

Effect of Surface Texture on Sheet Metal Formability in Boundary Lubrication Regime

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Abstract. Friction plays an important role on formability of deep drawn products. This necessitates an accurate description of friction in finite element formability analyses. It has been shown that constant coefficient of friction does not lead to precise prediction of product formability in these analyses. The multi-scale friction model developed at University of Twente takes the local contact conditions and textures of sheet metal and tools as the input at boundary and mixed lubrication regimes. To correlate the zinc coated sheet metal surface texture parameters with its formability, 60 different textures were analyzed. The multi-scale friction model is used to estimate friction for all the different surface textures. The effect of different textures on formability of the sheet metal was investigated by simulating cross-die forming using different sheet metal surface textures. The results show that different textures depict distinct formability behavior in the boundary lubrication regime (lubricant amount 0.5 gr/m²). Exploring the correlation between areal roughness parameters of the current dataset and formability of cross-die shows that besides surface roughness, autocorrelation length and skewness of height distributions are determining parameters.

Introduction

Friction plays a key role on formability of sheet metals. It has been shown that friction is a local phenomenon which depends on the contact conditions between tool and workpiece and varies during the forming process [1]. Contact condition is determined by tool and sheet metal surface topography, material properties of sheet metal and its coating as well as tool material behavior, lubrication mechanism, process variables such as contact pressure, temperature and strain during forming process [2, 3]. Contact conditions are further affected by variations in these parameters such as variations in lubricant distribution and tool surface texture due to wear [4].

Sheet metal surface texture is an important factor in determining friction between the tool and workpiece. Shape, height and spacing of the asperities on the sheet metal surface, coating thickness, substrate and coating material behavior control deformation or flattening of the asperities due to contact pressure and strain in the bulk of the sheet metal [5, 6, 7]. Furthermore, distribution of asperities governs lubricant distribution and its load bearing capacity [8].

As the tool comes into contact with the sheet metal, the highest asperities on the sheet metal are plastically deformed due to contact pressure. The plastic deformation of asperities is governed by the mechanical behavior of sheet metal and its coating (if any), geometry of the asperities and their distribution [9]. As the asperities are indented, the non-contacting asperities or valleys rise and may come into contact with the tool. The latter depends on asperities spacing and lubricant distribution as well. Strain hardening rate of asperities is another parameter that determines the load bearing capacity of the asperities and therefore real area of contact.

It has been shown that normal load combined with bulk strain in the sheet can substantially increase real area of contact. The effect of strain, however, depends on effective hardness of the sheet metal surface (substrate and coating material and thickness) and its texture. With increasing thickness of zinc coating on a steel substrate, the effect of strain is increased and with increasing sheet metal

surface roughness, the rate of increase in real area of contact due to bulk strain is reduced. Furthermore, by increasing the mean asperity spacing, real area of contact increases with the bulk strain more rapidly [5]. In general, it can be concluded that the surface texture determines the real area of contact, shape and distribution of the contact patches between workpiece and tool. The latter would affect the size, orientation and attack angle of the tool asperities which are in contact with the sheet metal surface. These will ultimately determine ploughing behavior of the tool asperities through the sheet metal surface which influence coefficient of friction [10].

In the current study, the validated contact and friction models are used to investigate the effect of sheet metal texture parameters on the formability of a cross-die product. For this purpose, a number of surface textures resembling EDT surfaces are artificially produced using an in-house algorithm.

Sheet Metal Surface Texture

To correlate the zinc coated sheet metal texture parameters with its formability, 55 different textures were artificially created using the bearing area method [11]. The texture is printed on a surface with an initial roughness obtained after the galvanization process. Three examples of the generated surfaces including the initial surface are shown in figure 1. Five additional textures were measured from industrial rolled products. Surface textures were generated such that different roughness parameters such as root mean square roughness, asperity spacing, summit density and auto correlation length (ACL) are varied within the industrial measured values. Figure 2 shows distribution of texture parameters for the generated surfaces. The average root mean square roughness of the all surfaces, including artificial and real ones is 1.48 (SD: ± 0.49), Table 1 lists the mean and standard deviation of the roughness parameters for the 60 surfaces used in the current study. For all the surfaces, zinc coating thickness is constant (7 μm) and substrate is DX57 with a thickness of 0.8 mm.

