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Published in:
Journal of Materials Processing Technology

DOI:
[10.1016/j.jmatprotec.2019.116311](https://doi.org/10.1016/j.jmatprotec.2019.116311)

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Document Version
Final author's version (accepted by publisher, after peer review)

Publication date:
2020

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Solhjo, S., Halbertsma, P. J., Veldhuis, M., Toljaga, R., Pei, Y., & Vakis, A. I. (2020). Effects of loading conditions on free surface roughening of AISI 420 martensitic stainless steel. *Journal of Materials Processing Technology*, 275, [116311]. <https://doi.org/10.1016/j.jmatprotec.2019.116311>

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Effects of loading conditions on free surface roughening of AISI 420 martensitic stainless steel

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Abstract

Free surface roughening affects the tribological behavior of contacting bodies in multistage metal forming processes. This phenomenon was investigated on sheets of AISI 420 martensitic stainless steel by applying uniaxial and radial straining modes via tensile and Erichsen cupping tests, respectively. By means of focus variation microscopy, the free surface roughness evolution was studied for each sample at different values of strain. Moreover, the microscopic deformation of grains was visualized using scanning electron microscopy and differential interference contrast microscopy. The results show that the free surface roughening rate in the uniaxial strain mode is higher than that in the radial one. Furthermore, the surface height distribution of the deformed surfaces was found to be dependent on the deforming strain and tended toward a Gaussian one at higher strains. Grain boundaries and chromium carbide particles were found to be responsible for the peaks formed in the roughened free surfaces. Analyses of the deformed free surfaces showed distortion of the grain morphology, which is the mechanism responsible for free surface roughening.

Keywords: free surface roughening; cupping test; microscopy; grain morphology; stainless steel.

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1. Introduction

Free surface roughening can occur during plastic deformation due to strain localization where and when the tool and workpiece are not in contact, as was shown by Romanova et al. (2013) through a series of numerical simulations. This phenomenon affects the quality of the product's surface as well as other surface properties, such as weldability, adhesion and the forming limit. For example, Furushima et al. (2014) investigated the forming limit of pure copper foils and sheets. They provided a fracture mechanism describing an increase of surface roughness due to the surface roughening phenomenon lowering the fracture strain. Moreover, this inevitable phenomenon affects the friction and lubrication conditions in later stages of the forming process. In most numerical studies of contacts, constant friction is assumed, although estimating its value is not straightforward; for example, examining a well-known model for the processing of Barrel Compression Test, Solhjoo and Khoddam (2019) discussed the narrow range of the validity of the model. Free surface roughening, however, heavily affects the friction condition from one stage to the other, as was described in a recent review (Vakis et al., 2018); this makes the investigation of a multi-stage forming process even more complicated. In a series of studies for boundary (Hol, Meinders, de Rooij, *et al.*, 2015) and mixed lubrication conditions (Hol, Meinders, Geijselaers, *et al.*, 2015), Hol et al. described a multiscale finite element method (FEM) approach combining fluid dynamics and non-linear structural mechanics for modelling free surface roughness and friction force evolution during sheet metal forming. Considering these recent developments together with the industrial need for more accurate predictive numerical simulations of friction evolution during multi-stage metal forming processes, studying the evolution of the surface roughness is an active research topic where the goal is to facilitate the implementation of comprehensive friction models in FEM packages.

Different mechanisms at various length scales, mostly at the atomic and grain levels are responsible for free surface roughening. For instance, Solhjoo and Vakis (2015), by means of molecular dynamics studies of single asperity contacts, showed that dislocation movements are responsible for surface roughening at the atomic scale. At the micro-scale, however, most studies discuss orange peel and slip bands as the main mechanisms for free surface roughening. Orange peel is the result of independent deformation and relative displacements of individual grains, and is characterized by out-of-plane displacement fields. Baydogan et al. (2003), in their experimental investigation of free surface roughening of AISI304 stainless steel, showed that slip bands are due to the presence of discontinuous yielding on the stress-strain curves, and are

