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Effect of Surface Texturing on the Stretchability of Electrogalvanized Steel Sheets

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ABSTRACT

The three-dimensional surface topography of electrogalvanized steel sheet affects its press-forming behavior and also influences the appearance of the end product. In this study, the three-dimensional surface topography of several steel sheets processed by a stochastic surface texturing method has been considered both theoretically and experimentally. In the presence of liquid lubricant, results indicate an increase in rate of mixed lubricated regime rather than boundary lubricated regime as well as improvement of stretchability of textured samples in comparison with non-textured samples.

Keywords: three-dimensional surface topography, surface texturing, electrogalvanized steel sheet

Introduction

Stretch forming is one the most significant processes for sheet metal forming (SMF). SMF consists of deformation processes where a steel sheet is shaped by tools or dies. Stretch forming is used in particular for forming body panels, such as doors, roofs or fenders for the automotive and other industries. The performance of SMF processes depends on characteristics of the forming process, the sheet metal, the tool material, frictional conditions at the tool or steel interface and other product requirements.[1]

In SMF processes, the sheet surface structures have the function of storage, transport and distribution of the lubricant as well as the take-up and transport of wear particles. In order to fulfill these functions, they can be separated as follows: (a) stochastic surface texturing and (b) deterministic surface texturing.[2]

It has been demonstrated that the frictional conditions during testing are controlled via lubricant viscosity, film thickness, surface roughness and deformation velocity.[3,4] Often, the friction force in a lubricated tribo-system is described as a function of one or even more of the operational parameters. Depending on the value of operational parameters, a tribo-system can operate in the following lubrication regimes: (a) hydrodynamic lubrication, (b) mixed lubrication or (c) boundary lubrication.[5]

In practice, the operational parameters of the three-dimensional surface topography are modified by some methods such as: (a) shot blast texturing, (b) electro-discharge texturing, (c) electron beam texturing and (d) laser beam texturing.[6] The interaction of surface texturing with coated and uncoated steel sheets during SMF has been considered in previous studies.[7] Evaluation of the tribo-system during the SMF processes has been carried out via different theoretical equations.

In the stretch forming process, the upper limit of the punch load is determined by the maximum tensile load that can be transmitted by the workpiece material, the angle γ between the sheet metal at the grippers and the direction of material of the punch (Fig. 1), the ultimate tensile stress of material UTS, the total width of the clamped sheet *b* and sheet thickness *s*, while frictional effects can be considered using a corrective friction factor *c*, per Equation 1.[1,8]

$$F_{max} = 2cbs(\mathrm{UTS})\cos\gamma \tag{1}$$

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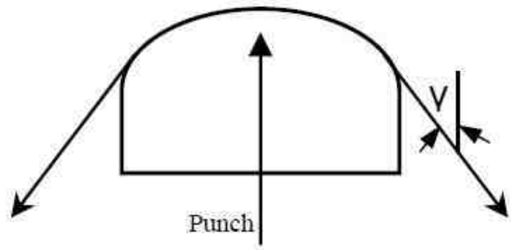

Figure 1 -Schematic diagram of a stretch forming process.

The aim of present work was to control the tribo-system of steel sheets during stretch forming so that samples were prepared by the stochastic texturing method, considering the texturing effects on both frictional status and stretchability. Therefore, two different ranges of normal forces as variable factors to texture the surface were studied and finally the stretchability of samples was tested.

Experimental procedure

Materials

Steel sheet stretchability samples with a 34 to 44 g/m^2 coating mass were used, which were produced by the Posco Steel Company (Table 1). In addition, metallic spherical steel shot with a range of 200 to 500 μm diameter and 390 to 530 VHN and 7.2 g/cm^3 density were used in order to texture the surface of the steel sheets.

Table 1 - Specification of electrogalvanized steel sheet.

Tensile strength	290 N/mm^2 (42,100 psi)
Yield point	154 N/mm^2 (22,300 psi)
Elongation	47%
Nominal coating thickness	5.6 μm (220 μ-in.)

Seventy-two samples were cut to dimensions 200 × 200 × 1 mm. The surface of the steel sheet was then cleaned and degreased by general alkaline solution and was immediately dried with a clean tissue. The steel sheet surface was then covered with a 200-μm thick layer of nylon. The steel shot was then spread over the surface so that it covered it entirely. A metallic roller was run over the shot with a reciprocating motion for about 10 min (Fig. 2). Based on the normal forces used, the samples were categorized in three groups: (a) coarse samples (40 N), (b) fine samples (20 N) and (c) non-textured samples.