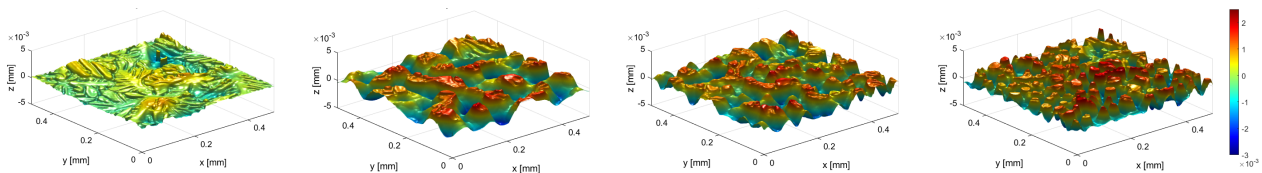


Fig. 1. Surface height of the initial untextured (left image) and three generated textures.

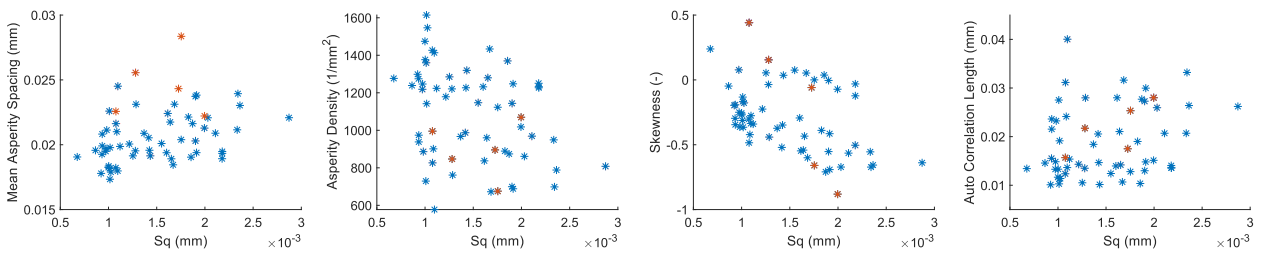


Fig. 2. Distribution of roughness parameters of the generated surfaces (blue markers) and real surfaces (red markers) at different surface roughness levels.

Table 1. Average and standard deviation of surface roughness parameters (n = 60).

Root mean square height (μm)	Mean asperity spacing (μm)	Summit density (mm^{-2})	Skewness (-)	Kurtosis (-)	Auto-correlation length (μm)
1.48 (± 0.49)	20.7 (± 2.2)	1080 (± 252)	-0.29 (± 0.27)	2.24 (± 0.28)	18.8 (± 7.2)

Multi-scale Friction Model

Accurate description of friction coefficient in finite element analyses is indispensable for the accuracy of formability predictions. In sheet metal forming, friction is a local phenomenon that is determined by local contact conditions. Tool and sheet metal surface morphology as well as their hardness levels (e.g. coating and substrate hardness), lubricant type and amount constitute the tribological system.

Process variables such as contact pressure, plastic strain, temperature in the contact and relative velocity of tool and sheet metal influence the tribological system and therefore determine frictional shear stress.

The multi-scale friction model developed at University of Twente by the author and colleagues [1,12,13] accounts for the micro and meso-scale phenomena which occur at the tool-sheet metal contact. In the boundary lubrication regime, flattening of sheet metal surface at different contact pressures and plastic strains is predicted using a semi-analytical contact model [6]. The model considers sheet metal topography (different shapes of asperities), coating thickness and its mechanical behavior. The model is validated at the meso-scale via dedicated experiments which enable the measurement of real contact area [5]. At the micro-level, shear strength of the boundary layers and ploughing of tool asperities which contribute to the friction stress are considered and validated through dedicated experiments [10, 14]. Furthermore, the effect of lubricant in the model is considered via solving averaged Reynolds equation at the contact of the tool-sheet metal [13, 15]. The model implements the topography of sheet metal and tool to calculate averaged lubricant flow. The multi-scale model was validated to industrial-scale forming process (cup drawing and cross-die forming) at boundary and mixed lubrication regimes [12, 13]. Figure 3 shows the multi-scale friction modeling approach in boundary lubrication. The input includes surface topography of sheet metal, tool and their material behavior. In the deformation step, contact models [5] are utilized to estimate the real contact area. In the sliding steps, contribution of boundary layers and ploughing of tool asperities through the sheet metal surface are calculated for individual asperities [10, 14] to estimate the total friction force. In the current study, behavior of different surface textures are investigated at boundary lubrication only.

