi-scale friction model which considers the surface topography of sheet metal and tool, coating effects, contact loads, and hydrodynamic effects of lubricant to determine the coefficient of friction. More details on friction modeling and its implementation in full-scale finite element analyses of deep drawing processes can be found in [1, 2]. The friction model was validated at different scales using different lab-scale experiments. This model is used here to determine the coefficient of friction between different textured surfaces and forming tool at different contact pressures with varying lubricant amount. Figure 3 shows the result of coefficient of friction for a textured surface determined using the boundary friction model at different nominal pressures and tool roughness.

Fig. 3 Model results for textured surface (texture density = 60%, crater diameter = 30 μm, crater depth = 1.1 μm and untextured surface roughness $Sq_{wp} = 0.25$ μm) at different tool roughness



Surface Texture Effects

The design variables for the laser-textured surface are surface roughness of untextured surface (Sqwp), crater diameter (DLT), and texture area density (ρLT). The crater depth (hLT) depends on the crater diameter and setting of the laser beam. Mustafa et al. [4] have performed lab-scale experiments to produce laser-textured surfaces of steel and GI sheets by varying laser energy, pulse time, and number of pulses. Empirical relations are developed to correlate crater diameter and depth. A relation proposed for a pico-second single pulse laser beam for GI sheet is used to determine the crater depth at a given crater diameter. The uncertainty or noise variables in this study are the surface roughness of the tool (Sqt) and lubricant amount present in the contact. In a typical deep drawing process, the roughness of the tool is much smaller than the sheet surface. However, it can substantially increase due to tool wear. In this study, a measured tool topography from the die corner region of the Ericson press used in validation of the friction model [1] is considered. The roughness of the tool is scaled appropriately to account for the tool wear. Table 1 shows the design variables and uncertainty parameters used in the current study.

The design variables are assumed to be discrete. The measured roughness of the existing tool is 0.07 μm. However, a range of tool roughness from 0.04 to 0.1 μm is assumed to consider the evolution of tool topography due to wear. The crater area density is defined as the fraction of area covered by the texture. There are in total 54 combinations of the surfaces corresponding to the range and distribution of design variables. The coefficient of friction for each textured surface is determined based on finite element simulation of a strip-draw experiment and varying lubricant amount and tool roughness. For this purpose the friction model is coupled with the finite element simulation. More details on coupling the friction model with the finite element simulations can be found in [1, 2]. Figure 4 shows the schematic of the virtual strip-draw experiment, typical friction curve obtained from FE analysis for different tool roughness and lubricant amounts. Figure 4 right depicts the total contact pressure and lubricant pressure distributions for different lubricant amounts representing boundary and mixed lubrication conditions.

Table 1 Design and uncertainty parameters for optimization

Design variables	
RMS roughness of untextured surface Sqwp (μm)	0.3, 0.5
Crater diameter dLT (μm)	30, 45, 60
Crater depth h_{LT} (μm)	1, 3, 5
Crater area density ρ_{LT} (%)	20, 40, 60
Uncertainty parameter	
RMS roughness of the tool Sqt (μm)	0.04, 0.07, 0.1
Lubricant amount (g/m^2)	0.2, 2

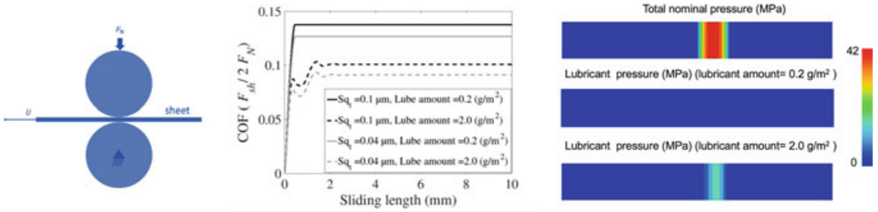


Fig. 4 Schematic of the virtual strip-draw experiment (left), typical coefficient of friction curve result from FE simulation (middle) and total and lubricant contact pressure distributions on the strip (right). The results are shown for the following conditions: $Sq_{wp} = 0.5$ μm, $\rho_{LT} = 60\%$, $D_{LT} = 30$ μm and $h_{LT} = 5.0$ μm

