APPLICATION

Failure analysis of AISI 430 stainless steel sheet under stretching and bending conditions

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Abstract
Ferritic stainless steels have been widely used to substitute austenitic steels because of their lower cost and higher deep drawing capacity. However, failures, such as shear fracture, have been observed in parts with small radii during the drawing process in applications where both bending and stretching occurs. Conventional techniques, such as failure criterion consideration, finite element method, and forming limit diagram, are unable to predict this type of fracture, which has hampered the development of new processes and products. To overcome this limitation, herein, we investigated the effects of tool radius, direction, and test speed on the formability to fracture of an AISI 430 stainless steel sheet under bending and stretching conditions. An equipment was used to perform the draw-bend fracture (DBF) test based on the bending under tension test. The DBF test efficiently reproduced the tensile, mixed, and shear fractures. Furthermore, we determined the fracture limit strain on the outer surface, thickness, and sidewall of the sample, as well as the coefficient of friction. The data showed that the radius to thickness ratio related to the process parameters had a direct impact on the experimental results. In addition, the results can be utilized for setting design guidelines and failure prevention.

Keywords Shear fracture · Nb-stabilized AISI 430 stainless steel sheet · Bending under tension test · Draw-bend fracture test · Process parameters

1 Introduction
Ferritic stainless steels (FSSs) are metallic alloys based on Fe–Cr with the <Cr> content of 10.5–27%, which exhibit high corrosion resistance and possess long shelf life [1, 2]. In recent years, FSSs have been widely used in various industries (e.g., civil, home appliances, food, pharmaceutical, chemical, bioengineering, and automotive) as an alternative to austenitic stainless steels, mainly because of their lower cost and excellent ability for deep drawing. In addition, they have a lower thermal expansion, higher thermal conductivity, and higher resistance to oxidation at high temperatures, and are not hardened by heat treatment, but by cold working [3, 4].

However, one of the considerable challenges of these and other metal alloys is the successful stamping of parts, which requires having an excellent surface appearance, minimal material consumption, high productivity, low tool wear, and absence of fractures. Over the years, researchers around the world have devoted efforts to primarily mitigate failures during the sheet metal forming (SMF) process, as this has been the main barrier for the wide-scale use of new materials and materials with specific properties [5–11]. Since it is addressing the use of new materials and materials with specific properties, we could highlight the fact that material characterization is very important, such as the scanning electron microscopy (SEM) and advanced manufacturing tools. For these reasons, advanced SEM equipment has been used in the microanalysis of the properties of materials in general [12].

It can be seen in Fig. 1a that the AISI 430 FSS failed in applications where the ratio of the tool radius to sheet
thickness \((R/t)\) was small. Filho et al. [13] also observed this type of failure during a deep drawing operation. This type of failure contrasts the crystalline texture of the material. Many studies have emphasized the excellent deep drawing capacity of the AISI 430 steel owing to the cold rolling texture in the center of the sheet [14, 15]. Damborg [16] revealed that most conventional low-C alloys typically fail in response to stretching in regions under plane strain or with soft radii. This type of failure is characterized as a shear fracture because it occurs in parts with small radii under low load with little or no apparent necking, in contrast to a tensile fracture. To date, this behavior has only been investigated in advanced high strength steels (AHSSs), but not in FSSs. Among the materials investigated is the DP590 steel, which has formability similar to that of the AISI 430 steel. Several authors have performed a series of studies on the shear fracture in AHSSs and concluded that a critical \(R/t\) for each test material exists between the safe and fail zones occurring during stretch and bending [7, 9, 17–19].

Ghosh and Hecker [20] observed that the bending on deformation has a positive influence on SMF processes. However, Baudelet and Ragab’s [21] experiment investigated the out-of-plane and in-plane stretch, and concluded that it is found that the former method produces higher limit strains than the latter under identical degrees of strain biaxiality and initial sheet thickness. Cheong [22] explained that the superposition of stretching and bending can lead to a nonlinear deformation path. Currently available techniques, such as failure criterion consideration, finite element analysis (FEA), and FLD, are based on localized strain before fracture; therefore, they are unable to predict the shear fracture in parts with small radii because there is almost no necking. Supporting these arguments, it can be seen in Fig. 1a, b that the fracture limit strain on the outer surface of the example part in the plane region (point P3) was above FLD\(_0\); on the other hand, in the regions with small radii (points P4 and P5), fracture limit strain was below FLD\(_0\), i.e., the fracture occurred in a region initially considered safe to stamp the part, denoting that the FLD method was ineffective in predicting faults in regions with small radii of parts.

Accordingly, experimental methods have been the most effective in the reproduction, characterization, and analysis of this type of failure. Recently, in an attempt to improve failure predictability, the crack opening modes were associated with the formability limits. Failure by fracture is characterized by the fracture forming limit line (FFL), originally proposed by Embury and Duncan [23] for cracks opening by tension (mode I of fracture mechanics [24]) and by the shear fracture forming limit line (SFFL), recently disclosed by Isik et al. [25] for cracks opening by in-plane shear (mode II of fracture mechanics). The mechanics and physics behind these two fracture lines are comprehensively discussed by Martins et al. [26]. Despite the above-mentioned advances in the characterization of fracture in a metallic sheet, the determination of the SFFL (mode II) and of the transition between the FFL and the SFFL (mixed-mode, consisting of crack opening by a combination of

![Fig. 1](image-url) a Fractures in an example part with AISI 430 steel; b forming limit diagram (FLD). RD-0° is the sheet rolling direction.
tension and in-plane shear) is still an open research topic. As with occur FLD, these methods cannot predict crack opening in regions with overlapping bending and stretching. However, there are few mechanical tests capable of reliably reproducing the shear fracture of metal sheets with small radii of the punch and die in a laboratory environment. Over the years, several experimental tests have been developed to evaluate the formability of metal sheets under bending and stretching conditions, such as the angular stretch-bend test (ASBT) [27], modified Duncan-Shabel apparatus [17], bending under tension (BUT) test [28, 29], and use of the stretch forming simulator (SFS) [18]. Among these, the latter two tests have been widely used because they accurately simulate the plastic strain mechanics of the sheet over the tool. Shih et al. [19] used the SFS and conducted the modified-BUT tests to reproduce shear fractures and observed that both fracture limit curves converged satisfactorily.

