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Quantitative characterization of the surface topography of cold rolled sheets — new approaches and possibilities

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Abstract

When processing cold rolled metal sheet with modified surfaces textures, the conventional roughness parameters are not sufficient to characterize aspects such as rolling mill wear phenomena, as well as sheet metal and lacquered surface, regarding their formability and/or gloss degree. Furthermore, metal sheet forming processes are increasingly focused on tribological parameters; where the sheet metal surface topography becomes a characteristic that shows great potential for process optimization. This work presents 3D surface characterization methods, searching on the basis of this characterization a correlation between the surface topography and the tribological behavior as well as the formability of Al 6016-T4 sheets. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Roughness; Friction; Forming; Metal sheet

1. Introduction

Better control in metal sheet forming processes still remains a great challenge. After reducing the scatter in mechanical properties, surface defects and lubrication conditions, the surface topography and its effects outstay as characteristics with a great potential for process and product optimization, as well as for the characterization of new processes [1,2].

New techniques are being applied for the surface structuring of metal sheets during their skin-pass rolling, resulting in lower and more stable friction. Due to some unique features of these new techniques, the structures of these news topographies are quite different from those usually applied. Traditional 2D parameters are not appropriated for a sharp characterization of those surfaces, which can be only sufficiently described in a quantitative base by new 3D surface analysis methods.

The authors also tried by ultrasonic techniques an in situ determination of parameters such as the real contact area [3,4] and have investigated the quality control of a metal sheet surface by using correlation and spectral analysis [5].

In the search of new approaches and possibilities for a quantitative characterization of the surface topography of cold rolled sheets, this paper presents 3D surface characterization methods and uses them to investigate the frictional behavior of an aluminum alloy sheets, looking for a correlation with their surface qualification parameters. Due to their lower formability, when compared to steel, aluminum alloy 6016-T4 sheets were chosen aiming an improvement of their formability by suitable tribological properties, in this case suitable surface topographies [6–9].

2. Surface texturing of cold rolled metal sheets

In forming processes the sheet surface structures have the functions of the 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 [10]:

1. *Stochastic surfaces* characterized by a random distribution of non-identical surface elements.
2. *Deterministic surfaces* characterized by a geometrically regular distribution of identical isolated surface elements that can act as hydrostatic lubrication pockets and take up wear debris.

Such surface textures depends on how the rolls are textured.

1. *Shot blast*: the rolls are textured by blasting them with hard particles. The surface structure has a random nature (stochastic).
2. *Electric discharge texturing*: the rolls are roughened by a small electric discharge similar to the process of spark erosion. The surface structure has a random nature (stochastic).

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3. *Laser texturing*: texturing is achieved by producing aligned craters (deterministic) in the roll by a chopped laser beam.
4. *Electron beam texturing*: similar to the laser texturing, but using an electron beam to create a deterministic crater pattern.
5. *Electrolytic hard chromium plating* (*ECD*): a cathodic roll is plated with spherical deposits of chromium, which rolls the so-called Pretex or ECD sheet metal topography.
6. *Mill finishing texturing*: where grinding in the tangential direction textures the roll surface.

3. Materials and experimental set-up

The experiments were carried out with specimens of aluminum alloy AA 6016-T4 (Al–Mg: 0.4; Si: 1.2) sheet, with three different texturing topographies: laser texturing, mill finishing and electric discharge texturing. Their mechanical properties are summarized in Table 1. Quantitative evaluation of the surface topography was proceeded using two different processes: conventional 2D roughness measurement with a mechanical sensor after DIN 4768, summarized in Table 2; and 3D surface parameters discussed in the following section.

A combined twist-and-compression test device was used to investigate the friction coefficient as a function of the contact normal stress and the sliding length. The specimens were loaded to 40, 80, 120, and 160 N/mm^2. Afterwards they were twisted under constant load, with the rotational die velocity set at 2.36 mm/s.

