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Original Research

Influence of Multi-Pass Forming on the Tribological Performance of AISI 430 Steel Sheet in Deep Drawing Process

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Abstract

In this paper, the effect of sheet pre-deformation on the change of the surface roughness parameters and friction coefficient value is investigated. For this purpose, strips of AISI 430 ferritic stainless steel with deep drawing quality (DDQ), measuring 0.8 × 25 × 500 mm, were pre-deformed using a uniaxial tensile test for five different true strain values. The correlation between the surface roughness parameters and hardness with the frictional conditions of the tested strips was investigated in the bending under tension test. The results revealed that the friction coefficient determined for all pre-deformed strips increased as the level of true strain also increased. An increase in the plastic deformation of sheets under the uniaxial tensile stress state causes a nearly linear increase in the value of basic amplitude parameters of surface roughness, however, the hardness tended to present a constant increase for deformations close to uniform elongation. Furthermore, scratches and severe wear occurred on the surface of the strips and intensified with increasing roughness.

Keywords: pre-deformation, AISI 430 ferritic stainless steel, bending under tension test, coefficient of friction

1. Introduction

AISI 430 ferritic stainless steel is widely used in applications that require good corrosion resistance, good mechanical strength and low cost compared to other stainless steels (Luiz & Rodrigues, 2021). It is mainly composed of chromium (around 16–18%), with a low carbon content, and is characterized by its ferritic microstructure, which provides magnetic properties and greater resistance to corrosion in moderate environments (Inya et al., 2023). Its main applications include the household appliances and utensils industry (e.g., kitchen sinks and bowls, coverings for stoves, refrigerators and pans), automotive industry (e.g., exhaust systems, aesthetic and structural components), civil construction and architecture (e.g., external coatings, decorative and structural elements), energy industry (e.g., heat exchangers and components in thermoelectric power plants), among other applications (e.g., decoration and crafts, light chemical industry, filters and industrial components) (Luiz & Rodrigues, 2022). These sectors increasingly demand products with stringent dimensional and mechanical specifications, driving the need for improvements in product development and manufacturing processes (Turkoglu & Ay, 2021).

This steel is especially valued in applications where cost-benefit is important and corrosion resistance requirements are not as severe as those found in highly aggressive environments, such as those requiring 300 series stainless steels (Luiz et al., 2023). The low cost is due to the lower concentration of Ni in its chemical composition, which acts stabilize the austenite phase (Faria et al., 2024; Gordon &

van Bennekom, 1996). However, the addition of niobium offers better formability due to the formation of Nb carbonitrides, which are homogeneously distributed in the ferritic matrix (Aksoy et al., 1999). Tanure et al. (2017) found that Nb stabilization provides good ductility and mechanical properties of AISI 430 stainless steel. In this way, the tested material can be used for manufacturing components requiring good surface finish and good ductility. The drawing process is widely used in the forming of metallic materials, being essential in sectors such as the automotive, household appliances and consumer goods industries. This technique involves the transformation of metal sheets into pieces with complex geometry, through the application of mechanical forces to specific tools, such as dies and punches.

During the drawing process, several variables influence the quality of the final part, among which friction plays a crucial role (Oliveira et al., 2024). Friction acts at the interface between the metal sheet and the tool, directly impacting phenomena such as wear, modification of the surface topography and the occurrence of defects, such as delamination, cracks, scratches, grooves and gallings (Arinbjarnar & Nielsen, 2023). Furthermore, the friction force influences energy consumption in the process, the distribution of stresses in the part and the efficiency of the process as a whole. Factors such as the type of lubricant used, the materials properties, the roughness of the surfaces in contact, the temperature conditions and the process speed are determining factors for the behavior of friction during drawing. Friction can change the strain distribution in specific areas of the drawpieces (Darendelliler et al., 2002). Formability and reduced tool wear can be improved by effective lubrication of the contact interface. Trzepieciński and Fejkiel (2017) emphasized that, for the adequate development of contact surfaces, it is essential to understand the influence of the surface roughness parameters of both the tool and the sheet on friction phenomena. Trzepieciński and Lemu (2020a) examined the effect of tool surface roughness, lubrication conditions and deformation of strip specimens on the friction coefficient of low-carbon steel sheets. It has been found that adhesion of the contacting surfaces and roughening of workpiece asperities exhibit a synergistic effect on the lubrication phenomenon. Luiz et al. (2023) demonstrated through different friction tests, such as the bending under tension test (BUT), strip tension test (STT) and pin-on-disk (PoD), that there is a strong dependence of the AISI 430 steel sheet friction properties under contact kinematic conditions. Faria et al. (2024) investigated the effect of different lubrication conditions on the tribological behaviour of AISI 304 and AISI 430 stainless steel samples, previously hardened by cold rolling. The type of lubricant used influenced the depth of the grooves produced on the surface of the sheets during the scratch test.