characterized by banded surface undulations, which typically extend along the rolling direction of the sheet. At the macro scale, a phenomenon called ‘ridging’ or ‘roping’ is known to occur in some metals due to the collective movement of bands of grains which have similar crystal orientations. This phenomenon is reported extensively for aluminum alloys used in the automotive industry. For example, Beaudoin et al. (1998) described the ridging phenomenon using FE analysis of deformation processes of crystallographic phases with the same orientation, confirming the role of similarly oriented bands on the formation of ridges. In another study, Baczynski et al. (2000) studied the influence of rolling conditions on the ridging phenomenon in plastically strained automotive aluminum by means of experiments and numerical simulations, and observed that ridging occurs parallel to the rolling direction. Ridging is application-specific and has not been reported in the case of AISI 420 stainless steel, as far as the authors have been able to find, although it does occur in similar stainless steels. Takechi et al. (1967) reported ridging phenomenon in 17%-Chromium stainless steel cold-rolled sheets. They developed a crystallographic-based model, explaining that the shear strains caused by tensile deformation in crystals oriented with [011] parallel to the rolling direction are the characteristic surface relief due to ridging; however, Wright (1972) questioned the generality of their model. Instead, studying the plasticity of textured ferritic stainless steel sheets, he proposed another model, explaining that the roping phenomenon is attributed to a transverse plastic buckling instability due to certain nonrandom texture mixtures. Shin et al. (2003) tested the validity of the abovementioned models in comparison with the solutions of crystal-plasticity FEM (CPFEM) models. They showed that those models do not take interactions or compatibilities among grains into account, and consequently their results differ from CPFEM solutions. In another work, Wu et al. (2006) proposed a simplified crystal plasticity model for predicting ridging texture in ferritic steels, which could successfully correlate crystal orientation and shear stresses to ridging. In a recent study, Zhang et al. (2018) investigated the surface roughening of pure copper samples in tensile tests. They modelled different samples with different thicknesses by full-field CP modelling using a spectral method solver based on the fast Fourier transform (CPFFT). They showed the dependence of surface roughening on the grain size, morphology and orientation of neighboring grains. Defining λ as the ratio of sample thickness to grain size, they found that, for $\lambda \geq 6$, the roughening weakly depends on thickness and occurs in the form of inter-granular ridges and valleys, while it is highly affected by thickness for $\lambda \leq 3$.

Free surface roughening has been studied extensively via different methods:

experimentally, numerically, and analytically. These have shown that many parameters are involved in the free surface roughening phenomenon, such as crystal structure, strain mode, loading path, grain size, grain orientation, plastic anisotropy, sheet thickness, work hardening exponent, and so on. Among these factors, some depend on the nature of the forming process and the deforming material, e.g. crystal structure and strain modes. These parameters are usually fixed for a production process. Other factors, however, can be altered in the production line, e.g. with a proper heat treatment. Regarding the grain size, all investigations have shown that the rate of free surface roughening is smaller for sheet metals with smaller grain sizes. For example, in a recent study, Xu et al. (2015) conducted micro-compression tests on pure aluminum samples with different grain sizes and showed that the free surface roughening on samples with an ultrafine grain size of $\sim 1.5 \mu\text{m}$ was negligible. Regarding the strain mode, studies have shown that the roughening of free surfaces in a tensile test is lower than that under compression. For example, Osakada and Oyane (1971) studied the surface roughening rate of an aluminum alloy in two deformation modes of tension and compression. They showed that the roughening rate is significantly affected by deformation mode, and is more pronounced in compression. They explained this behavior by relating the free surface roughness to the amount of surface area changes during deformation. In another work, Abe (2014) proposed an analytical model of a polycrystalline metal. Analyzing plastic deformation in the model, Abe showed that compression produces larger surface roughness compared to tension. However, different trends have been reported on whether uniaxial or biaxial tensile tests result in higher roughening rates. Mahmudi and Mehdizadeh (1998) investigated the surface roughening of 70-30 brass sheets and reported that the uniaxial tests resulted in higher roughness.