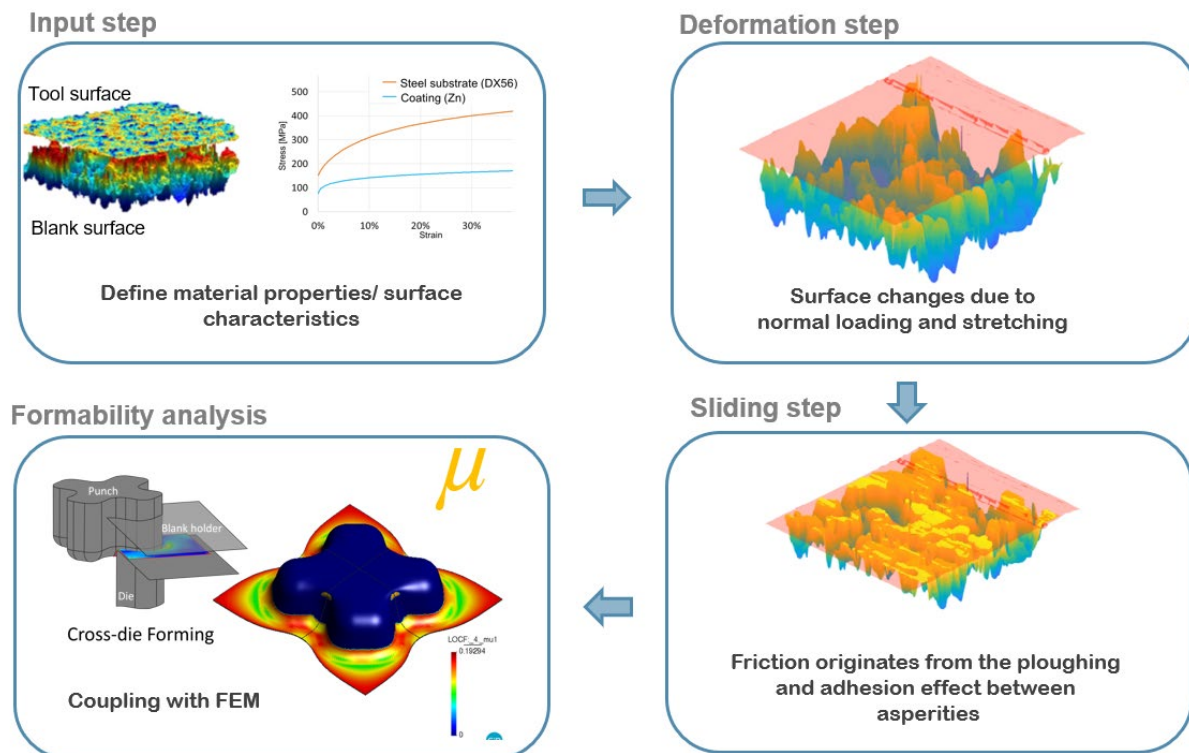


Fig. 3. Multi-scale modelling approach of friction in sheet metal forming.