Table 1
Average sheet thickness and mechanical properties for the different surface textures

Properties	LT	MF	EDT
Mechanical strength (MPa)	211.20	219.20	221.30
Plastic anisotropy ratio	0.68	0.64	0.66
Planar anisotropy ratio	0.21	0.24	0.22
Strain hardening exponent	0.23	0.24	0.24
Average sheet thickness (mm)	1.20	1.20	1.19

Table 2
2D roughness parameters for the different surface textures of the AA 6016-T4 sheets

Roughness parameter DIN 4768	LT	MF	EDT
R_a, longitudinal (μm)	1.11	1.06	1.13
R_a, transversal (μm)	0.79	1.10	1.24
R_z, longitudinal (μm)	4.37	5.89	7.99
R_z, transversal (μm)	4.49	5.51	6.95
R_{max}, longitudinal (μm)	7.32	7.17	11.29
R_{max}, transversal (μm)	6.06	7.16	9.73

4. 3D surface analysis measuring and data evaluation

The surface topography was mapped using an optical sensor within a Rodenstock RM600 surface-measuring instrument. The optical sensor maps the topography of the surface using a laser beam, which is focused on the surface. Based on the measured surface data, the bearing ratios can be calculated for a constant area by varying the penetration of the surface from 0 until 100%, or at a constant penetration by a numerical reduction of the measured area. Surface qualification analysis was made by means of a 3D surface analysis module. More details of the procedure and numerical process can be seen in [11–14]. This model assumes the load on a surface as transmitted by three different kinds of bearing ratios (Fig. 1). These are the solid contact, the static and the dynamic lubricant pockets. Thereby the solid contact corresponds to the real contact area.

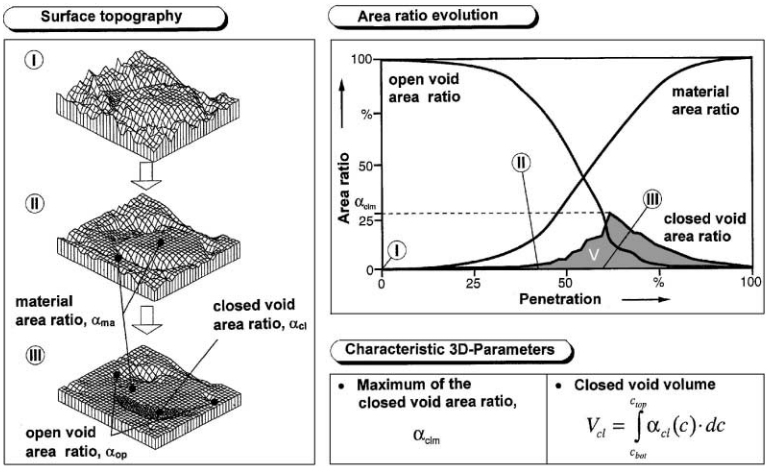


Fig. 1. 3D surface parameters results of a laser-textured surface qualification [5].

The dynamic lubricant pockets are the lubrication areas of the total surface, where the lubricant can flow out of the loaded area during the forming process. In the dynamic lubricant pockets, a hydrodynamic pressure transmits the load. In contrast with the dynamic lubricant pockets, the static lubricant pockets have no connection to the boundary of the loaded area and the lubricant is thus entrapped in the pockets. As shown in Fig. 2, this model has been used to derive new 3D surface parameters, more appropriate for the case of a surface contact under mixed lubrication. As illustrated in Fig. 1, the bearing ratio of the solid contact (material area ratio) corresponds to the Abbot-Firestone curve that is well known from 2D surface analysis. Like the bearing ratio of the solid contact, the bearing ratios of the static (closed-void area ratio) and the dynamic lubricant pockets (open-void area ratio) are also results from the penetration of the surface. Starting the calculation with a penetration of 0%, there are no static lubricant pockets but only dynamic lubricant pockets. With further penetration of the surface, the bearing ratio of the dynamic lubricant pockets decreases while the bearing ratio of the solid contact increases. It can be seen from Figs. 1 and 2, that a curve represents the static lubricant pockets which results from the closing of dynamic lubrication. Note that with further penetration the dynamic lubrication pockets tend to disappear.