The roughness of the workpiece is a parameter that is highly sensitive to shape changes throughout the stamping process. In many cases, the final product may require multiple passes of plastic deformation, as occurs drawing of multi-pass stamping forming (Fig. 1). It is important to highlight that, after the first forming pass, the roughness parameters of the part do not remain unchanged, since the surface topography undergoes changes due to the plastic deformation caused by stretching. Studies show that the roughness of metal sheets tends to increase with increasing plastic deformation, which, in turn, increases resistance to friction during the drawing process (Masters et al., 2013; Oliveira et al., 2024; Trzepieciński, 2019). In addition to increasing friction, the superposition of stretching and bending in the drawing die radius can lead to a nonlinear deformation path, increasing the possibility of premature fractures in the workpiece, for example, shear fractures (Luiz & Rodrigues, 2022).

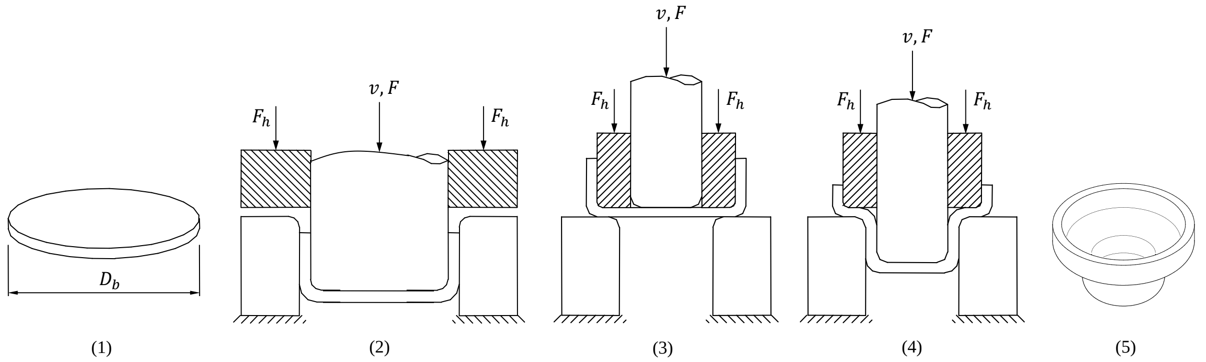

Fig. 1. Schematic drawing of multi-pass stamping forming: (1) workpiece, (2) drawing, (3) redrawing beginning, (4) redrawing end and (5) final piece. Where D_b is workpiece diameter, v is the drawing speed, F is the drawing force and F_h is the blank-holder force.

In the case of AISI 430 steel, the increase in roughness presents an even more significant challenge. Shin et al. (2003) reported that AISI 430 steel exhibits ridges parallel to the rolling direction when subjected to drawing operations, with depths varying between 20 and 50 μm. In general, these ridges negatively affect the surface quality of the part, especially in the case of thin sheets. The appropriate dimensions of the ridges (width, depth) determine the distribution of force parameters and the differentiation of lubrication conditions in the same tribological system (Luiz & Rodrigues, 2021). Therefore, understanding and controlling friction in the drawing process is, therefore, essential to guarantee the dimensional accuracy, structural integrity and surface finish of the parts produced. From this perspective, studies on the tribological interaction between the materials involved contribute to optimizing the process, reducing costs and increasing its sustainability and economic viability.

This study aims to investigate the influence of multi-pass forming on the tribological performance of AISI 430 steel sheet using BUT test. The BUT test simulates the contact conditions occurring in the radius area of a drawing die. Before of the friction tests, the strip samples were subjected to six different levels of uniaxial tensile pre-deformation, ranging from 0 to 0.161. The coefficient of friction (CoF) was determined and variations in the hardness values and roughness parameters (Ra, Rq and Rt) of the samples were also analyzed.

2. Materials and methods

2.1. Test material

Metal strips cut along the rolling direction of the AISI 430 steel sheet, with thickness of 0.8 mm, width of 25 mm and a length of 500 mm, were used as test material. In the as-received state, the AISI 430 steel sheet has an excellent surface finish, classified as type 2B, in accordance with ASTM A480/A480M-22 (American Society for Testing and Materials, 2022). This finish is obtained through an annealing and final lamination process in polished rolls called a ‘skin pass’, resulting in a smooth and shiny surface, ideal for applications that require high aesthetic quality and corrosion resistance. The bending pins (countersamples) were machined from VND steel (DIN: 1.2510) and heat treated. VND steel is widely used in the manufacture of cutting tools and molds due to its high hardness, wear resistance and ability to withstand high mechanical stress. The chemical compositions of steels used in tribological pair are presented in Tables 1 and 2.