Originally, the BUT test was developed to simulate the contact and the deformation of a sheet metal at the die radius. During the test, a metallic strip is forced to slide over a fixed or free cylindrical pin using two independently controlled hydraulic actuators arranged at a 90° angle [28, 29]. The strip is subjected to the combined effect of the bending, unbending, and stretching efforts [30]. Subsequently, Sung et al. [7] modified the BUT test to operate it at a wide range of stamping speeds and $R/t$ ratios, ensuring high consistency and reproducibility of results. This test became known as the tensile draw-bend fracture (DBF) test. The mechanics and physics behind these and other formability tests are comprehensively discussed by Trzepiecinski and Lemu [31] and Schell and Groche [32]. In addition, the authors discussed applications relevant to SMF processes, machines, and process integration.

However, to date, no study has been conducted to analyze the failures in AISI 430 steel under bending and stretching conditions, causing a gap in our knowledge related to the formability of this material. Therefore, the present work aimed to reproduce, characterize, and analyze the failures presented by this material under these deformation conditions. For this, an equipment based on the BUT test was used to perform the DBF test. In addition, process parameters, such as pin radius, direction, and test speed, were varied to investigate their effects on the fracture limit deformation on the outer surface, thickness, and sidewall of the sheet, as well as on the coefficient of friction value. The results were plotted as a function of the $R/t$ ratio and then compared, analyzed, and discussed.

## 2 Materials and methods

### 2.1 Material and sample preparation

The material investigated was an FSS AISI 430 sheet with an initial thickness, $t_0$, of 0.8 mm, and the bending pins were made of the AISI O1 steel. The steel sheet under the as-received condition was cold-rolled, annealed, and pickled, with a slight skin pass. Its chemical composition is shown in Table 1.

| C    | Mn  | Si   | P    | S    | Ni   | Cr   | Mo   | Nb   | Ti   | N   | (ppm) |
|------|-----|------|------|------|------|------|------|------|------|-----|-------|
| 0.0164 | 0.2454 | 0.2447 | 0.0362 | 0.0009 | 0.2964 | 16.481 | 0.0234 | 0.3384 | 0.0035 | 231 |

The surface roughness (Ra) of the samples and bending pins were measured with a portable rugosimeter, model Ruggsurf 20 (Tesa SA, Renens, Switzerland), and the average results were $0.051 \pm 0.010 \, \mu m$ and $0.270 \pm 0.048 \, \mu m$, respectively. Their hardness was determined using a Vickers microhardness tester, model HMV-2 T (Shimadzu, Kyoto, and Japan), with a load of 4.9 N, and the average results were $158 \pm 6 \, HV$ and $746 \pm 11 \, HV$, respectively.

The tensile mechanical properties of the AISI 430 steel were determined using a universal testing machine, model DL30000 (Instron/Emic, Massachusetts, USA). Three tensile samples, with geometry according to ASTM E8/E8M [33], were cut in different directions ($0^\circ$, $45^\circ$, and $90^\circ$) in relation to the original direction of sheet rolling using the wire electrical discharge machining, model EURO-EW1 (Eurostec, Caxias do Sul, Brazil). The mechanical properties of the AISI 430 steel sheet are listed in Table 2. The procedures described

### Table 2 Tensile properties of the AISI 430 steel sheet

| Sample direction | $S_y$ (MPa) | $S_u$ (MPa) | $\varepsilon_u$ (%) | $\varepsilon_t$ (%) | $n$ | $r$ | $r_p$ | $\Delta r$ |
|------------------|-------------|-------------|---------------------|---------------------|-----|-----|-------|----------|
| $0^\circ$        | 316.1       | 464.9       | 22.3                | 32.7                | 0.205 | 1.419 |
| $45^\circ$      | 343.4       | 475.6       | 17.9                | 27.2                | 0.188 | 1.196 | 1.366 | 0.340   |
| $90^\circ$      | 317.5       | 466.5       | 19.8                | 33.2                | 0.201 | 1.654 |

$S_y$ yield strength, $S_u$ ultimate tensile strength, $\varepsilon_u$ uniform elongation, $\varepsilon_t$ total elongation, $n$ coefficient of hardening, $r$ normal anisotropy coefficient, $r_p$ mean normal anisotropy coefficient, and $\Delta r$ planar anisotropy coefficient.
by Banabic et al. [34] were used to determine coefficients $n$, $r$, $r_p$, and $\Delta r$.

The samples used in the conformability tests were cut on a mechanical guillotine according to the geometry shown in Fig. 2a. However, notches that induced a plane deformation state were achieved using a waterjet cutting machine, model IFB-4137 (Flow Corp., Washington, USA). Subsequently, a deterministic grid of secant or interlaced circles (Fig. 2b) with a 2.0 mm initial diameter, $d_0$, was electrochemically deposited in the notched region of the samples for use of the circle grid analysis (CGA) method introduced by Keeler [35].

2.2 Draw-bend fracture (DBF) test

As shown in Fig. 3a, an apparatus based on the BUT test has been used in the execution of the DBF test. Its limit characteristics consist of the application of a force of 44.5 kN, a speed of 75 mm/s, and displacement of the hydraulic actuators by up to 250 mm. In addition, conformability tests may be performed using free and fixed pins. As can be seen in Fig. 3b, a fixed pin tool holder was specially designed to vary the radius of the bending pin in this study. The top surface of the pins was positioned at the intersection of the lines of action of the two hydraulic cylinders to maintain tangency at an angle of 90°.

As illustrated in Fig. 4, the data acquisition system (DAS) of the equipment used USB interface devices (Loadstar Sensors, Fremont, USA), which were responsible for the acquisition and signal processing of load and displacement sensors. This equipment still contained a meter and torque sensor, but it was used only in applications with free pins. With the aid of an application software (SensorVUE), these data were stored simultaneously on a computer. Subsequently, the graphs were plotted for an analysis of the results. Purosshit [36] used a DAS similar to that shown in Fig. 4.

Table 3 lists the operational parameters adopted in the DBF test. In each new test, the tribo-surfaces were cleaned with acetone, and then a mineral oil–based lubricant was applied abundantly using a silicone oil brush. Three samples were tested under each test condition to ensure the repeatability of the results.

2.3 Constitutive equations and fractured samples analysis

Figure 3c shows that the DBF test is based on the operating principle of the BUT test, wherein four components of forces are assumed during the sliding of the sheet under the bending pin’s radius of curvature. Several authors [29, 38, 39] have explained that the force required to pull the strip ($F_1$) around...
the radius must overcome the three basic forces shown in the balance of the total forces shown in Eq. (1).

\[ F_1 = F_2 + F_b + F_f \]  

(1)

where \( F_1 \) is the frontal or pulling force, \( F_2 \) is the back or restraining force, \( F_b \) is the bending force, and \( F_f \) is the frictional force.