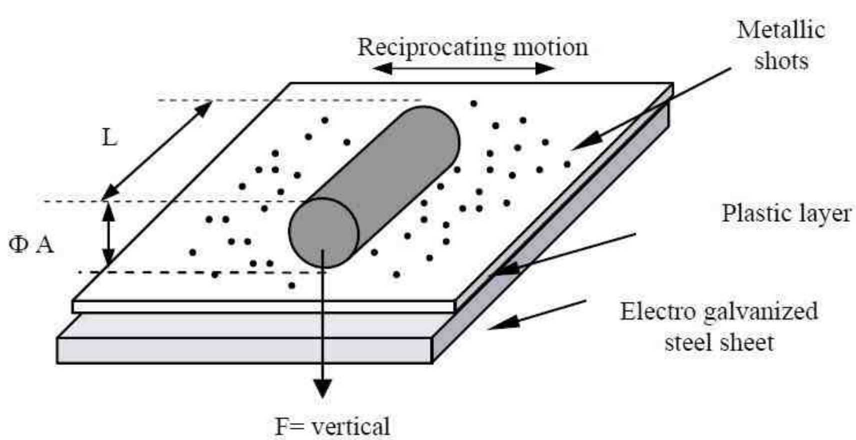

Figure 2 - Schematic diagram of the texturing process used.

To calculate the depth of artificial indentation in terms of diameters and the normal forces used, the following equations were used, whereas the parameters are described in Fig. 3.

$$\tan \propto = \frac{t}{d/2}; \tan \propto = \frac{d/2}{D-t} \quad (2)$$

$$t = \frac{1}{2}\left(D \pm \sqrt{D^2 - d^2}\right) \quad (3)$$

$$\sigma = \frac{F}{A} = \frac{F}{\pi D t} \quad (4)$$

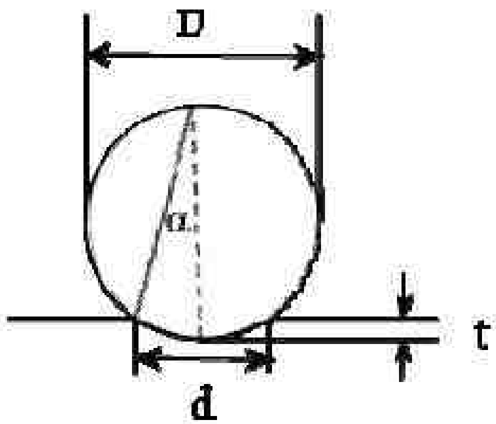

Figure 3 - Schematic diagram of one shot indentation on the surface.

Because of the fairly large scale of the texturing process, a method to analyze the surfaces on a three-dimensional scale was used, consisting of scanning electron microscopy (SEM) and roughness measurements.[9,10] In order to study the surface topography before and after texturing and to measure the dimension of asperities on the surfaces, microscopic tests were done using a Tescan model VG20805731R with secondary electron capability.

The surface roughness measurements of the textured steel sheets were made using a MarSurf perthometer M2 as a universal standard instrument. Parameters such as R_a, R_{max}, R_k, R_p and R_{vk} were recorded by moving the stylus indenter through cross directions (approximately 8 mm). Samples were then subjected to a simulated drawing test in order to consider the interaction of texturing with stretch forming.[11] The Erichsen cup test was done using a Universal Sheet Metal Testing Machine Model 142-20. In addition, solid and liquid lubricants were employed during the simulation test to study the interaction of lubricating system with three different types of surface texturing.[12]

Results

Figures 4(a) and (b) show the SEM micrograph images of samples which were textured by 40 N and 20 N normal forces, respectively.

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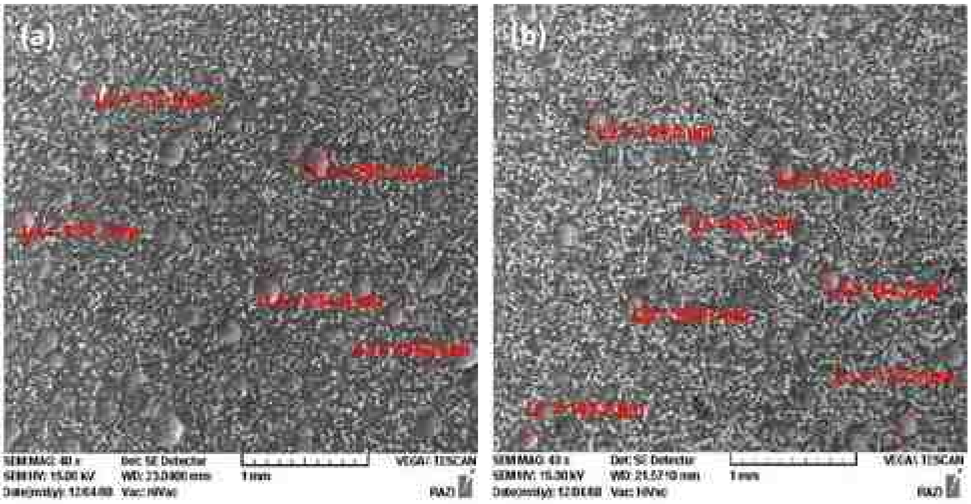