Extensive numerical studies based on crystal plasticity and finite element models showed different behaviors. For example, in an extensive numerical study, Becker (1998) explored several factors affecting surface roughening, including straining modes, by means of CPFEM. They showed that the roughening rate in a biaxial tensile straining is lower than in a uniaxial one. On the other hand, Furushima et al. (2011) employed an inhomogeneous 3D FE model, and reported the roughening rate from the biaxial tension to be higher than for the uniaxial one, confirming their experimental results. Moreover, most studies showed that roughness linearly increases with the applied strain. For example, Stachowicz (2016) explored the surface roughness of different brass sheets in uniaxial and biaxial tensile tests, and found linearity between the surface roughness increment and the effective strain. Most studies, however, reported that the roughness increment is not a linear function. Wilson et al. (1981) investigated

the influence of sheet thickness and grain size in weakly textured copper sheets during biaxial stretching, and found a non-linear dependence of surface roughness on strain at large plastic strains. Moreover, the nonlinear relation is reported by many modelling studies. For example, Zhang et al. (2017) modelled the tensile test of aluminum alloy sheets using CPFET. They expressed the roughness of the deformed sheet as a nonlinear function of sample's tensile direction with respect to the rolling direction, plastic strain, initial roughness and grain size. Furthermore, the influence of the rolling direction with respect to the straining direction was addressed in numerous works and the findings were not consistent. For example, Wright (1976) investigated surface roughening of a ferritic stainless steel during tensile deformation and showed that the roughening rate became larger as the straining was closer to the rolling direction. In a more recent study, Zhou and Su (2011) showed that the surface roughening rate of austenitic stainless steels sheets is higher for the rolling direction compared to the transverse direction. For fcc metals, however, the opposite results are reported in the literature. For example, Wittridge and Knutsen (1999) showed that, for elongation perpendicular to the rolling direction, aluminum alloys subjected to uniaxial tension exhibit severe surface roughening, while the overall topography of the surface is flat when the tensile axis is parallel to the rolling direction. This effect was also observed in simulations. For example, Zhao et al. (2004), and in a more recent work, Romanova et al. (2013), numerically studied the uniaxial tensile tests of polycrystalline aluminum sheets and showed that straining along the transverse direction results in a higher roughening rate.

In most of these investigations, the surface roughness was reported as a simple statistical parameter, either as the arithmetic average height (S_a) or the root mean square (RMS) roughness (S_q). Other methods for studying surface roughness were reported in literature, as in Wouters et al. (2005), for example, who studied the surface roughness of polycrystalline aluminum alloys during uniaxial tensile deformation and, under the assumption of self-affinity, analyzed surface roughening using height-height correlation functions. In another work (Solhjoo and Vakis, 2017), without the assumption of self-affinity for the roughness, the authors proposed a hybrid roughness parameter (connecting RMS roughness, RMS gradient and lateral correlation length) for evaluating surface roughness. Herein, the surface roughness is characterized in terms of different statistical parameters, including S_a , S_q , skewness and kurtosis, because they are sufficient for describing the degree of randomness of surface roughness in the current study.

In this paper, two modes of uniaxial and radial straining were tested on sheets of AISI 420

martensitic stainless steel, and the evolution of free surface roughness due to the straining processes was characterized. The elongation was performed in two modes: continuous and stepped. While some literature is available regarding the stepped uniaxial elongation test, no comparison between the two abovementioned modes could be found by the authors. In addition, the evolution of grain boundaries was examined via differential interference contrast microscopy and scanning electron microscopy. The results showed that grain deformation was the dominant mechanism of the free surface roughening, i.e. the dislocation slip within grains and the orange peel effect caused by grain deformation. Moreover, it was found that this roughening mechanism resulted in the evolving surface roughness tending towards a Gaussian distribution. No indication of ridging/roping was found in the tested AISI420 material.