The fracture limit strain on the outer surface of the sheet (\( \varepsilon_{1f} \)), which occurred in the direction perpendicular to the fracture of the samples during the DBF test, was obtained by Eq. (2), as described by Silva et al. [40]. For CGA, we used the Zürich procedure n.5 presented by Parniere and Sanz [41], which evolved into the position-dependent method described by norm ISO 12004–2 [42]. To improve the accuracy of measuring the strains imposed on the samples, a digital microscope (up to 1000× magnification and 2.0 MP resolution) and Image-Pro Plus software (version 6.0) were used to capture images and measure the deterministic grid of secant circles (before and after the experimental tests), respectively.

\[ \varepsilon_{1f} = \ln\left(\frac{l_{\text{major}}}{d_0}\right) \]  

(2)

where \( l_{\text{major}} \) is the length of the major axis of the ellipses resulting from the longitudinal deformation of the secant circles.

The thickness reduction (\( R_f \)) and fracture limit strain in the sheet thickness (\( \varepsilon_{3f} \)) were determined using Eqs. (3) and (4), respectively, as reported by Nielsen and Martins [43]. The fracture thickness (\( t_f \)) was obtained using a digital micrometer with 0.001 mm precision, and its value corresponded to the average of five measurements at different locations in the fractured section of the sample. Since the deformation was compressive, its result was plotted in modulus for comparison purposes.

\[ R_f = \frac{t_0 - t_f}{t_f} \]  

(3)

\[ \varepsilon_{3f} = \ln\left(1 - R_f\right) \]  

(4)

The fracture limit strain on the sample wall due to stretching was determined by the ratio between the maximum length and initial of the notch, \( L_{\text{max}}/L_0 \). \( L_{\text{max}} \) was obtained by an LVDT sensor (KTM series 275, 0.05% accuracy) attached to the front hydraulic cylinder rod of the apparatus shown in Fig. 3a. On the other hand, \( L_0 \) was obtained by a digital caliper (Mitutoyo 0–200 mm, 0.01 mm accuracy). The morphology of the fracture surfaces was analyzed using a scanning electron microscope, model JSM-6510LV (Jeol, Tokyo, Japan) with an acceleration of 20 kV.

The COF (\( \mu \)) was calculated using Eq. (5). This equation has been used for decades [38, 44] in the tribology of SMF with cylindrical tools because it considers the geometric parameters of the tribological pair in the constitutive equation, such as the sheet thickness and tool radius.

\[ \mu = \frac{2}{r} \left(1 + \frac{l_0}{2R}\right) \ln\left(\frac{F_1 - F_b}{F_2}\right) \]  

(5)

The bending force (\( F_b \)) was determined using Eq. (6), as introduced by Swift [45]. The sample width (\( w \)) was assumed to be the notch width because the localized deformation was concentrated in this region.

\[ F_b = \frac{S_i t_0^2 w}{2R} \]  

(6)

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Table 3 Operating parameters used in the DBF test

| Operating parameters | Description |
|----------------------|-------------|
| Sample direction*   | RD-0° and TD-90°** |
| Test speed, \( v \)  | 2.5 and 25 mm/s |
| Bending pin radius, \( R \) | 1.5, 3.0, 4.5, 6.0, 7.5, 9.0, 10.5, 13.5, 16.5, and 19.5 mm |
| Lubricant           | Viscosity (\( \eta \)) of 120 mPa.s and density (\( \rho \)) of 0.894 g/cm³ |

*TD-90° is the transversal direction of sheet rolling.
3 Results and discussion

3.1 Characterization of fracture types

Figure 5a shows the schematic representation of the deep drawing process and Fig. 5b–d show the different types of fractures that were reproduced during the DBF test: tensile, mixed, and shear fractures. These fractures were designated as types 1, 2, and 3, respectively. A condition of plane strain was assumed during the experimental tests of the samples. The experimental results showed that as radius/thickness (R/t) ratio revealed, the fracture tends to move from the curvature region to the flat region of the sheet.

Figure 5a, b show that type 1 is similar to the fracture that occurs in the sidewall of stamped parts. Generally, this failure is referred to as ductile fracture and is observed in metallic materials in a conventional tensile test, as the fracture occurred when the sample-resistant section was reduced by localized deformation or necking. Dieter [46] explained that before the ductile fracture, the necking introduces a triaxial stress state, and a hydrostatic component of stress acts at the center of the notch region until the sample reached its minimum dimensions (Fig. 6a) and, consequently, its final rupture. A commonly accepted interpretation is that a tensile fracture originates from the initiation, growth, and coalescence of microscopic voids during plastic deformation [47]. This void nucleation generally occurs at the interfaces of inclusions and second-phase particles, and the dissociation of these interfaces is the dominant mechanism in void nucleation. These behaviors were confirmed by an interrupted tensile test, as shown in Fig. 7a. The fracture propagated from the center to the edges of the notch (Fig. 7b), and the morphological aspect of the fracture surface (Fig. 7c) was similar to that of the sample subjected to the DBF test (Fig. 6b). Both fracture surfaces were characterized by the presence of equiaxed dimples, which, from a macroscopic perspective, are normal to the direction of the applied force (F).

In contrast, Fig. 5a, d show that type 3 tends to occur under the tool radius and is similar to brittle fracture, which, by definition, occurs with low energy absorption (i.e., with little or no macroscopic plastic deformation) under stresses lower than those corresponding to the generalized yielding, and with a significantly high crack-propagation velocity [46, 47]. Furthermore, the fracture started at the edge of the sample and propagated perpendicularly to its longitudinal axis while its minimum dimensions (Fig. 8a) were still much

![Fig. 5](image-url) Different fracture types reproduced in the DBF test.

(a) schematic representation of deep drawing process; (b) type 1 (tensile fracture at sidewall); (c) type 2 (mixed fracture at the tangent point); (d) type 3 (shear fracture in the punch radius)
larger than those of type 1 (Fig. 6a). Supporting these results, Martínez-Donaire et al. [48] demonstrated that the fracture initiation site was shifted closer to the sheet free edge as the punch radius decreased and with low plastic strain. Figure 8b clearly shows that the fracture surface morphology contains sheared dimples or highly elongated, characteristics typical of those obtained in a shear fracture. The shear fracture mechanism during an SMF operation is not by pure shear as seen in sheet metal cutting, which would result in a flat surface practically without any significant topographic relief, but by sliding between crystallographic planes. The presence of cleavage facets on the fracture surface (Fig. 8b) supported these arguments, since they occurred due to the separation of the crystallographic planes by rupturing atomic bonds [49].