This is summarized in the three area ratio curves, shown in Fig. 1, i.e., the open-void area ratio (α_{op}), the closed-void area ratio (α_{cl}) and the material area ratio (α_{ma}). An integration results in their respective volume, V_{op}, V_{cl} and V_{ma}, related to the evaluated area, when integrated between c_{bot}, defined by the penetration corresponding to the lowest amplitude value, and c_{top}, which is a penetration on which the highest amplitudes are still taken into account. The choice of the amplitudes to be taken into account must be based on how they are distributed and also on their measurement procedure. The difference between c_{top} and c_{bot} is described as the topography depth of the surface, S_t. Further, parameters can also be obtained from the amplitude distribution.

Similarly to the 2D parameters, these can be defined for a 3D measured amplitude distribution: the arithmetic mean deviation of the surface (S_a) and the root-mean-square deviation of the surface (S_q). The skewness (S_{sk}) and the kurtosis (S_{ku}) of the topography height distribution can also be used for a 3D characterization of the surfaces. However, the establishment of a relationship between both and the tribological behavior is still ambiguous sometimes, as the amplitude distribution sometimes deviates from a classical Gauss distribution.

From the standard DIN 4776 [15], three other parameters are used to correlate tribological properties and the surface qualification: the core roughness depth (R_k), the reduced peak height (R_{pk}) and the reduced valley depth (R_{vk}). It should be stressed, however, that these parameters are more applicable for surfaces flat on the top and highly grooved or pored on the bottom, and depend on a suitable filtering: otherwise they may result in unreliable information. More details about the definition of 3D surface characterization parameters can be found in Refs. [16–19].

The choice of the filtering process for the measured data is important to obtain a more conclusive analysis. As for assessing the tribological properties, it is necessary to separate shape variations, waviness and signal noises from the roughness measured data by suitable filtering. The filtering of the surface waviness is especially important, as in metal forming it can be smoothed out during the contact evolution [20,21]. Although by 2D roughness measuring the Gauss filter is almost a universal choice, for the filtering of surfaces under friction or wear contact it is regarded as possibly producing distortions. This drawback has stimulated some researchers to develop new filters in order to improve the relationship between roughness and tribological behavior [20,21]. In this work, the 3D surface parameters were evaluated after rectangular filtering, regarded here as good enough for consistency between the tribological behavior.

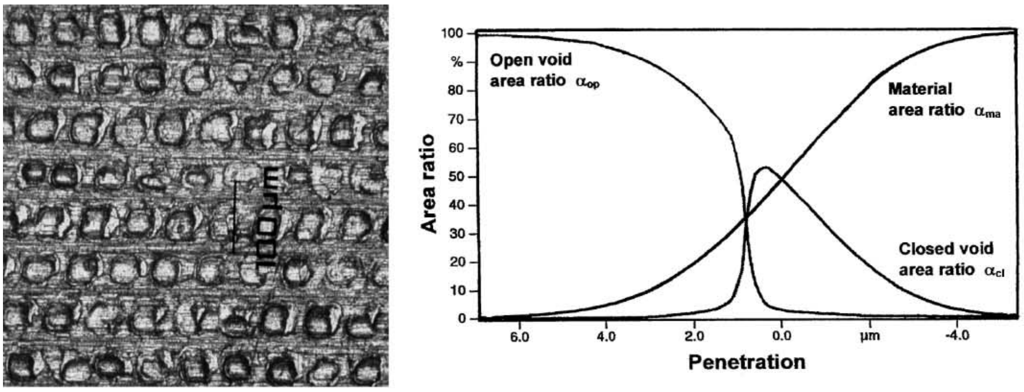
However, vast the range of 3D surface topography parameters available in the literature, in order to maintain a consistency between the tribological behavior those parameters, α_{clm} and V_{cl} has been chosen. The evolution of α_{clm} and V_{cl} are used as characterization parameters for the understanding of the frictional behavior of textured surfaces tested under a mixed lubrication regime on a combined twist-and-compression test with different normal stresses.