Figure 4 - SEM micrographs of textured samples with respect to asperity dimension: (a) coarse, (b) fine (40×).

Table 2 compares the result of roughness tests for two different samples with two different types of texturing in accordance with the rate of normal forces used.

Table 2 - Results of roughness tests for the coarse and fine textured samples.

	Fine	Coarse
R_a	1.225 µm	1.785 µm
R_p	1.330 µm	1.410 µm
R_{max}	10.600 µm	15.800 µm
R_k	3.580 µm	4.740 µm
R_{vk}	2.430 µm	3.990 µm

Table 3 shows the results of the Erichsen cup test, categorized in three major groups: (a) non-textured and textured with (b) 20 N and (c) 40 N normal forces individually. Results are shown for tests done using liquid lubricant, solid lubricant and without lubricant.

Table 3 - Comparison among the results of three different samples after the Erichsen cup test with two different lubricant systems.

	Oil lubricant			Solid lubricant (grease)			Without lubricant		
	Non-textured	Fine	Coarse	Non-textured	Fine	Coarse	Non-textured	Fine	Coarse
Max. drawing force (kN)	19.04	18.84	18.78	18.15	18.22	18.60	19.51	18.96	18.96
	19.00	18.82	18.80	18.62	18.30	18.55	19.46	18.90	18.88
Cupping depth at F_{max} (mm)	10.45	10.50	10.70	10.40	10.50	10.40	10.35	11.00	10.50
	10.43	10.50	10.75	10.50	10.52	10.30	10.30	11.00	10.47

Discussion

Surface topography

In this section, the effects of the surface texturing process used on the surface topography are considered. SEM images demonstrate that closed void areas result in hemispherical asperities on the sample surfaces. As can be seen in Fig. 4, there are trivial differences among diameters of the closed void areas. By increasing the rate of normal force, the average diameter increases in a range from 149.3 to 165.9 µm. Differences among the diameter sizes result from different factors, such as rate of normal force, or the hardness of sheet surface and so on.[13] Diameters were assessed statistically by applying a *t*-test analysis to determine if there was a statistically significant difference between the result of applied process and initial assessment. A *t*-test analysis of these results shows that for the fine texturing there is a 90% probability that the diameters range between 133.09 and 152.54 μm if the true diameter is 137.2 μm. When comparing coarse texturing, p = 90% that diameters range between 155.38 and 173.89 μm if the true diameter is 162.8 μm. Moreover, Fig. 5 shows the histograms of textured samples in accordance with the *t*-confidence interval for the mean of fine and coarse samples separately.

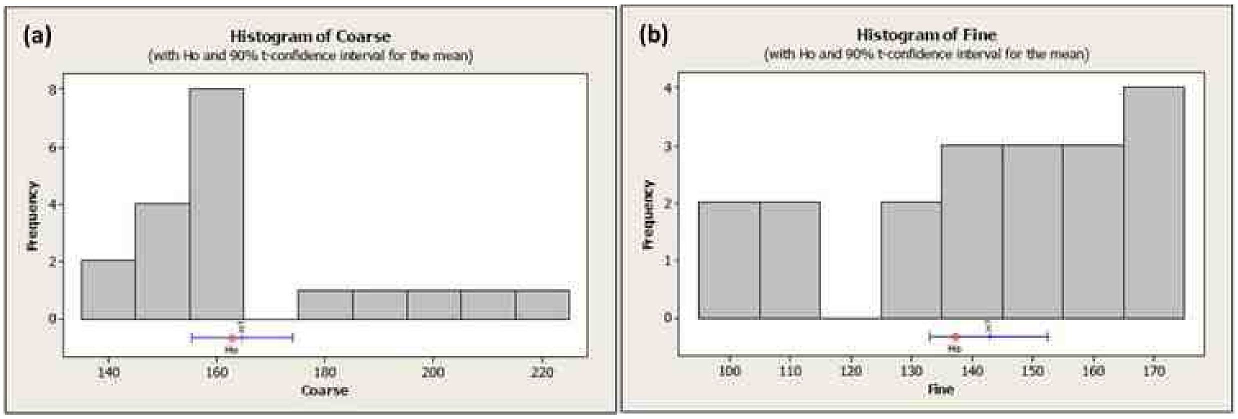

Figure 5 - Histogram of textured samples in terms of the *t*-confidence interval.