A comparative analysis between Figs. 8b and 9b evidenced that the failure that occurred in the example part is a shear fracture, as both surfaces presented the same fracture mechanisms, i.e., sheared dimples and cleavage facets. This also indicated that the DBF test efficiently reproduced, in a laboratory environment, a fracture commonly observed in industrial practices, especially in the region of small radii of the punch.

On the other hand, type 2 is called mixed because it occurs during the transition between a shear and tensile fracture. Figure 5a, c show that this type of fracture tends to occur on the tangent point line between the side wall and punch radius. Sung et al. [7] explained that, in industrial practices, this type of fracture usually starts close to the edge of the sample like a type 3, but tends to propagate at a similar angle to type 1. However, it is unlikely to occur frequently as the $R/t$ ratio is quite high in most SMF applications. Shih and Shi [18] emphasized that this type of fracture is significantly sensitive to the restraining condition ($F_2$) or the tension level applied during the bending.

### 3.2 Fracture limit strain at outer surface ($\varepsilon_{1f}$)

Figure 10 shows the effect of the ratio $R/t$ on the fracture limit strain on the outer surface ($\varepsilon_{1f}$) of the samples subjected to different directions and test speeds. In a first analysis, the results indicated that $\varepsilon_{1f}$ increased significantly with increasing $R/t$ ratio. This behavior was due to the increase in the yield stress of the sample by strain hardening. In recent experimental studies, several researchers have observed the same tendency for other materials [50–53]. In general, the results showed that $\varepsilon_{1f}$, in the RD direction, reached its maximum values for a critical $R/t$ ratio, approximately equal to 13.0 and 9.0 for the velocity of 2.5 and 25 mm/s, respectively. On the other hand, in the TD direction, the critical $R/t$ ratio was approximately 10.0 for both speeds. Most likely, the differences observed can be attributed to the balance between the combined effect of bending and stretching on the stress gradient during plastic deformation of the metallic strip.

Additionally, $\varepsilon_{1f}$ decreased in both directions as the test speed increased. It is well known that in SMF processes the increase in velocity has a significant effect on the strain rate and, consequently, on the material properties. At room temperature, the work hardening of the material increases with increasing strain rate due to a more
enhanced movement of dislocations, resulting in increased mechanical strength and decreased ductility of the material [34, 46, 47]. Yoshida et al. [54] demonstrated, through an analytical prediction of the behavior of metal sheets under stretching and bending, that $\varepsilon_{1f}$ tends to be higher for materials with a high hardening coefficient ($\eta$); however, for a higher $R/t$ ratio, this value tends to decrease, as stretching dominates the plastic deformation process. This reported behavior can be clearly seen in Fig. 10a, b, approximately from $R/t > 12.0$. At lower speeds, the TD direction ($9.0 < R/t < 12.0$) exhibited the highest possible value of $\varepsilon_{1f}$. These different behaviors can be attributed to the heterogeneity of the material properties. Supporting these arguments, Table 2 shows that the TD sample showed a higher anisotropy coefficient (~17%) than the RD sample, indicating that the sheet plane surface deform more until necking and fracture occurred.

A more careful analysis of the results showed that as $R/t$ increased, $\varepsilon_{1f}$ tends to move from the curvature region to the flat region of the sheet, agreeing with the discussion in the previous section. Therefore, the sheet fracture mechanism changed from the sheet fracture in the punch radius to the tensile fracture in the punch sidewall. This behavior has also been observed in studies of other materials [7, 19, 50]. Supporting these arguments, the macrographic images of the fractured samples (Fig. 5b–d) and the results shown in Fig. 10 demonstrated that type 1, type 2, and type 3 occurred when $R/t > 6.0$, $4.5 < R/t < 6.0$, and $R/t < 4.5$, respectively.

A comparative analysis between Figs. 1a and 10 revealed that the magnitudes of the deformations were very similar, indicating again that the DBF test effectively reproduced an SMF industrial operation. Therefore, these results could be used as design guidelines and failure prevention criteria in the development of processes and products from FSS AISI 430. In addition, they can be used in the SMF processes to avoid problems related to conformability in the parts’ radii.

### 3.3 Fracture limit strain of thickness ($\varepsilon_{3f}$)

Figure 11 shows the effect of the ratio $R/t$ on the fracture limit strain upon the thickness ($\varepsilon_{3f}$) of samples subjected to different directions and test speeds. From this figure, it is clear that $\varepsilon_{3f}$ increases with an increase in the ratio $R/t$, i.e., the sheet thickness decreases. In this regard, Yoshida et al. [54] explained that during stretching and bending, the yield strength of the sheet ($S_y$) increases with the outer surface strain $\varepsilon_{1f}$ because of its cold work hardening; however, the thickness of the sheet decreases. Since the sample is in a plane strain state, this behavior obeys the law of volume constancy.

A more careful analysis of the results showed that $\varepsilon_{3f}$ tends to stabilize more quickly in the TD ($9.0 < R/t = 7.5$) than in the RD ($9.0 < R/t = 13.0$). This behavior was explained by the mechanical properties of the material (Table 2); the higher the normal anisotropy coefficient ($r$), the higher is the material’s resistance to thinning, allowing the surface and wall of the strip...
to deform more until the fracture. The results also showed that when the $R/t$ ratio was very low ($\leq 1.5$), type 3 occurred almost instantly, as there was practically no apparent necking in the sample section ($\epsilon_y < 7\%$), indicating that the thickness strain ceased even before the sample reached uniform elongation. However, this behavior differed from that of type 1 because when $R/t$ was high the ductility of the sheet still remained quite significant ($\epsilon_y > 30\%$), even after reaching the uniform elongation, ceasing only with the sample fracture. Increasing the test speed had a more significant effect on the RD, most likely due to its lower normal anisotropy coefficient; consequently, the thickness reduction tended to increase.

In summary, these results suggested that for predicting a fracture in SMF processes, the FLD is valid only for failures induced by necking on flat surfaces and under approximately proportional loading conditions. In this regard, Baudelet and Ragab [21] emphasized that nonlinear deformation trajectories and out-of-plane deformations are excluded from FLDs, which explains the unpredictability of the fracture of AISI 430 steel shown in Fig. 1.