Table 1. Chemical composition of AISI 430 steel sheet (wt.%).

C	Mn	Si	P	S	Cr	Ni	Nb	Fe
0.0164	0.2454	0.2447	0.0362	0.0009	16.481	0.2964	0.3384	balance

Table 2. Chemical composition of VND steel (wt.%) (Longhai Special Steel, 2025).

Mn	S (min.)	V (max.)	Si	W	C	Fe
1.25	0.5	0.12	0.25	0.50	0.95	balance

All uniaxial tensile tests were performed using a universal tensile testing machine (Emic, model DL30000) at room temperature. To determine the basic tensile properties (Table 3), flat dog-bone specimens with dimensions specified in ASTM E8/EM-22 (American Society for Testing and Materials, 2021) standard, with 50 mm gauge length, were used in the tests. The following parameters have been determined: ultimate tensile strength R_m, yield stress $R_{p0.2}$, uniform elongation A_u, and elongation after fracture A_{50}. Moreover, the strain hardening properties have been determined by approximation of the true stress–true strain relation using the Eq. (1). This expression is commonly known as the Hollomon equation and is widely used to describe the behavior of metallic materials during plastic deformation, especially in forming processes. This equation establishes a mathematical relationship between the true stress (σ) and the true strain (ε) of the material.

$$\sigma = K\varepsilon^n \tag{1}$$

where K is the strength coefficient and n is the strain hardening exponent.

Table 3. Basic mechanical properties of AISI 430 steel sheet.

$R_{p0.2}$ (MPa)	R_m (MPa)	A_u (%)	A_{50} (%)	K (MPa)	n
334.1	467.64	22.3	32.7	359.31	0.205

On the other hand, the requirements for basic mechanical properties of VND steel are equal to (Longhai Special Steel, 2025): $R_{p0.2} \geq 681$ MPa, $R_m \geq 779$ MPa and A = 32%.

The hardness of the AISI 430 steel sheet (as-received state) and of VND steel (after being treated and polished) was measured using a Vickers microhardness tester (Shimadzu, model HMV-2T), with a test load of 1.96 N and loading time of 15 s. The final hardness value of both materials corresponds to the average of ten measurements, resulting 190±8 HV and 760±12 HV, respectively. Surface roughness parameters were determined using a portable surface roughness tester (Tesa, model Rugosurf 20), according to the ISO 21920-2 (International Organization for Standardization, 2021) standard. The final value being the average of five measurements in transverse direction to the sliding. The values of selected surface roughness parameters of sheet metal and tool are presented in Table 4.

Table 4. The values of selected surface roughness parameters of sheet metal and tool.

Material	Surface roughness parameter		
	Arithmetic mean roughness Ra, µm	**Root-mean-square roughness Rq, µm**	**Total height of the roughness profile Rt, µm**
AISI 430 steel (sheet metal)	0.06	0.10	1.00
VND steel (pins)	0.27	0.36	2.28

2.2. Friction tribotester and test conditions

The friction test used was the bending under tension test. Oliveira et al. (2024) explain that this test is widely used in the simulating the mechanics of plastic deformation and the friction phenomenon of a metal sheet sliding under the radius of the tool in deep drawing processes (Fig. 2a). The BUT test was developed by Littlewood and Wallace (1964) and consists of bending and sliding a metal strip with a certain thickness *t* over a pin with a predetermined radius *R* (Fig. 2b). In the present article, the bending angle is 90° and pin radius used was 9.0 mm. During the friction test, one end of the sheet metal is fixed in the movable fixture of the friction tester. In this way, a tensile force F_1 is applied to one end of the metal strip. The opposite end of the metal strip is loaded with a tensile force F_2 (Trzepiecinski and Lemu, 2020b; Wenzloff et al., 1992).