5. 3D surface analysis of unloaded surfaces

The surface topography aspect of the unloaded surfaces for the three different surfaces, i.e., surface (I) — a laser textured surface, a deterministic structure with separated craters; surface (II) — an EDT surface; a stochastic structure, with less closed-voids; surface (III) — a mixed structure with aspects of mill finishing, are shown in Fig. 2.

The 3D surface parameter results obtained by the surface analysis module for these three unloaded surfaces are shown in Fig. 2. Observing this figure, it can be pointed out that laser texturing results in a deterministic and anisotropic surface, as it presents a craters pattern having different intervals in different directions in space. The 3D surface analysis parameters for this case presents a structure with a greater closed-void volume, as well as a greater closed-void area ratio. The EDT structure is characterized as stochastic and isotropic, with a smaller closed-void volume, as well as a smaller closed-void area ratio. The mixed mill finish structure stays as a stochastic surface structure, however anisotropic, due to its strong orientation dependence. It is shown in Fig. 3 just for comparison.

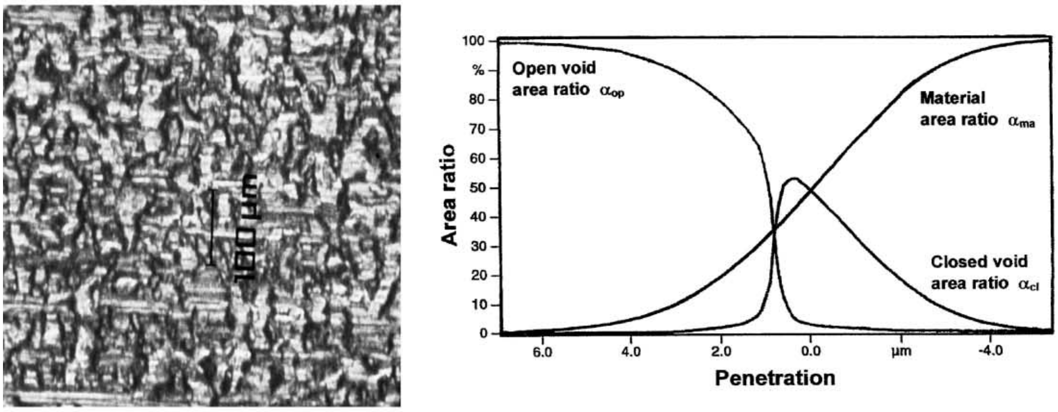
The results of the friction-coefficient measurements determined by a combined twist-and-compression test are presented in Fig. 3a for the three different textured surfaces as a



LT

Maximum of the closed void area ratio, α_{clm}, 51 %
Closed void volume, V_{cl} 1345 mm^3/m^2

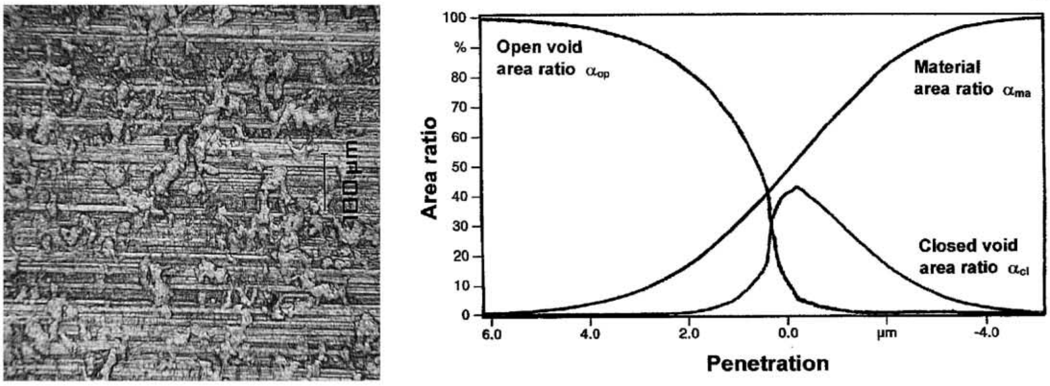
(a)