### 3.4 Limit wall stretch ($L_{\text{max}}/L_0$)

Figure 12 shows the effect of the $R/t$ ratio on the limit wall stretch of the samples subjected to different test directions and speeds. It is clearly noted that $L_{\text{max}}/L_0$ increased significantly with increasing $R/t$ because of the lower strain hardening of the material as the bending severity decreased. According to the bending theory [34, 46], the larger the radius of curvature, the smaller the decrease in sheet thickness in the bending region and, consequently, the higher the capacity of the sheet to stretch or deform longitudinally. Several researchers [18–21, 54–57] have investigated the effect of the radius of curvature on the limit wall stretch of other materials and observed the same trend.

Notably, it is known that during pure bending, the convex side of the bend (outer surface) experiences tension and the concave side experiences compression. Due to this non-uniform status through the thickness, a strain gradient is generated with a neutral layer (NL) where neither tension nor compression is observed. Generally, more severe bending provides a stronger strain gradient [22, 30, 46]. In sheet metal forming, the bending mode is one of plane strain since the width of the sheet is generally much larger than the sheet thickness. However, the difference between the different stress states along the material thickness causes a displacement of the NL. In this regard, Ma and Welo [58] explained that for most metallic materials during bending, the NL moves away from the center of the sheet as the...
radius of curvature increases, causing changes in the strain gradient. Cheong [22] emphasized that the strain gradient has a critical impact on strain instability, and even though the outmost layer reaches the critical strain limit from FLD, the inner layers that are in moderate tension or compression provide stability and serve to mitigate necking. In this context, Tharrett and Stoughton [50] proposed an empirical concave side rule (CSR), which stated that strain instability occurs only when all of the material layers in the sheet have exceeded the forming limit strain. As a result, in forming operations with in-plane tension and out-of-plane bending, the initiation of necking is delayed until the innermost layer has reached the limit strain. Figure 11 confirms this behavior as the \( R/t \) ratio increased. Therefore, under these conditions, the strip wall tends to reach higher levels of stretch, as can be seen in Fig. 12a, b.

Additionally, the magnitude of \( L_{\text{max}}/L_0 \) decreased with an increase in the test speed. As discussed, increasing the strain rate caused the yield strength of the material to increase due to strain hardening and, as result, the sheet ductility decreased. Fractures occur when all fibers close to the outer surface reach the limit strain (\( \epsilon_{u1} \)) [52]. At high speed, both directions (RD and TD) showed very similar behavior; however, at low speed, the TD sample (Fig. 10b) exhibited a higher \( L_{\text{max}}/L_0 \) value, most likely, due to the high normal anisotropy coefficient in this direction, which increased the resistance to thinning and, consequently, their stretching capacity.

Therefore, the experimental results showed that the limit strain of the sheet metal (\( \epsilon_{\text{limit}} \)) under bending and stretching is assumed to be the superposition of the bending limit deformation (\( \epsilon_{\text{bend}} \)) and stretch (\( \epsilon_{\text{stretch}} \)). This suggests that the smaller the contribution of \( \epsilon_{\text{bend}} \) in the plastic deformation process—this occurs with the displacement of the NL out of the plane as the ratio \( R/t \) increases—the more \( \epsilon_{\text{limit}} \) approaches \( \epsilon_{\text{stretch}} \) and, consequently, of FLD. Considering this, the industrial practice has produced thicker parts and with large bend radius to ensure success in SMF operations. However, these practices directly impact the other parameters; for example, an increase in the force required to deform a part, an increase in production costs, and an increase in the friction and wear process between the tribo-surfaces. Experimental analysis is a very powerful tool in this context, as it allows a more curated analysis of the physical phenomena involved in the plastic deformation process of a metallic sheet, which can determine more assertive solutions in developing processes and products.

### 3.5 Coefficient of friction (COF)

Figure 13 shows the effect of the \( R/t \) ratio on the COF of the samples subjected to different test directions and speeds. We
noticed that the COF increased with a decrease in the pin radius; however, this behavior changed from a critical $R/t$ ratio, from which the COF increased with an increase in the pin radius. Nanayakkara et al. [38] observed a similar behavior for a galvanized steel sheet subjected to the BUT test and concluded that from a critical radius, the tribo-system changed from a mixed lubrication regime to a hydrodynamic lubrication regime. Andreasen et al. [59] explained that this change may be related to the varying contact pressure and sheet roughness due to the plastic strain by stretching.

Kim et al. [60] demonstrated that the contact pressure increases as the radius of the pin decreases; moreover, it is not uniformly distributed on the contact surface. According to the Stribeck curve, when the contact pressure increases ($p$), the lubricant viscosity ($\eta$) or speed ($v$) decreases [61]. Under these conditions, the ability of the lubricant to separate the contact surfaces and stabilize the COF is diminished [62]. Several authors [63–65] have reported that at higher pressures, the lubricating film can be expelled from the friction zone or break, increasing the interaction between the asperities of the tribo-surfaces and, consequently, the friction resistance. Once the sheet surface is softer (~4.8 times) than the bending pin, an increase in this interaction produces deep galling on the sheet surface and with the material transfer, as shown in Fig. 14a. This suggests that the high level of friction and galling may have contributed to the occurrence of shear fracture. Figure 14b also supports these arguments by showcasing the different micro-effects of friction and wear mechanisms that governed the interface of the tribo-contact.

Still according to the Stribeck curve, the COF in fluid-lubricated contacts is a nonlinear function with the Hersey number ($\eta v p$) [61]. From a critical value of this number, the COF tends to increase continuously, suggesting that significant changes occur at the contact interface, which explains the increase in the COF from the $R/t$ ratio critical. In SMF operations, the lubricating film is very thin; therefore, the lubrication regime is said to be micro-hydrodynamic [63]. This lubrication regime is very sensitive to topographical changes at the contact interface. Recent studies have shown that the surface roughness and COF increase as the relative elongation of the sheet increases [66, 67]. This increase in surface roughness is explained by a theory about the formation of Lüders bands during the plastic deformation of steels with low carbon [68–70]. Makhkamov [71] emphasized that in addition to the plastic deformation altering the surface roughness, it also eliminates most of the elastic effects on contact and opens a new surface by the action of dislocation sliding.

However, the contribution of roughness to the tribo-system cannot be analyzed in isolation. It is well known that a higher surface roughness guarantees enhanced lubrication due to the presence of more valleys; however, this is true only to a certain extent, as varying the contact pressure affects the adhesion mechanisms and plastic strain of sheet asperities. Since sheet asperities are softer than tool asperities, at high pressures, they tend to undergo a greater degree of flattening and, consequently, adhesive forces, frictional resistance, and surface wear tend to increase.