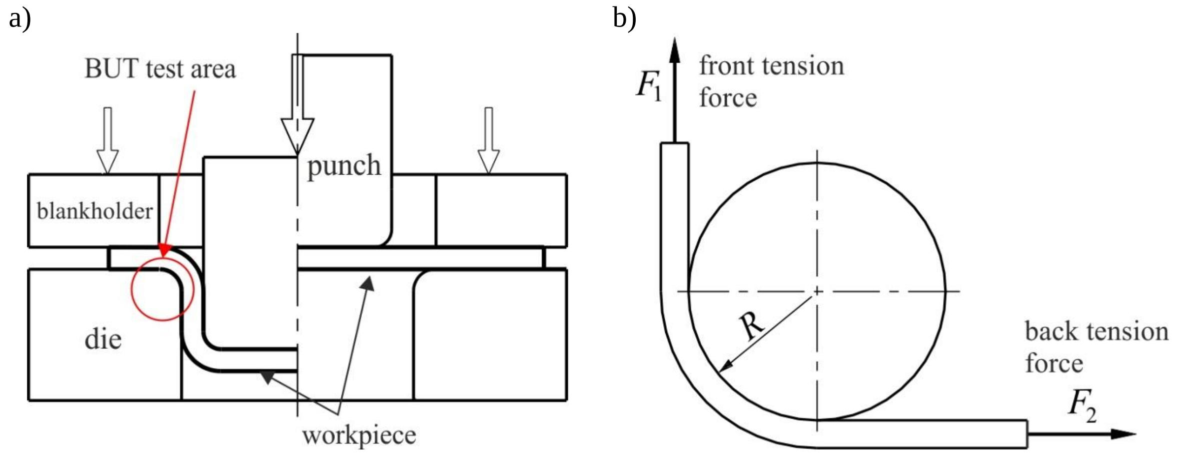

Fig. 2. a) BUT test area and b) forces acting on the metal strip (Oliveira et al., 2024).

The tribological tester used is shown in in Fig. 3a and their details are summarized schematically Fig. 3b. Before starting each new friction test, the strip and pin surfaces were cleaned with acetone to remove contamination. In the tests a mineral-based lubricating oil with a density of 0.894 g/cm^3 and a kinematic viscosity of 120 mPa•s was used. This oil is designed for use in cold metal forming conditions. All tests were conducted with a sliding speed of 2 mm/s.

To evaluate the effect of multi-pass forming in on the tribological performance of AISI 430, samples in triplicate were fabricated with six different levels of true pre-deformation (0, 0.021, 0.056, 0.091, 0.126 and 0.161), as shown in Fig. 4.

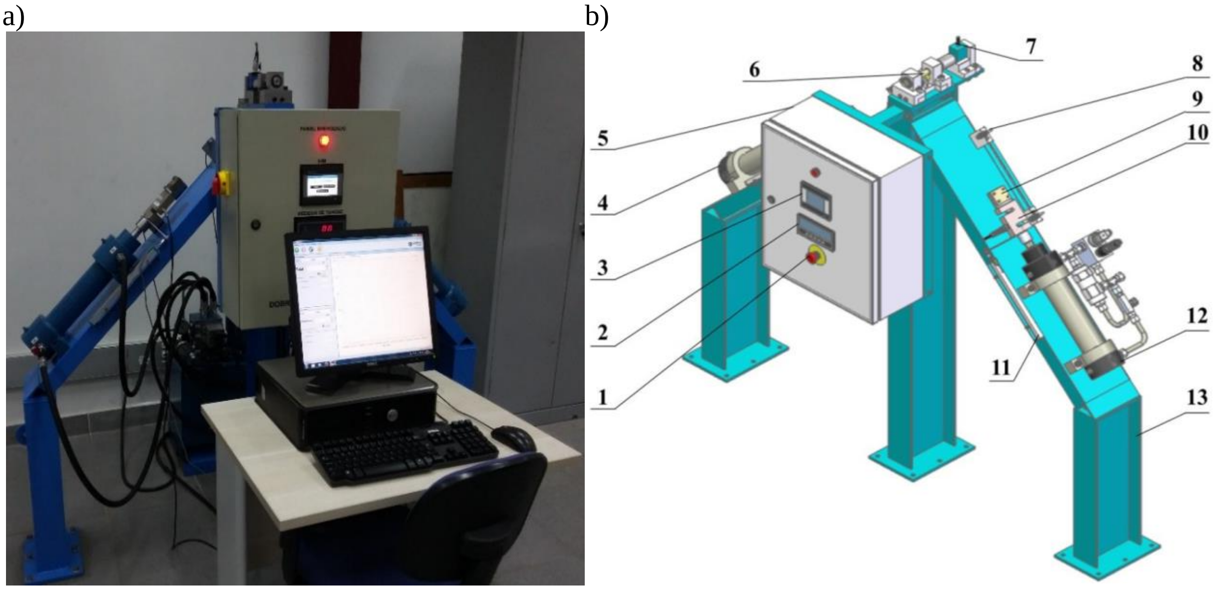

Fig. 3. a) experimental apparatus and b) three-dimensional scheme: 1 – emergency button, 2 – torque meter, 3 – human- machine interface (HMI), 4 – front hydraulic cylinder, 5 – control panel, 6 – bending pin, 7 – torque sensor, 8 – inductive proximity sensor, 9 – gripper, 10 – load cell, 11 – linear voltage displacement transducer (LVDT) sensor, 12 – rear hydraulic cylinder and 13 – mounting structure.