2. Research methodology

In this research, AISI 420 martensitic stainless steel sheets with two thicknesses of 0.2 mm and 0.5 mm were used for studying the free surface roughening phenomenon in uniaxial and radial tensile tests: the 0.5 mm thick samples were used only for studying the influence of the rolling direction on the free surface roughening, while the 0.2 mm thick samples were subject to other tests. The reason for this choice was based the limited availability of wide-strip sheets from the same batch: only a few such sheets were available for the 0.5 mm thick samples.

2.1 Mechanical tests

2.1.1 Uniaxial tensile tests

Uniaxial tensile tests were performed with a Zwick/Roell Z030 hydraulic testing machine, at a low strain rate of $\sim 4.4 \times 10^{-3} \text{ s}^{-1}$. The tensile samples were cut from a 0.2 mm thick AISI 420 steel sheet along the rolling direction, and the gauge dimensions were 120×20 mm. The tensile test was performed in two modes: continuous and incremental. For the continuous mode, different values of elongation between 5~20% were applied, while, for the stepwise mode, the total elongation of 30% was reached in 6 consecutive steps, with an elongation of 5% for each step with respect to the initial length L_0 .

Furthermore, the straining angles of 0°, 45° and 90° with respect to the rolling direction were studied for 0.5 mm thick AISI 420 steel sheet. These tests were done only in the continuous mode, and up to an elongation of 25%.

2.1.2 Erichsen cupping tests

Free surface roughening was also investigated in axisymmetric tension using the Erichsen cupping test, in which the sample can be stretched to obtain a semi-spherical shape of the punch. The samples were produced from the 0.2 mm thick sheet. The cupping test was performed by means of a punch with a diameter of 15 mm, where the inner and outer diameters of the blank holder were 17 mm and 70 mm, respectively. The punch moved with a constant velocity of 1 mm s^{-1} , with a maximum punching depth of 6 mm.

2.2 Analysis methods

At the end of each test, an area of $0.7 \times 0.7 \text{ mm}^2$ on the free surface of the center of the deformed samples was selected for further analysis, as illustrated in Figure 1. Focus variation microscopy (FVM) and differential interference contrast (DIC) microscopy were employed for analyzing the surface roughness and investigating the evolution of grain boundaries, respectively. Moreover, scanning electron microscope (SEM) was used for investigating the cross section of the samples deformed by the Erichsen cupping test.

Figure 1. Schematic representation of the measurement area in uniaxial (top) and cupping (bottom) tests. Numbers are in the scale of mm.

The three-dimensional surface topography at selected areas of the samples was extracted using FVM as described in the works of Danzl et al. (2009 and 2011). In this method, by

changing the distance between the sample and the optics, a number of images with different focuses would be captured. Then, the images would be filtered using the plane with the best focus at each position. The result would be sharp image of the surface topography, which was then converted into xyz data. FVM was performed using Alicona Infinite Focus, with an uncertainty per measurement of ± 3 nm. The measuring device was set at a magnification of 50X, vertical resolution of 50 nm, and a brightness of 190 lm. Samples were cleaned with acetone prior to the FVM measurement.

DIC microscopy was used for investigating the evolution of grain boundaries of a tensile sample at different elongations of 10, 15 and 20%. For this test, samples were extensively polished before the tensile test, which was done by a two-step polishing procedure: mechanical polishing with fine particle sizes down to 1 μm and chemical polishing with ethane diol and a particle size of 0.25 μm . Finally, the samples were etched with ferric chloride mixed with 30% ethanol for ~ 15 s.

The cross sections of the 0.2 mm thick sheet were further investigated with SEM. The samples were cut from the undeformed sheet and the Erichsen-cupping-tested sheet with a forming depth of 5.5 mm along the rolling direction. Then, the samples were mounted in conductive Bakelite (see Figure 2). Next, they were mechanically polished with particle sizes down to 1 μm , followed by a chemical polishing with ethane diol and a particle size of 0.25 μm . The preparation was finalized by ~ 10 s etching in ferric chloride mixed with 30% ethanol.

Figure 2. Samples mounted in conductive Bakelite for cross sectional microscopy: (1) undeformed sheet and (2) Erichsen cupping tested.