Cross-die Forming Simulations

To investigate the effect of different sheet metal textures on its formability, cross-die forming simulations were carried out using the friction cards estimated for each surface in the boundary lubrication regime. One single tool surface topography in combination with sheet metal surface topographies was used to estimate friction coefficients at different contact pressures and equivalent plastic strains. Figure 4 shows the tool surface topography. Friction cards were later implemented in finite element simulations of cross-die forming using in-house FE code DiekA

(www.dieka.huetink.nl). Hydrodynamic effect of the lubricant on friction is negligible in boundary lubrication regime. Lubricant type used in the simulations was Anticorit RP4107S, with dynamic viscosity of 30 mPa.s and density of 0.896 gr/cm³ [13]. The maximum forming depth is 60 mm. The tools are modelled as rigid contours. For the material properties, the yield surface of DX57 sheet metal is described by Vegter's yield criterion and the Bergström-Van Liempt hardening rule is used to describe the sheet material hardening [16]. Due to symmetry in geometry a quarter of the part is modelled.

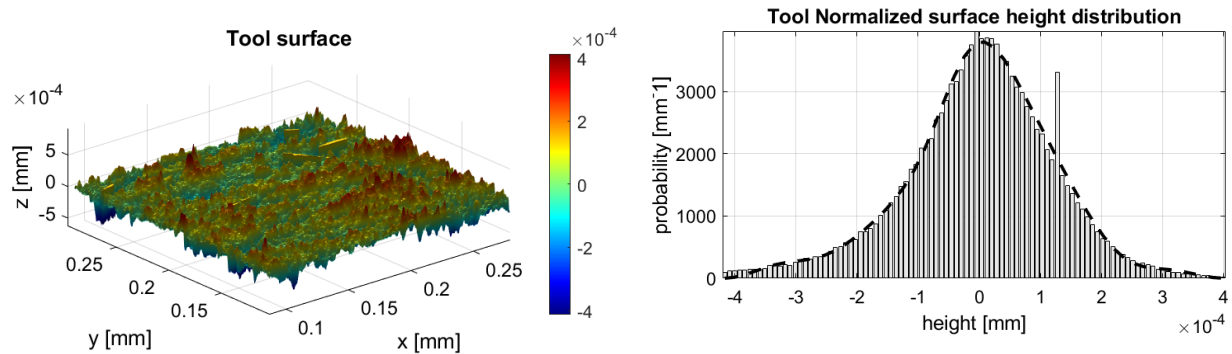


Fig. 4. Tool surface topography used to estimate friction coefficients for different sheet metal textures in cross-die forming simulations

The results show that different textures depict distinct formability behavior despite having similar roughness. Major-minor strain distribution in 26 out of 60 textures go beyond the forming limit curve (FLC) at the lubricant amount of 0.5 gr/m² where boundary lubrication prevails. Four typical textures with comparable root mean square roughness and height distributions selected from the investigated textures are shown in figure 5. Surfaces 5, 15 and surfaces 8, 39 have similar roughness values and height distributions, however different areal roughness parameters such as summit density and autocorrelation length. Forming limit diagrams (FLD) and coefficients of friction (COF) distributions for each finite element at drawing depth of 60 mm depict how surfaces with comparable height distributions but different texture would affect the formability of the sheet metal.

Figure 6a shows two additional surfaces with similar height distributions and root mean square roughness values of 1.02 and 1.08 μm for surfaces 48 and 49, respectively. Roughness parameters of the two surfaces are listed in table 2. Figure 6b depicts the FLDs obtained from cross-die forming simulations, the results show that sheet metal using texture 48 goes beyond the FLC for DX57-Z due to larger friction coefficients. Figure 6 additionally shows the distribution of friction coefficients at each finite element for the two surfaces at the drawing depth of 60 mm. Surface 48 clearly uses higher coefficient of friction values for the given contact conditions: contact pressure and equivalent plastic strain. The variation in coefficient of friction at each increment leads to variations in contact pressure. Therefore surface 48 results in slightly lower contact pressures and higher equivalent plastic strains and consequently higher thinning in the blank.