Figure 5 shows the coefficient of friction results at different tool roughness values, untextured sheet metal surface roughness of 0.3 and 0.5 μm and lubricant amount of 0.2 and 2 g/m^2 where boundary and mixed lubrication regimes are mainly expected, respectively. In the boundary lubrication regime, initial workpiece roughness (untextured) can well affect the coefficient of friction (Fig. 5a–c). For surfaces with crater depth (h_{LT}) of 1 μm, the lubricant amount of 0.2 g/m^2 is enough to fill surface valleys hence a mixed lubrication condition prevails, therefore coefficient of friction is lower. By increasing the lubricant amount, coefficient of friction in general decreases due to the mixed lubrication regime. The results show that mixed lubrication regime leads to more robust friction behavior and coefficient of friction becomes less sensitive to the workpiece texture parameters. Furthermore, with increase in tool roughness for both 0.2 and 2 g/m^2 lubricant amounts, rise in coefficient of friction can be observed.

Figure 6 shows the maximum deviation in coefficient of friction due to tool roughness variation for each surface texture design with the initial workpiece roughness of 0.5 μm. It is shown that in the mixed lubrication regime (2 g/m^2), coefficient of friction is less affected with variations in the tool roughness. However, at 60% crater density and larger crater depth, 2 g/m2 is not sufficient to fill the valleys completely and therefore boundary lubrication will be prevalent. As a general trend, in the boundary lubrication regime (0.2 g/m2) the sensitivity of workpiece texture to the deviations in tool roughness is reduced by increasing the crater diameter.

Conclusions

In this study, the first steps to determine the surface texture parameters for a robust friction condition in laser-textured GI sheets are taken. The design variables used for the textured surfaces are the crater diameter, crater area density, and surface roughness of initial untextured surface. The uncertainty parameters used in this study are the roughness of tool surface and lubricant amount distribution. The textured surfaces are modeled for the given range of design parameters. A multi-scale friction model is used to determine the coefficient of friction for each surface by varying the tool roughness