2.3 Numerical study: equivalent strain in Erichsen cupping test

While the elongation measurement can be used for calculating the engineering strain via $e = (L - L_0)/L_0$ and its conversion to true strain $\varepsilon = \ln(1 + e)$, it is not that straightforward for the Erichsen cupping test to convert the deformation depth into either engineering or true strain. This conversion, however, is necessary for comparing the results of the two modes of uniaxial and radial straining performed in this study. Therefore, a relation between the deformation depth and plastic strain was established by means of non-linear FEM simulation of the process. The constitutive behavior of the material was modelled using the collected data of the tensile tests. Moreover, the quadratic Hill yield criterion for plane stress (Hill, 1948) was applied to capture the normal anisotropy effects.

The validation of the simulation was done by geometrical comparison between the measured and simulated cups at a punching depth of 6 mm. It should be noted that friction was a main controlling parameter of the simulation; therefore, different values of the coefficient of friction were tried to reach an agreeable comparison by trial and error. A comparison between the simulation and experimentally measured contours with a compatible coefficient of friction are shown in Figure 3. Then, the simulation was repeated for different punching depths, and the strain of a corresponding area of $0.7 \times 0.7 \text{ mm}^2$ was derived from the simulation. Figure 4 shows the results of these simulations. In order to convert the deformation depth into equivalent strain, a fourth order polynomial was fitted to data as follows:

$$\varepsilon_{eq} = \begin{cases} 0, & d < 0.15 \text{ mm} \\ -0.0009d^4 + 0.0106d^3 - 0.0309d^2 + 0.0746d - 0.0105, & d \geq 0.15 \text{ mm} \end{cases} \quad \text{Eq. 1}$$

It should be noted that the equivalent strain was defined only for the plastic deformation regime, which is reflected in dividing Eq. 1 into two ranges: an elastic range for $d < 0.15 \text{ mm}$ and a plastic range for $d \geq 0.15 \text{ mm}$.

Figure 3. (a) An overview of the simulated deformed sheet, (b) a zoomed-in section at the top of the cup, showing the similarity between the simulation and the measured contours.

Figure 4. Equivalent strain as a function of punching depth (d) in the Erichsen cupping test.

3. Results and discussion

3.1 Roughness evolution

The surface topography of each tested sample was mapped via FVM in the Cartesian space, and in the form of a height function $h(\mathbf{p})$, where $\mathbf{p} = (x, y)$ is a 2D vector in the plane $z = 0$. Figure 5 shows an schematic rough surface comparable to the collected data. The surface roughness was analyzed via different statistical parameters of arithmetic average height $S_a = \langle |h| \rangle$, root mean square (RMS) roughness $S_q = \sqrt{\langle |h|^2 \rangle}$, skewness $S_{sk} = \langle \hat{h}^3 \rangle / \langle \hat{h}^2 \rangle^{3/2}$, and kurtosis $S_{ku} = \langle \hat{h}^4 \rangle / \langle \hat{h}^2 \rangle^2$, with $\hat{h} = h - \langle h \rangle$, where $\langle \dots \rangle$ denotes the average.

Figure 5. (a) A schematic representation of a rough surface with a high aspect ratio. The rough surface is colored based on its height values h changing from blue (minimum h) to green (maximum h). The black horizontal plane represents the mean plane at a height of $\langle h \rangle$; (b) the surface profile of the cross section at $y = 50$ mm indicating the rough surface and the mean plane after deformation. It should be noted that the values of h are assigned to be positive in this schematic, resulting in $\langle h \rangle = \langle |h| \rangle$.

3.1.1 Uniaxial straining

Figure 6 shows the arithmetic average height and RMS roughness of the uniaxial samples.

The results show that the values of S_a and S_q increased with applied strain. Moreover, the free surface roughening was independent from the continuous and incremental tension modes, and the evolution of these two parameters could be described by linear and quadratic formulae. Regression coefficients are reported in Table 1.