In addition, several researchers [38, 72] have demonstrated that the bending force is significant in friction analysis and, therefore, cannot be ignored. Equation (6) shows that $F_b$ decreases with increasing pin radius. According to Eq. (1), the force required to pull the strip ($F_1$) over the pin increases as $F_b$ decreases, resulting in an increase in the normal load on the sheet surface that causes a greater degree of flattening of its asperities. Equation (5) also supports these arguments.

The COFs obtained showed the same tendencies as other researchers [60, 63] observed in their experiments, COF decreased as the test speed increased. At higher speeds, it was observed that the RD and TD samples presented very similar behaviors, suggesting that the COF became more independent of the contact pressure under this condition. The Stribeck curve also supports this argument. This was because the lubrication regime at the contact interface became more similar to micro-hydrodynamic lubrication, where the load was carried more by the lubricating film.

However, at lower speeds, the COF in the RD direction was higher than that in the TD direction, most likely due to ridging of the AISI 430 steel sheet under plastic.

Fig. 14 SEM image showing a galling on the contact surface and the b effects of friction and wear mechanisms
deformation. Shin et al. [73] explained that FSS exhibits ridges parallel to the rolling direction when subjected to drawing or deep drawing operations. Generally, the ridges have a depth in the range of 20–50 μm. Luiz and Rodrigues [39, 67] explained that, although the ridges are considered superficial defects that negatively affect the visual aspect of parts, the depth and width of the ridges are relevant for thin sheets, because the distribution of the lubricant and the efforts are not uniform at the contact interface, which can cause different lubrication regimes in the same tribo-system and, as result, the friction resistance tends to increase.

4 Conclusions

The main conclusions obtained from the analysis of the experimental results are summarized below:

- The DBF test was able to reliably reproduce, under a plane strain state, three different types of fractures in an AISI 430 sheet steel: type 1 (necking failure in the punch sidewall), type 2 (failure in the tangent point between the punch radius and sidewall), and type 3 (failure in the punch radius).
- The fracture limit strain on the outer surface increased with increasing \( R/t \) and, simultaneously, shifted and changed its typical characteristics. The tensile fracture occurred when \( R/t > 6.0 \), mixed fracture when \( 4.5 < R/t < 6.0 \), and the shear fracture when \( R/t < 4.5 \). The results showed that in the RD direction, fracture limit strain on the outer surface reached its maximum values for a critical \( R/t \) ratio, approximately equal to 13.1 and 9.0 for the velocity of 2.5 and 25 mm/s, respectively. On the other hand, in the TD direction, the critical \( R/t \) ratio was approximately 10.3 for both speeds.
- The fracture limit strain at the thickness increased with increasing \( R/t \); however, beyond a critical point in their relationship, it exhibited a tendency to stabilize. This indicated that the FLD was valid only for necking-induced failures on flat surfaces and under approximately proportional loading conditions.
- The wall stretch limit increased with increasing \( R/t \), most likely due to lesser work hardening of the material. The increase in sheet resistance to thinning in the TD provided a more enhanced stretch than the RD.
- The COF increased with the decrease in the pin radius; however, this behavior changed from a critical \( R/t \) ratio, where the COF increased with increasing pin radius. Parameters such as the variation of contact pressure, bending force, lubrication regime, roughness, and sheet surface ridging had a direct impact on the COF.
- Finally, these results can be used as design guidelines and failure prevention criteria in the development of processes and products from AISI 430 steel. In addition, they can be used to avoid failures related to conformability in parts’ radii.

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Author contribution Luiz VD: resources, methodology, investigation, data curation, writing—original draft. Rodrigues PCM: resources, conceptualization, methodology, writing—review and editing, supervision, project administration, formal analysis, funding acquisition.

Availability of data and material All data generated or analyzed during this study are included in this published paper. Requests for material should be made to the corresponding authors.

Declarations

Ethics approval Not applicable for that section.