On the other hand, Fig. 6 illustrates the cumulative probability plot including percentile points for corresponding probabilities of diameters. The middle line is the expected percentile from the distribution based on maximum likelihood parameter estimates. The left and right lines represent the lower and upper bounds for the confidence intervals of each percentile. The coarse samples demonstrate less standard variance than the fine samples, while the Anderson-Darling (AD) normality statistic for coarse samples is bigger than fine ones. Thence, it is probably better to choose the fine process in lieu of coarse texturing. It relates to the interaction of texturing with the surface coating, so that applying lower normal force in fine texturing brings about a more optimized state.

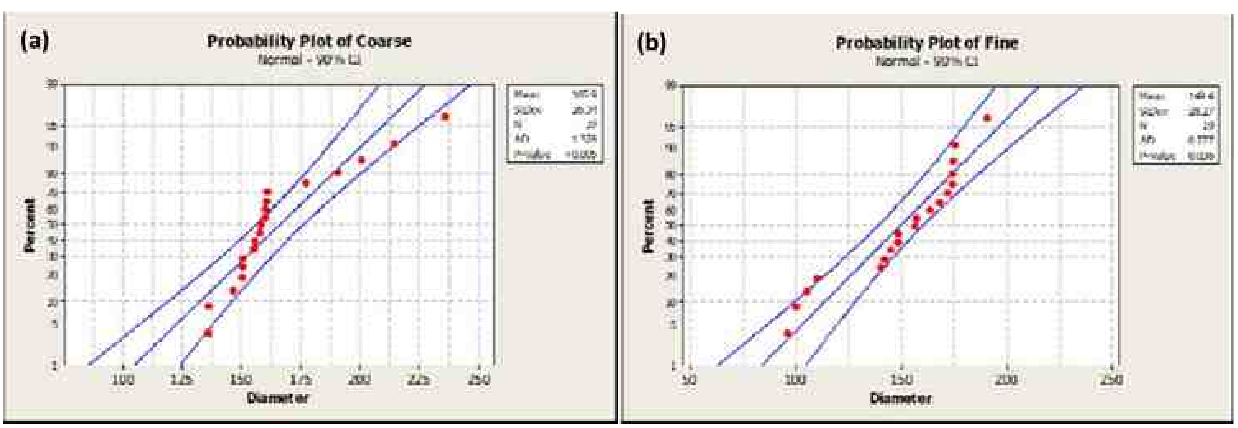

Figure 6 - Probability plot of two different textured samples.

As matter of fact, squeezing the metallic spherical shot particles on the surface results in a micro-plastic deformation on the surface. Therefore, there is portion of the surface area that is either peeled or squeezed, so that our prior results[7] prove out this concept. Increasing the normal force causes a greater depth of indentation as well as "pile-up" height around the indentations.[5,14] In this research, in order to minimize the electrogalvanizing coating defects thru galling during texturing, a polymeric layer (low density polyethylene sheet) was used. The polymeric layer acts as a boundary lubrication system during surface texturing.[15]

According to the roughness test results, the coarse samples show a higher level of R_a than the fine samples, which accounts for deeper asperities, and in wider sense, a higher level of spikiness appears on surface. By theoretical calculation (Equation 3), indentation depth changes from 14.3 to 21.75 μm, while the empirical results show that R_{max} of the textured sample with a 40 N normal force is about 5 μm more than the fine samples. Hence, there is little difference between the theoretical results and roughness test results. R_p for the coarse samples is generally larger than R_p for the fine ones. This is related to a much greater pile-up height so that it may cause a higher rate of work hardening.[14] Controlling the rate of work hardening from texturing may also be studied as future work.