Table 1. Regression coefficients of quadratic and linear fits to arithmetic average height S_a and RMS roughness S_q for the uniaxial straining mode (see Figure 6); both are reported as $a\varepsilon^2 + b\varepsilon + c$, where dimensions of all coefficients are μm , together with the coefficients of determination R^2 for all fits.

		a	b	c	R^2
S_a	Quadratic	4.34	0.16	0.25	0.93
	Linear	—	1.17	0.22	0.87
S_q	Quadratic	5.73	0.13	0.32	0.93
	Linear	—	1.47	0.27	0.86

Figure 6. The evolution of (a) arithmetic average height S_a , and (b) RMS roughness S_q as functions of true strain for both continuous and incremental uniaxial straining modes. The small and long dashed lines are quadratic and linear fits, respectively. Regression coefficients are summarized in Table 1.

By comparing the values of the coefficient of determination for the fits, it can be concluded that the quadratic fits are better descriptors of the roughness evolution. It is challenging to say how the coefficients of this phenomenological model relate to actual macroscale material properties, since the macroscale behavior is the result of the confounding effects of smaller scale deformations. More specifically, macroscale straining induces microscopic grain deformations through strain localization. The confounding effect of these interacting microscopic deformations results in an increased roughness throughout the specimen. It is not surprising that metal plasticity is associated with nonlinear behavior of metals; however, why macroscale straining induces a quadratic roughening effect is difficult to say without considering the smaller scales. At low plastic strains, the smallest out-of-plane roughening occurs within the grains through dislocation glide. As the strain level increases, deformation of individual grains comes into play, attributing to an orange-peel effect. Moreover, on the mesoscale, the collective deformation of larger sets of similarly oriented grains can result in a banded surface topology, known as ridging and roping phenomena. For a review of roughening mechanisms at other scales, from dislocation movement to grain scale levels, readers are referred to the literature, e.g., the work of Raabe et al. (2003). In this study, the ridging phenomenon was not observed. Presumably, the accumulation of these roughening phenomena, which come into play at different strain levels, causes a nonlinear strain-roughness effect. This is clearly illustrated by the observed roughness evolution as depicted in SEM images (discussed in section 3.2.1) where accumulation of roughening phenomena on different scales occurs.

From Figure 6 we additionally conclude that the quadratic fits in the case of continuous straining show a plateau or minimum before the roughening increases. This is contrary to the quadratic fits in the case of incremental straining. Whether the occurrence of a plateau is exclusive to continuous straining or it is a fitting artefact will be checked in a subsequent study.

3.1.2 Radial straining

The values of S_a and S_q for the Erichsen cupping test are shown in Figure 7; the deformation depth was converted into the equivalent strain via Eq. 1. The results show that the values of S_a and S_q increased with applied strain, and this evolution could be described with, either, linear or quadratic fits almost with the same accuracy (see Table 2).

Figure 7. The evolution of (a) arithmetic average height S_a , and (b) RMS roughness S_q as functions of equivalent strain for the radial straining mode. The small and long dashed lines are the quadratic and linear fits, respectively. Their coefficients are summarized in Table 2.

Table 2. The regression coefficients of quadratic and linear fits to S_a and S_q for the uniaxial straining mode (see Figure 7). See the caption of Table 1 for more details on the reported coefficients.

		a	b	c	R^2
S_a	Quadratic	0.35	0.28	0.24	0.85
	Linear	—	0.44	0.23	0.84
S_q	Quadratic	0.61	0.28	0.31	0.86
	Linear	—	0.55	0.29	0.85

A comparison with the results of the uniaxial straining mode (see Figure 6) shows that the increasing rates of both S_a and S_q for the Erichsen cupping test were smaller than the corresponding parameters for the tensile test. In other words, the roughening rate of the free surfaces for the uniaxial straining mode was higher than that of the radial one, which is in accordance with the literature (Mahmudi and Mehdizadeh, 1998). The reason for such a

difference is that the microscopic roughening phenomena during the radial loading are suppressed by the presence of the tensile components in all radial directions of the Erichsen cupping test. Moreover, the sample in the radial straining is in contact with the tool, which affects not only the roughness of the touching surface side, but also the local roughening mechanism. Compared to the tensile test, both the sample's surfaces are free and the global stress is nonzero only along the tensile direction. Therefore, the crystals are freer to distort, resulting in a more pronounced surface roughening.