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References

1. ASTM A240/A240M-20a (2020) Standard specification for chromium and chromium-nickel stainless steel plate, sheet, and strip for pressure vessels and for general applications. ASTM International, West Conshohocken, PA
2. Krauss G (2005) Steels: processing, structure and performance, 1st edn. ASM International, Ohio
3. ISSF (2007) The ferritic solution: properties, advantages, applications. https://www.worldstainless.org/Files/issf/non-image-files/PDF/ISSF_The_Ferritic_Solution_English.pdf. Accessed 27 Apr 2021
4. Lo KH, Shek CH, Lai JKL (2009) Recent developments in stainless steels. Mater Sci Eng Rep 65(4-6):39–104. https://doi.org/10.1016/j.mser.2009.03.001
5. Keeler SP, Backofen WA (1964) Plastic instability and fracture in sheets stretched over rigid punches. ASM Trans Q 56(11):25–48
6. Marciniak Z, Kuczyński K (1967) Limit strains in the process of stretch forming sheet metal. Int J Mech Sci 9(9):609–612. https://doi.org/10.1016/0020-7403(67)90066-5
7. Sung JH, Kim JH, Wagoner RH (2012) The draw-bend fracture test and its application to dual-phase and transformation induced plasticity steels. J Eng Mater Technol 134(4):041015. https://doi.org/10.1115/1.4007261
8. Scales M, Tardif N, Kyriakides S (2016) Ductile failure of aluminum alloy tubes under combined torsion and tension. Int J
Solids Struct 97–98:116–128. https://doi.org/10.1016/j.solstr.2016.07.038
9. Roth CC, Mohr D (2018) Determining the strain to fracture for simple shear for a wide range of sheet metals. Int J Mech Sci 149:224–240. https://doi.org/10.1016/j.ijmecsci.2018.10.007
10. Kim JH, Sung JH, Kun P, Wagner RN (2011) The shear fracture of dual-phase steel. Int J Plast 27:1658–1676. https://doi.org/10.1016/j.ijplas.2011.02.009
11. Park N, Stoughton TB, Yoon JW (2020) A new approach for fracture prediction considering general anisotropy of metal sheets. Int J Plast 124:199–225. https://doi.org/10.1016/j.ijplas.2019.08.011
12. Chee AKW (2020) Unravelling new principles of site-selective doping contrast in the dual-beam focused ion beam/scanning electron microscope. Ultramicroscopy 213:112947:1–10
13. Ferreira Filho A, Herrera C, Lima NB, Plaut RL, Padilha AF (2007) Texture evolution of ferritic (AISI 430) stainless steel strips during cold rolling, annealing and drawing. Mater Sci Forum 539–543:4926–4931. https://doi.org/10.4028/www.scientific.net/MSF.539-543.4926
14. Raabe D, Lücke K (1993) Textures of ferritic stainless steel. Mater Sci Technol 9(4):302–312. https://doi.org/10.1179/mst.1993.9.4.302
15. Labiapuri WS, Ardila MAN, Costa HL, Mello JDB (2019) Abrasion-corrosion of ferritic stainless steel. In: Duriguíná Z, editor. Stainless Steels and alloys. 1st ed. London: IntechOpen. https://doi.org/10.5772/intechopen.81913
16. Damborg FF (1999) Bending-under-tension formability: a comparison between aluminium and steel. PhD Dissertation, Aalborg University.
17. Walp MS, Wurm A, Siekirk III JF, Desai AK (2006) Shear fracture in advanced high strength steels. SAE Tech Pap 2006–01–1433. https://doi.org/10.4271/2006-01-1433
18. Shih H-C, Shi MF (2008) Experimental study on shear fracture of advanced high strength steels. Proceedings of the 2008 International Manufacturing Science and Engineering Conference; 2008 Oct 7–10; Evanston, Illinois, USA. New York: ASME International. p. 41–47. https://doi.org/10.1115/MSEC_ICMP2008-72046
19. Shih H-C, Shi MF, Xia ZC, Zeng D (2009) Experimental study on shear fracture of advanced high strength steels: part II. Proceedings of the 2009 International Manufacturing Science and Engineering Conference; 2009 Oct 4–7; West Lafayette, Indiana, USA. New York: ASME International. p. 513–519. https://doi.org/10.1115/MSEC2009-84070
20. Ghosh AK, Hecker SS (1974) Stretching limits in sheet metals: in-plane versus out-of-plane deformation. Metall Trans B 5(10):2161–2164. https://doi.org/10.1007/BF02643929
21. Baudelet B, Ragab AR (1982) Forming limit curves: out-of-plane and in-plane stretching. J Mech Work Technol 6(4):267–276. https://doi.org/10.1016/0378-3804(82)90027-4
22. Cheong DWK (2019) On the influence of the through-thickness strain gradients for characterization of formability and fracture of sheet metal alloys. PhD Dissertation, University of Waterloo.
23. Embury JD, Duncan JL (1981) Formability maps. Ann Rev Mater Sci 11:505–521
24. Silva MB, Skjoedt M, Atkins AG, Bay N, Martins PAF (2008) Single point incremental forming and formability-failure diagrams. J Strain Anal Eng Design 43(5):15–36. https://doi.org/10.1016/j.strain.2007.05.004
25. Isik K, Silva MB, Tekkaya AE, Martins PAF (2014) Formability limits by fracture in sheet metal forming. J Mater Process Technol 214(8):1557–1565. https://doi.org/10.1016/j.jmatprot.2014.02.026
26. Martins PAF, Bay N, Tekkaya AE, Atkins AG (2014) Characterization of fracture loci in metal forming. Int J Mech Sci 83:112–123. https://doi.org/10.1016/j.ijmecsci.2014.04.003
27. Narayanaswamy OS, Demeri MY (1983) Analysis of the angular stretch bend test: novel techniques in metal deformation testing. The Metallurgical Society, St. Louis, MO 99–112
28. Wenzloff GJ, Hylton TA, Matlock DK (1992) Technical note: a new test procedure for the bending under tension friction test. J Mater Eng Perform 1(5):609–614. https://doi.org/10.1007/BF02649242
29. Vallance DW, Matlock DK (1992) Application of the bending-under-tension friction test to coated sheet steels. J Mater Eng Perform 1(5):685–693. https://doi.org/10.1007/BF02649250
30. Marcianiz K, Duncan JL, Hu SJ (2002) Mechanics of sheet metal forming, 1st edn. Butterworth-Heinemann, Oxford
31. Trzepieciński T, Lemu HG (2020) Recent developments and trends in the friction testing for conventional sheet metal forming and incremental sheet forming. Metals 10:47. https://doi.org/10.3390/met10010047
32. Schell L, Groche P (2021) In search of the perfect sheet metal forming tribometer. In: Daehn, G., Cao, J., Kinsey, B., Tekkaya, E., Vivek, A., Yoshida, Y. (eds) Forming the Future. The Minerals, Metals & Materials Series. Springer, Cham. https://doi.org/10.1007/978-3-030-75381-8_7
33. ASTM E8/E8M-16a (2016) Standard test methods for tension testing of metallic materials, ASTM International, West Conshohocken, PA, USA
34. Banabic D, Bunge H-J, Pöhlandt K, Tekkaya AE (2000) Formability of metallic materials: plastic anisotropy, formability testing, forming limits. Springer, Berlin
35. Keeler SP (1968) Circular grid system—a valuable aid for evaluation sheet metal formability. SAE Tech Pap 680982
36. Purohit Z (2010) Performance of polymer coatings under forming conditions. PhD Dissertation, Texas A&M University.
37. Loadstar Sensors (2020) RAS1 S Beam Load Cell, https://www.loadstarsensors.com/assets/specsheets/ras1.pdf; 2020. Accessed 8 Jan 2022