EDT

Maximum of the closed void area ratio, α_{clm} 40 %
Closed void volume, V_{cl} 944 m^3/m^2

(b)



MF

Maximum of the closed void area ratio, α_{clm} 43 %
Closed void volume, V_{cl} 1007 mm^3/m^2

(c)

Fig. 2. Surface topography aspect of the surface and 3D surface parameters analysis: (a) surface (I) — a laser-textured surface (LT), a deterministic structure with separated craters and greater closed-void area ratio; (b) surface (II) — an EDT surface, with a stochastic structure and smaller closed-voids area ratio; (c) surface (III) — an MF surface, with a stochastic and anisotropic roughness pattern with aspects of mill finishing surface texturing with directional grooves, presenting values of the closed-void area ratio and closed-void volume near to the values for the surface (II), however, anisotropic.

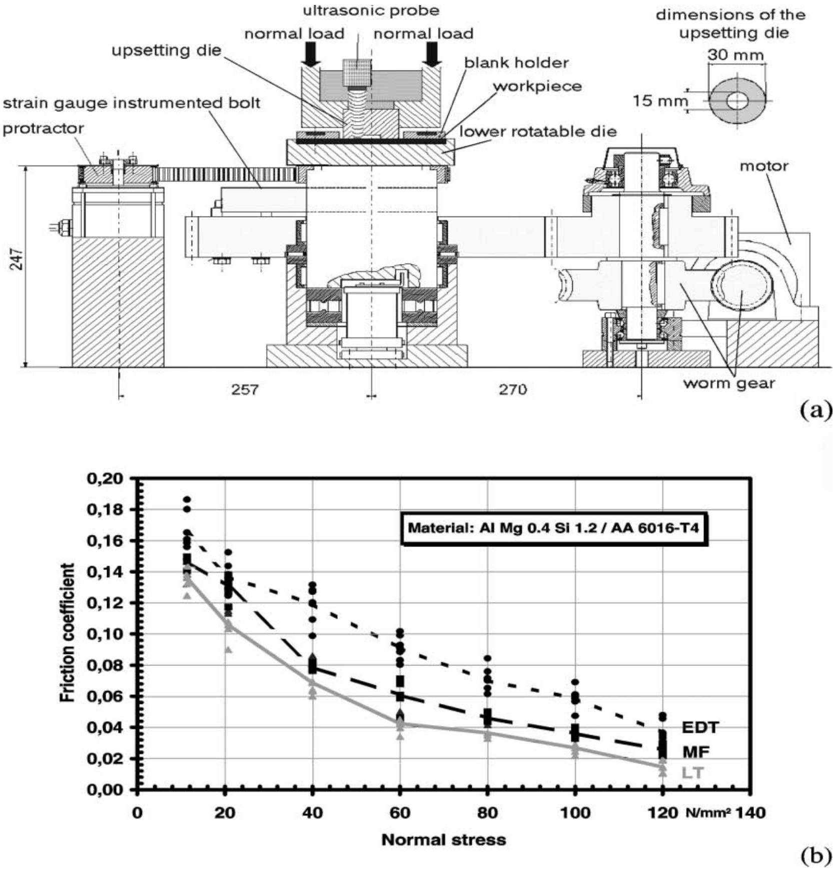


Fig. 3. (a) The combined twist-and-compression test. (b) The friction coefficient vs. the normal stress for three different surface textures.

function of the normal stress. Their respective values of α_{clm} and V_{clm} of the twisted-and-compressed specimens over the normal stress range investigated are shown in Figs. 4 and 5. The three types of roughness tested (LT, EDT and MF) show a similar behavior.