3.1.3 Gaussianity of the roughness distribution

The skewness and kurtosis (respectively statistical measures of symmetry between asperities and valleys, and asperity spikiness) of the roughness distribution of the surfaces at different strains were examined, in order to investigate their Gaussianity. The results are shown in Figure 8. As can be noted, with increasing applied strain, the skewness decreases toward zero for all modes of straining and the kurtosis decreases towards a value of 3 so that, indeed, the surfaces are becoming Gaussian for all modes of straining. Physical mechanisms responsible for this behavior are investigated in the following sections.

Figure 8. The values of (a) skewness, and (b) kurtosis as functions of strain for the samples with uniaxial (continuous and incremental) and radial straining modes.

It should be noted that the initial values of skewness and kurtosis were the results of the manufacturing process, such as rolling, and stamping of the samples (during the sample preparation process). These manufacturing processes produce grooves along the rolling direction, which resemble wide valleys, and spiky peaks, suggesting that $S_{sk} > 0$ and $S_{ku} > 3$. Due to the deformations, however, the roughness distributions tend towards Gaussian ones. This can be explained by both roughening of asperities and valleys by grain deformation, which seems to diminish the spikiness of valleys and asperities, and simultaneously seems to increase the symmetry between asperities and valleys.

3.1.4 Effect of straining angle with respect to the rolling direction

The influence of the rolling direction on the free surface roughening was investigated with uniaxial tensile experiments. The roughness was measured via FVM, and the corresponding values of RMS roughness were calculated, as shown in Figure 9. The results show that the samples elongated along and perpendicular to the rolling direction had the highest and lowest final RMS roughness values, respectively. Hence, the roughening rate of the free surface increased as the strain direction was closer to the rolling direction, which is in agreement with literature. Specifically, Wright (1976) performed tensile tests on strips of a ferritic stainless steel, and reported that the corrugation amplitude was greatest when the straining was aligned with the rolling direction; the undulation decreased as the tensile axis diverged from the rolling direction.

The sheet thickness used in these experiments was 0.5 mm. Although the initial roughness for these samples was comparable to that of the ones used in the previous section for the uniaxial experiment (see Figure 6(b and d)), the dependence of S_q on strain is not directly comparable, because the thickness of the samples was different: the roughening rate decreased as the sheet was thicker.

Figure 9. The dependence of RMS roughness on strain and straining angle with respect to the rolling direction.

3.2 Microscopic roughening mechanisms

3.2.1 Scanning electron microscope

SEM images were taken from the cross sections of Erichsen cupping tests to study the shape of grains before and after deformation; however, it was impossible to keep track of the same grains before and after straining, due to the destructive sample preparation process required for SEM imaging. The SEM images of the sample before and after deformation are shown in Figure 10 and Figure 11, respectively; the figures clearly show the grains and the free surface roughness. Comparing the samples before and after straining, it can be noted that a more wavy roughness can be seen where the peaks are located on the grain boundaries and the valleys are located on the grain surface. This is the result of the difference between the deformability of the grains and the grain boundaries: the grain boundaries are harder to deform than the grain surfaces because of extensive local dislocation density. Moreover, SEM images show that the particles of chromium carbide limited the grains' deformations; therefore, the peaks could be formed where the chromium carbide particles were located close to the sample's free surface.

Figure 10. SEM micrograph showing the cross section of stainless steel sheet before cupping deformation. Three distinctive aspects can be noticed in the image: (1) smooth surface of the cross section, (2) grains and their boundaries, and (3) a few particles of chromium carbide, which are typically visible in stainless steel before hardening.

Figure 11. SEM images of the deformed cupping sample. It should be noted that (a) and (b) were taken from the same sample, but from different locations.