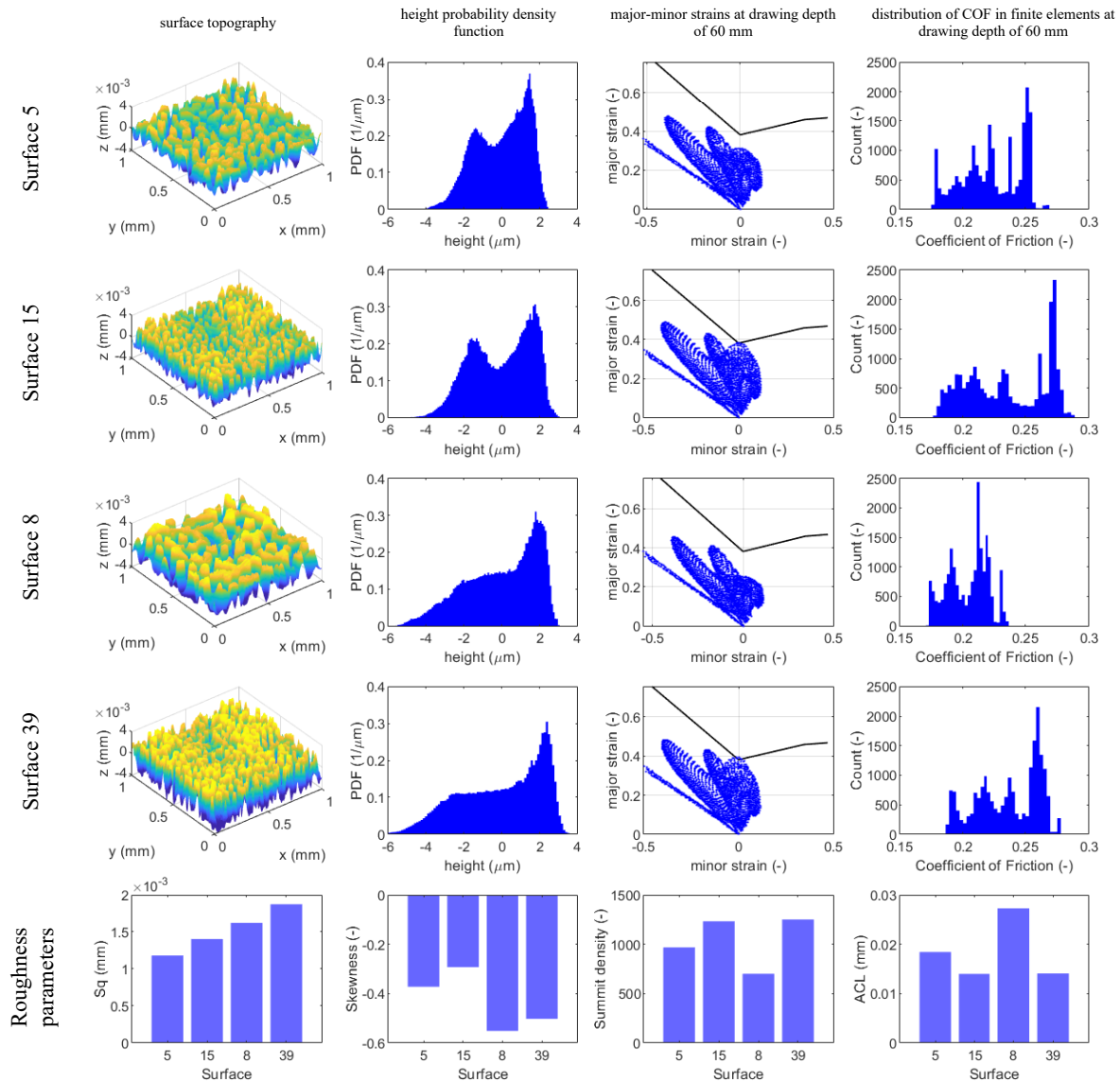


Fig. 5. Four surface textures (5, 15, 8 and 39) with similar height distributions and their FLDs obtained from cross-die forming simulations. The bottom row shows the areal roughness parameters for the selected surfaces.