The EDT surface, characterized by higher roughness and less closed-void lubricant area, has a higher friction-coefficient over the whole normal stress range, contrasting with the laser textured surface, characterized by a deterministic pattern of closed-void lubricant areas, which evidences an additional hydrostatic lubrication, and consequently a smaller friction coefficient. The mixed grade mill finished, due to the oriented grooves in the roughness, shows a orientation dependence that when tested by a combined twist-and-compression test, results in an averaged friction behavior, here included as a comparative example. The lubricant viscosity and amount as well as the interfacial velocity effects are still under investigation.

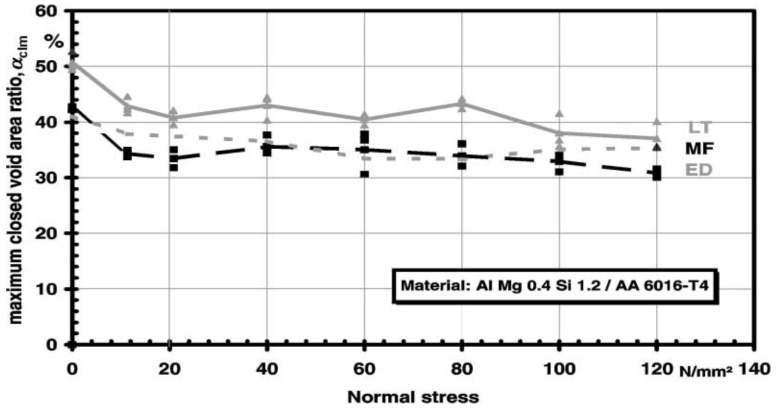


Fig. 4. The 3D parameter, the maximum closed-void area ratio, α_{clm}, as defined in Fig. 2, vs. the normal stress for the different surfaces.

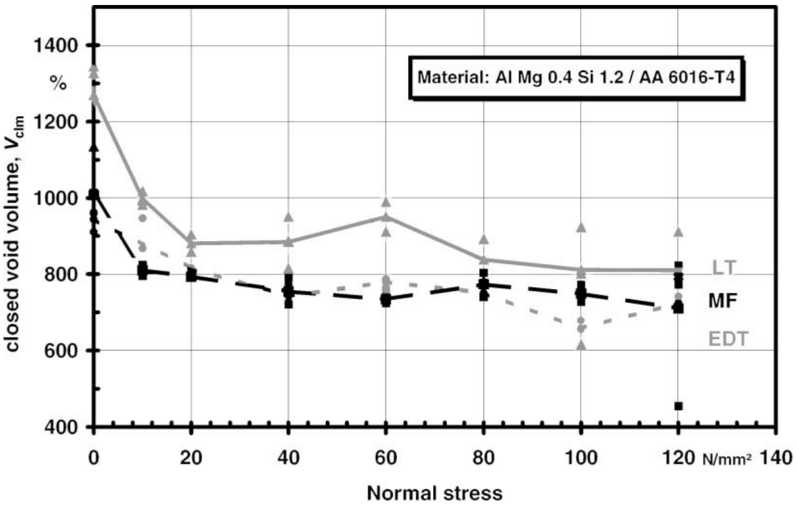


Fig. 5. 3D parameter closed-void volume, V_{clm}, as defined in Fig. 2, vs. the normal stress for the different surfaces.

6. Conclusions

The parameters α_{clm} and V_{clm} are regarded as suitable 3D surface analysis parameters for the description of metal forming tribological behavior, being usable both for deterministic (LT) as for stochastic (EDT) surfaces.

The combined twist-and-compression test, configured for metal sheet specimens, has provided the possibility to investigate the friction behavior of the three different aluminum sheets. The rougher, with closed-void areas EDT, has presented a consistently higher friction-coefficient over the normal stress range. The LT surface, characterized by the presence of a deterministic pattern of closed-void areas, potentially acting as a hydrostatic lubricant pocket, has presented a smaller friction coefficient over the normal stress range. The effect of strong directional textures, such as the MF texture, where the friction also depends on the movement orientation, cannot be completely studied by the twist-and-compression test. In this case, the measurement values are regarded as averaged.

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