Theoretical calculation indicates that the compressive pressure during texturing is changed from 2.8 to 5.6 N/mm^2 (406 to 812 psi), such that this pressure range could partially deform the substrate. Roughness test results at some points showed that the substrate had been deformed up to roughly 5 to 10 micron-meters (Equations 3 and 4). Meanwhile, the roughness values of the textured samples show similar results with the difference of only a slight increase of the core roughness depth R_k, the reduced peak high R_{pk} and the reduced valley depth R_{vk} from the fine to coarse samples after texturing was carried out. In comparing the roughness values of the coarse and fine textured samples, different wear results were detected during the Erichsen cup testing.[8] From these roughness measurements, it can be said that an applied fine texturing can prevent excessive wear between die and sheet. Achieving the linear or nonlinear correlation between normal force and depth and diameters in the process may also be studied as future work.

Erichsen cup test analysis

Variations of the coefficient of friction can cause non-uniform stress distributions and, therefore, non-uniform local strain distributions. Sufficient uniform lubrication is essential for achieving maximum strains.[1] As mentioned earlier, by simulative stretch forming testing, the interaction of texturing with the stretching process was evaluated. The results of the simulative tests indicate sophisticated friction conditions for different types of texturing and also for the different lubricants used.

Using an oil lubricant requires a lower punching load than when no lubricant is applied. This effect may be related to a change in the lubrication system from a boundary to mixed system. Comparing the stretch forming results for a specific cupping depth accounts for lower energy consumption for coarse samples while these figures increase by decreasing the depth of the asperities (Table 3). In other words, the force-displacement gradient is lower for the coarse samples than for the fine and non-textured samples.[16] In regard to the Erichsen cup test results, using a solid lubricant leads to a more satisfactory lubricant system condition (Table 3). This is due to a higher viscosity and greater durability of the lubricant film.[7]

In Fig. 7, the quantity of F_{max} for all samples is considered graphically. As can be seen, a functional variation is observed for the three groups of samples. The graph shows a similar variation for three types of lubricant used. The fine samples require a lower rate of F_{max} in comparison with other ones, although using the oil lubricant causes the values to approach those of the coarse samples. The non-textured samples exhibit higher forces than for the fine or coarse samples in spite of a few fluctuations which may result from environmental effects. According to the results, the texturing process undoubtedly has a positive role in improving friction behavior during stretch forming. The differences among the fine and the coarse samples can result from the different effects of texturing.

Regarding Equation 1, if the depth is assumed to be the same for all samples, it can be clearly seen that by decreasing the rate of F_{max}, the friction factor c is decreased. On the other hand, if the depths assumed are those obtained during the tests, the lower rate of c for both the fine and coarse samples can be again confirmed. Therefore, lower rate of c is related to a lower friction coefficient.[1]

Overall, the closed void areas improve the pressure delivery from die to sheet surface by increasing the hydrostatic condition.[16,17] It improves the pressure delivery from the die to the sheet surface by increasing the hydrostatic conditions. In a wider sense, the normal force between the die and the sheet decreases, because of the increased area of the interface between the moving surfaces based on Coulomb's friction model.[16,17]

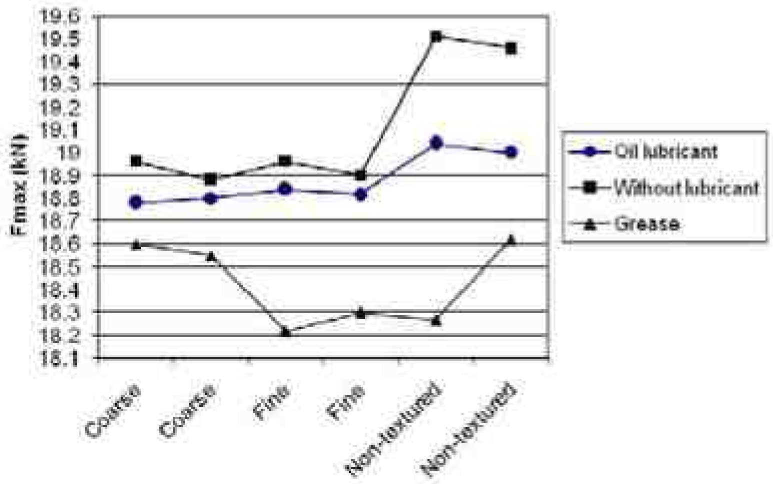

Figure 7 - Erichsen cup test results, F_{max} of samples.

Conclusions

In this work, the interaction of surface texturing with the stretchability of electrogalvanized steel sheets during sheet metal forming was considered. Using texturing is effective in changing the lubricant system from a boundary to a mixed system during the stretch forming process. By these theoretical and experimental analyses, it has been shown that the artificially closed void areas are effective in improving the formability of textured electrogalvanized steel sheet during the stretch forming process by oil and grease lubricants in comparison with non-textured samples.

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