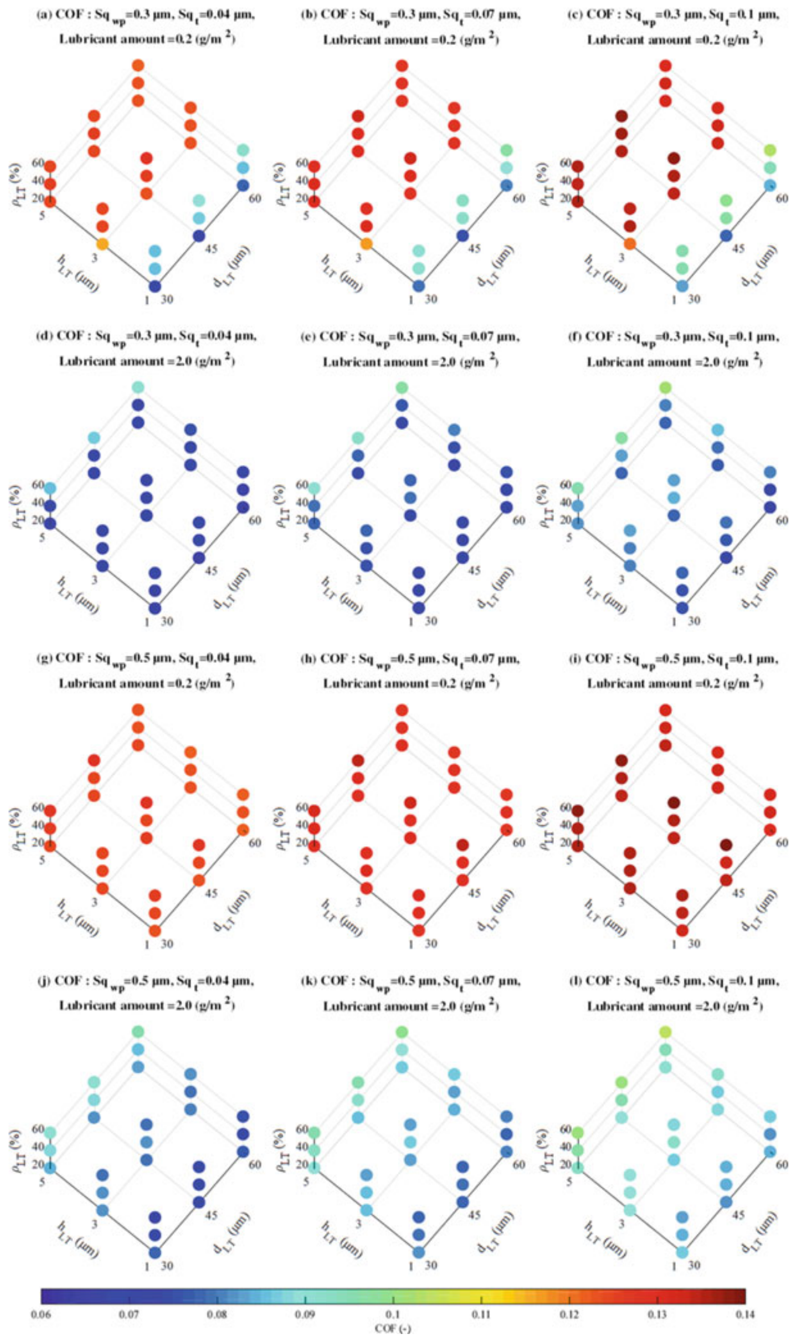


Fig. 5 Coefficient of friction for textured surfaces for the variation in tool roughness and lubricant amount

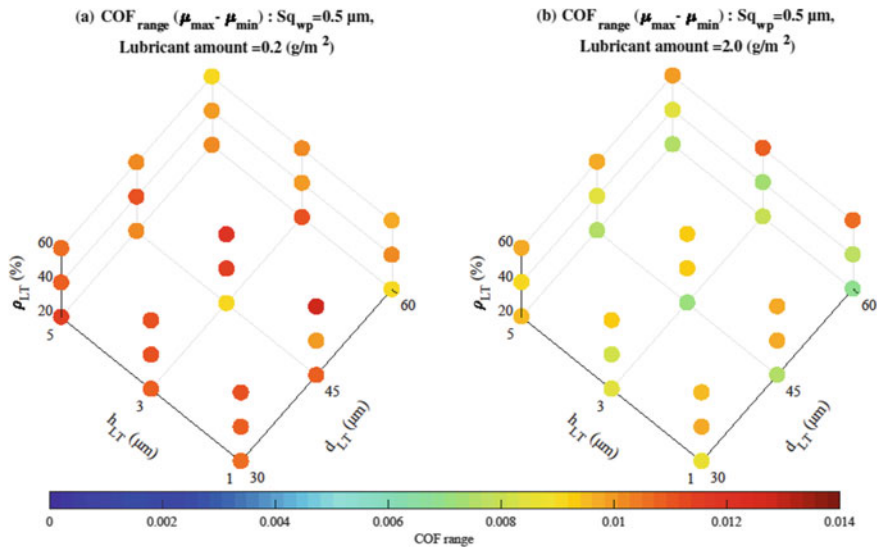


Fig. 6 Range of coefficient of friction with respect to tool roughness at lubricant amounts of (a) 0.2 and (b) 2.0 g/m^2

and lubricant amount in boundary and mixed lubrication regimes. The robustness in friction behavior is quantified in terms of variation in friction coefficient for each surface. The variation in coefficient of friction decreases with decrease in roughness of initial untextured surface and increase in crater diameter in boundary lubrication. The results show that mixed lubrication regime is less susceptible to variations in tool roughness.

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