To study the effect of surface texture on the formability of the sheet metal, friction behavior of the surface at different contact conditions were analyzed using the multi-scale friction model. Figure 6c shows the ploughing force at each tool asperity in contact with the sheet metal (contact patch) as the sheet metal is subjected to 20% plastic strain and contact pressure of 20 MPa. The asperities are arranged in descending order based on the quantities. The results show surface 48 leads to larger number of individual contact patches (29 contact patches or tool asperities) due to lower auto-correlation length, asperity spacing and higher summit density compared to 21 contact patches in surface 49. Checking the individual tool asperities in contact with surface 48 reveals that asperities are more elongated than the tool asperities in contact with surface 49. The latter is evaluated by fitting elliptical paraboloids to the tool asperities penetrated to the sheet metal surface. It has been shown that ellipticity ratio would largely influence the load bearing capacity of the asperity while ploughing on the sheet metal surface [10]. However, the latter further depends on the orientation of asperity during ploughing. The fitted ellipses to the base of contacting asperities have larger major to minor radii ratio in surface 48 compared to 49. More importantly, calculating the attack angles of individual asperities explains the higher ploughing forces and therefore higher friction coefficients of surface 48. Tool asperities in contact with surface 48 have higher attack angles relative to surface 49. Based

on friction regimes diagram developed by Challen-Oxley [17], higher attack angle results in higher coefficient of friction in the ploughing regime.

Table 2. Roughness parameters of the surfaces 48 and 49.

Surfaces	Root mean square height (μm)	Mean asperity spacing (μm)	Summit density (mm^{-2})	Skewness (-)	Kurtosis (-)	Auto-correlation length (μm)
48	1.02	19.77	1142	-0.36	2.40	19.141
49	1.08	21.01	901	-0.42	2.46	24.134