3.2.2 Differential interference contract microscopy

Figure 12 shows the results of the DIC microscopy of the free surface of a sample, which

was deformed by a uniaxial tensile test. In contrast to the SEM, DIC microscopy could be used to capture the evolution of the same grains during subsequent straining increments. The grain roughening due to dislocation slip and grain deformation due to the plastic deformation of the bulk material are clearly visible; the increase in surface roughness influences the sharpness of the images, as is most pronounced in images of the sample with 15 and 20 percent elongation.

Figure 12. The DIC microscopy of a tensile sample at different straining values of (a) 0%, (b) 10%, (c) 15% and (d) 20% (with the loading direction indicated by a couple of arrows). Four grains were labeled as A, B, C, and D, and tracked during the incremental straining process, with results reported only for grain A.

Moreover, the grains' motion in the surface plane was investigated by analyzing one of the grains that was clearly visible over all the images using visual methods. A very simple but effective method was used. The motion of grain A (marked in Figure 12) was analyzed as follows: three points on the grain of interest were selected, and according to Figure 13, the angles α and β were estimated, as summarized in Table 3. It should be noted that roughening is a three-dimensional phenomenon that should ideally be studied within the corresponding space; however, in this work, we used the collected DIC data to estimate the projection of the elongation phenomenon of a selected grain on a plane (a two-dimensional space). It should also be noted that the sample was elongated along the horizontal direction of the image, and both angles α and β decreased due to deformation, implying a dilatation of the grain in the straining direction (with corresponding distortion in the coordinate system relative to which the angles

are defined). Had one of the angles increased while the other decreased, a rotation-like motion would have been observed; however, visually analysis confirms that the grains in Figure 12 exhibit elongation instead of rotation in the surface plane.

Figure 13. Grain A (marked in Figure 12) was analyzed for its morphology via measuring the angles α and β at different elongations. It should be noted that the deformation direction was along the horizontal line. The measured values are summarized in Table 3.

Table 3. Measurements of angles α and β .

Elongation (%)	α	β
0	57°	61°
10	50°	57°
15	45°	55°
20	39°	52°

4. Conclusions

In this paper, the free surface roughening of AISI 420 martensitic stainless steel under two different modes of uniaxial and radial straining was investigated.

First, the free surface roughness was measured via optical focus variation microscopy. It was shown that the samples' free surface became rougher due to plastic deformation. The surface roughness was measured at different strains, and it was found that quadratic fits could

be used for describing the roughness evolution for both cases of straining. In addition, in the case of uniaxial straining, both continuous and incremental loading conditions favored a quadratic fit. This seems to be due to a cumulative effect of roughening on different scales as the strain level increases. Additionally, it is shown that, for the uniaxial straining mode, the roughening rate became higher as the straining direction was closer to the rolling direction. This is due to the nature of the rolling process, which already extensively deforms the grains in the direction of straining, making dislocation movement within grains harder and therefore causing entire grains to deform more extensively at smaller strains.

Moreover, it was found that the roughening rate depends on the strain mode: the free surfaces became rougher with a higher rate under a tensile test than for the Erichsen cupping test. Analyzing the surface roughness distributions showed that these became Gaussian by increasing the plastic strains under uniaxial (continuous and incremental) and radial loading. This is explained by different roughening mechanisms. The initial roughness at zero strain is the result of the sheet rolling process, which does not yield a normal surface roughness distribution, but rather a distribution with $S_{Sk} > 0$, and $S_{Ku} > 3$. However, as the DIC images show, the plastic deformation of the material changes the free surfaces roughness, which results in a convergence towards Gaussianity by roughening of the valleys and asperities. The result is a more symmetrical and less spiky surface profile.

The SEM images revealed that, during deformation, the peaks are formed above the grain boundaries and chromium carbide particles, which are harder to deform compared to grain bulks due to a high dislocation density. Furthermore, the optical DIC microscopy showed that the plastic deformation resulted in deformation of the grains' morphology, which influenced the free surfaces to become rougher. Finally, it was revealed that uniaxial straining stretches the grains, and no grain rotation is found in the free surface plane.

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