38. Nanayakkara NKBMP, Kelly G, Hodgson P (2005) Application of bending under tension test to determine the effect of tool radius and the contact pressure on the coefficient of friction in sheet metal forming. Mater Forum 29(1):114–118
39. Luiz VD, Rodrigues PCM (2022) Design of a tribo-simulator for investigation of the tribological behavior of stainless-steel sheets under different contact conditions, Mater Res 25:e20210220. https://doi.org/10.1590/1980-5373-MR-2021-0220
40. Silva MB, Isik K, Tekkaya AE, Martins PAF (2015) Fracture loci in sheet metal forming: a review. Acta Metall Sin 28(12):1415–1425. https://doi.org/10.1007/s40195-015-0341-6
41. Parniere P, Sanz G (1976) Appréciation des Caractéristiques d’Emboutissabilité des Tôles Minces – Mise en forme des métaux et alliages. Centre National de la Recherche Scientifique-CNRS, Paris
42. ISO 12004-2 (2021) Metallic materials—sheet and strip—determination of forming-limit curves—Part 2: Determination of forming-limit curves in the laboratory; ISO standards, Geneva
43. Nielsen CV, Martins PAF (2021) Metal forming: formability, simulation, and tool design, 1st edn. Elsevier, London
44. Trzepieciński T, Lemu G (2015) Proposal for an experimental-numerical method for friction description in sheet metal forming. J Mech Eng 61(6):383–391. https://doi.org/10.5545/sv-jme.2015.2404
45. Swift HW (1948) Plastic bending under tension. Engineering 166:333–359
46. Dieter G (1989) Mechanical metallurgy, 3rd edn. McGraw Hill, New York
47. Li H, Fu M (2019) Deformation-based processing of materials: behavior, performance, modeling, and control, 1st edn. Elsevier, Amsterdam
48. Martínez-Donaire AJ, Morales-Palma D, Valdellano C (2020) On the use of strain path independent metrics and critical distance
rule for predicting failure of AA7075-O stretch-bend sheets. Metals 13:3660. https://doi.org/10.3390/ma13173660
49. Bitzek E, Kernode JR, Gumbsch P (2015) Atomic aspects of fracture. Int J Fract 191:13–30. https://doi.org/10.1007/s10704-015-9988-2
50. Tharrett MR, Stoughton TB (2003) Stretch-bend forming limits of 1008 AK steel. SAE Tech Pap 2003–01–1157. https://doi.org/10.4271/2003-01-1157
51. Luo M, Wierzbicki T (2010) Numerical failure analysis of a stretch-bending test on dual-phase steel sheets using a phenomenological fracture model. Int J Solids Struct 47:3084–3102. https://doi.org/10.1016/j.ijsolstr.2010.07.010
52. Morales-Palma D, Valdellano C, García-Lomas FJ (2013) Assessment of the effect of the through thickness strain/stress gradient on the formability of stretch-bend metal sheets. Mater Des 50:798–809. https://doi.org/10.1016/j.matdes.2013.03.086
53. Min J, Stoughton TB, Carsley JE, Lin J (2016) Compensation for process-dependent effects in the determination of localized necking limits. Int J Mech Sci 117:115–134. https://doi.org/10.1016/j.ijmechsci.2016.08.008
54. Yoshida M, Yoshida F, Konishi H, Fukumoto K (2005) Fracture limits of sheet metals under stretch bending. Int J Mech Sci 47:1885–1896. https://doi.org/10.1016/j.ijmechsci.2005.07.006
55. He J, Xia ZC, Zhu X, Zeng D, Li S (2013) Sheet metal forming limits under stretch-bending with anisotropic hardening. Int J Mech Sci 75:244–256. https://doi.org/10.1016/j.ijmechsci.2013.07.007
56. Neuhauser FM, Terrazas O, Manopulo N, Hora P, Van Tyne C (2019) The bending dependency of forming limit diagrams. Int J Mater Form 12:815–825. https://doi.org/10.1007/s12289-018-1452-1
57. Gihyun BG, Park N, Song J, Lee J, Jang I, Park K, Seo Y, Oh K (2020) Stretch-bending crack simulation for advanced high-strength thick steel sheets considering the contact pressure effect. Procédia Manuf 50:574–578. https://doi.org/10.1016/j.promfg.2020.08.103
58. Ma J, Welo T (2021) Analytical springback assessment in flexible stretching bending of complex shapes. Int J Mach Tools Manuf 160:103653. https://doi.org/10.1016/j.ijmachtools.2020.103653
59. Andreasen JL, Olsson DD, Chodnikiewicz K, Bay N (2006) Bending under tension test with direct friction measurement. Proc Inst Mech Eng B J Eng Manuf 220(1):73–80. https://doi.org/10.1243/095440505X32913
60. Kim YS, Jain MK, Metzger DR (2012) Determination of pressure-dependent friction coefficient from draw-bend test and its application to cup drawing. Int J Mach Tools Manuf 56:69–78. https://doi.org/10.1016/j.ijmachtools.2011.12.011
61. Jeyaprakash N, Che-Hua Y (2020) Friction, lubrication, and wear. In: Patnaik A, Singh T, Kukshal V, editors. Tribology in Materials and Manufacturing. 1st ed. IntechOpen, London. https://doi.org/10.5772/intechopen.93796
62. Trzepieciński T, Lemu HG (2020) Effect of lubrication on friction in bending under tension test-experimental and numerical approach. Metals 10(4):544. https://doi.org/10.3390/met10040544
63. Roizard X, Rahariyona F, von Stebut J, Belliard P (1999) Influence of sliding direction and sliding speed on the micro-hydrodynamic lubrication component of aluminium mill-finish sheets. Tribol Int 32:739–747. https://doi.org/10.1016/S0301-679X(99)00008-6
64. Bart JCI, Guciardi E, Cavallaro S (2013) Biolubricants: science and technology, 1st edn. Woodhead Publishing, Sawston
65. Blau PJ (2008) Friction science and technology: from concepts to applications, 2nd edn. CRC Press, Florida
66. Trzepieciński T (2019) A study of the coefficient of friction in steel sheets forming. Metals 9(1):1–11. https://doi.org/10.3390/met9090088
67. Luiz VD, Rodrigues PCM (2021) Effect of the test conditions on tribological behavior of an Nb-stabilized AISI 430 stainless steel sheet. J Braz Soc Mech Sci 43:505. https://doi.org/10.1007/s40430-021-03235-7
68. Piobert A (1842) Expériences sur la pénétration des projectiles dans le fer forgé. Mémoire L’artillerie 5:502
69. Lüders W (1860) Ueber die aeußerung der elasticität an stahlarti gen eisenstäben und stahlstäben, und über eine beim biegen sol cher stäbe beobachtete molecularbewegung. Dingler Polytech J 155:18–22
70. Brilić T, Rešković S, Vodopivec F, Jandriči J (2018) Lüders bands at the beginning of the plastic flow of materials. Metalurgija 57(4):357–359
71. Makhkamov A, Wagle D, Baptista AM, Santos AD, Malheiro L (2017) Tribology testing to friction determination in sheet metal forming processes. Cienc e Tecnol dos Mater 29:249–253. https://doi.org/10.1016/j.ctmat.2016.07.002
72. Purohit Z, Zhang A, Wang J (2015) On surface damage of polymer coated sheet metals during forming. J Manuf Process 20(2):389–396. https://doi.org/10.1016/j.jmapro.2014.09.002
73. Shin HJ, An JK, Park SH, Lee DN (2003) The effect of texture on ridging of ferritic stainless steel. Acta Mater 51(16):4693–4706. https://doi.org/10.1016/S1359-6454(03)00187-3

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