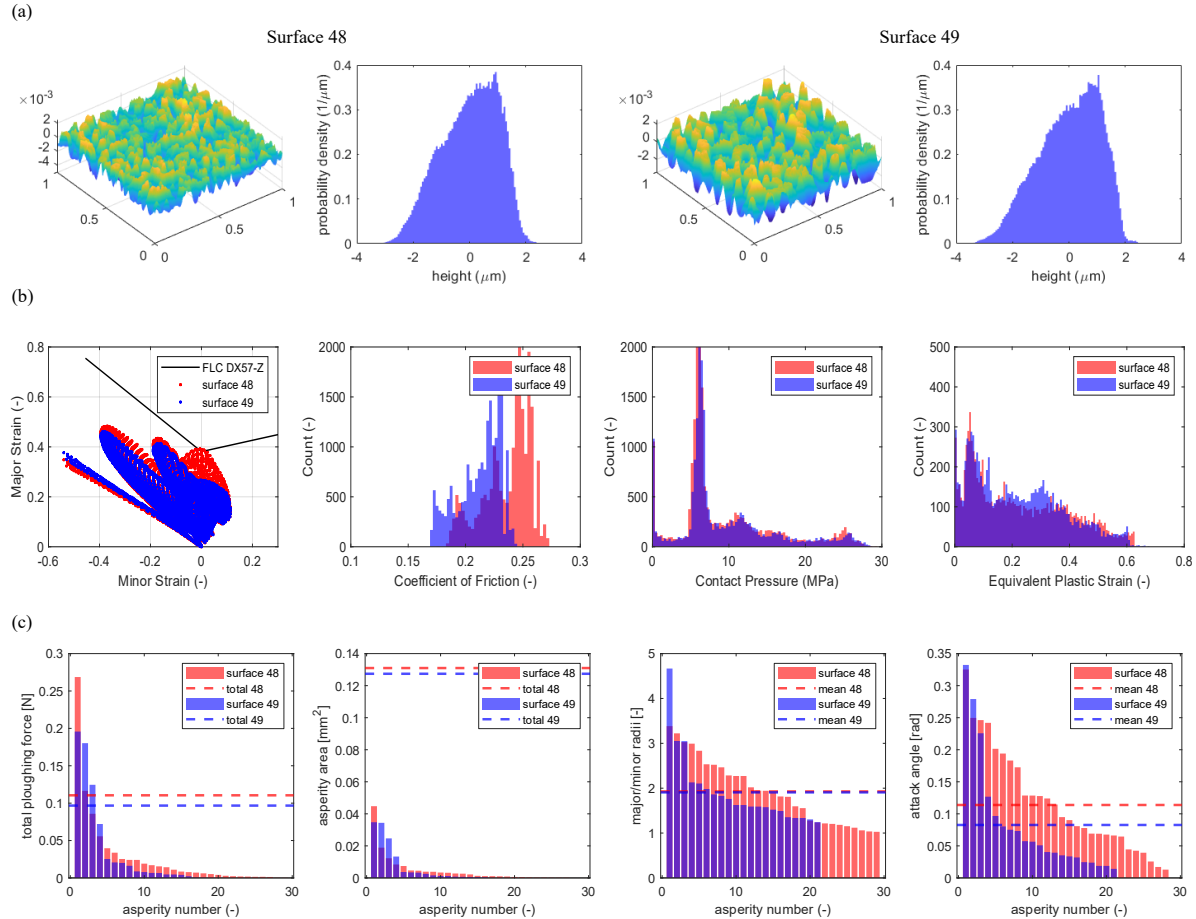


Fig. 6. (a) surface textures 48 & 49 height distributions, (b) FLDs and distribution of friction coefficients, contact pressure, plastic strain at each element in 60 mm drawing depth, (c) analysis of tool asperities in contact with sheet surfaces at contact pressure of 20 MPa and equivalent plastic strain of 20%.

Exploring the correlation between areal field parameters and formability of cross-die; surface roughness, summit density, autocorrelation length and skewness of height distributions are determining parameters (figure 7). However, autocorrelation length and summit density can be used interchangeably. The results show that for the current dataset, higher autocorrelation length in combination with negative skewness and higher roughness lead to better formability of the sheet metal. In figure 7, black and blue filled circles represent the textures which do not go beyond the FLC (below maximum major strain in plane strain state: 0.381). Although the plot does not provide a crisp separation on the formability of different surface textures, however, provides a strong indication about the formability of the textures. It should be noted that the root mean square roughness (Sq), autocorrelation length (ACL) and skewness values for different textures were normalized by the absolute maximum value in the dataset for each parameter.

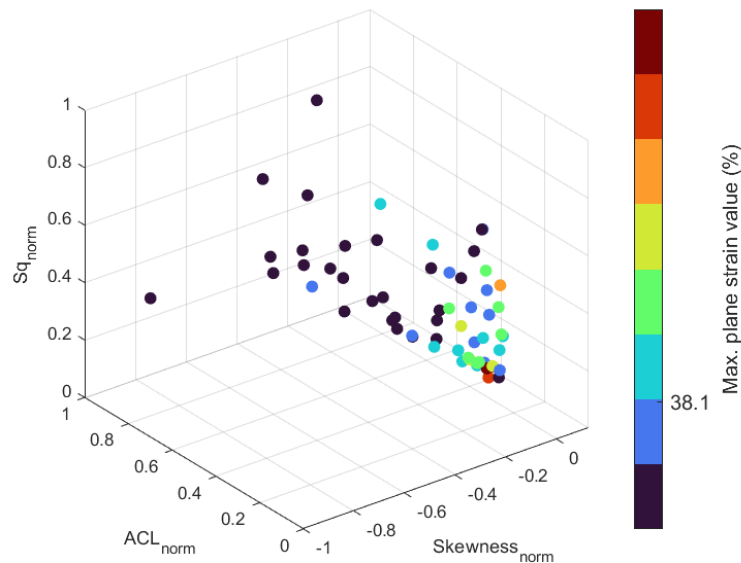


Fig.7. Correlation between surface roughness parameters and maximum major strain at plane strain in cross-die forming simulations. The parameters were normalized by the maximum absolute value from the dataset for each parameter.

Conclusions

In the current study, the validated multi-scale friction model in combination with a surface generating algorithm are used to determine the effect of surface texture or different roughness parameters on formability of sheet metal. The results show that apart from sheet metal roughness, autocorrelation length and skewness values play important roles on formability of sheet metal. The framework developed in the current study can be used to optimize sheet metal texture to control friction such that it is insensitive to variations in tool roughness and lubricant amount.

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