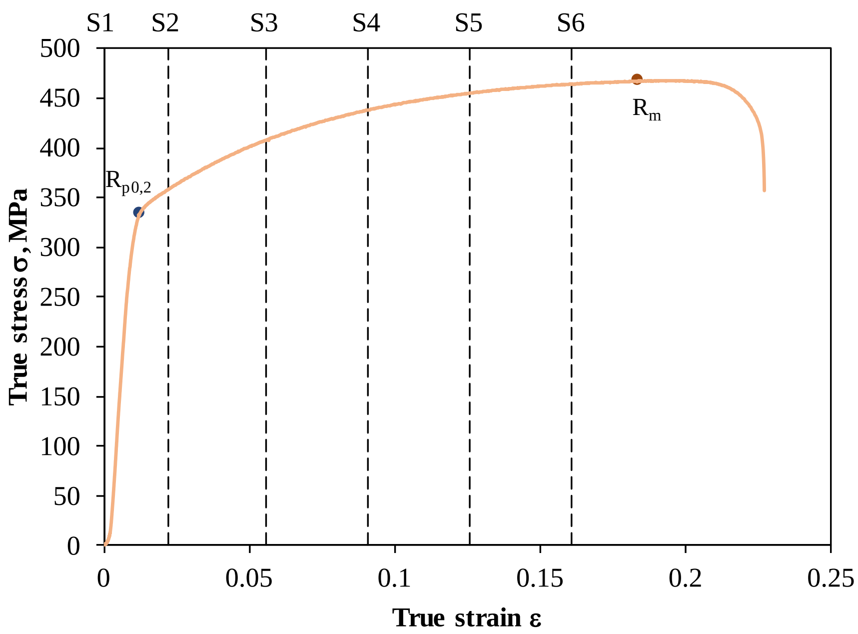

Fig. 4. True stress-true strain curve of AISI 430 steel.

The CoF value was determined according to Eq. (2) (Sulonen et al., 1981):

$$\mu = \frac{2}{\pi}\left(1 + \frac{t}{2R}\right) ln\left(\frac{F_1 - F_b}{F_2}\right) \tag{2}$$

where F_b is the bending force.

Bending force was determined by Eq. (3) proposed by Swift (1948):

$$F_b = \frac{R_{p0.2} \cdot t^2 \cdot w}{2R} \tag{3}$$

where $R_{p0.2}$, w and R are the yield stress of the metal strip, width of metal strip and radius of bending pin, respectively.

3. Results and discussion

As a result of experimental investigations using the variable values of the process parameters, graphs of the changes in front tension force (F_1) and the back tension force (F_2) were obtained (Fig. 5a). The average value of the coefficient of friction (μ) was determined from the stabilized stage, as illustrated in the friction characteristic curve for the strip pre-deformed at ε = 9.1% (Fig. 5b). The period of 0-5 s refers to the time required for the test to begin. The increasing the tensile forces can be attributed to the strain hardening phenomenon. However, the behavior observed in the friction curve results from the variations in friction and strip wear during its sliding under the bending pin. Blau (2005) explains that this behavior is characteristic of lubricated metallic contacts, with generation of wear debris and formation of transfer layer, manifesting itself in two distinct periods in the friction curve: running-in and steady-state. The running-in (Fig. 5b) period refers to the initial stage of contact between the two surfaces in relative motion, during which a mutual adaptation of their tribological characteristics occurs. This stage is characterized by significant changes in the coefficient of friction, roughness and surface interaction. The two fresh surfaces in relative sliding motion begin to experience intimate contact at the asperities level (Khonsari et al., 2021). Generally, the coefficient of friction increases and decreases rapidly throughout this stage. Some investigators contend that running-in is exclusively associated with the surface roughness reaching a steady-state condition (Blau, 2005; Kragelsky & Kombalov, 1969). After this phase, the friction curve tends to reach a more stable region. However, from this stage onwards, it can be seen in Fig. 5b that the friction characteristic curve showed a tendency to increase. This behavior can be attributed to the increase in asperity peaks with the pre-strain (Trzepiecinski, 2019). The hardened asperities are less susceptible to the flattening process and, under load, the peaks easily break the lubricating film, increasing the metallic contact. Under these conditions, there is a gradual increase in the coefficient of friction and intensification of the surface wear of the sample.

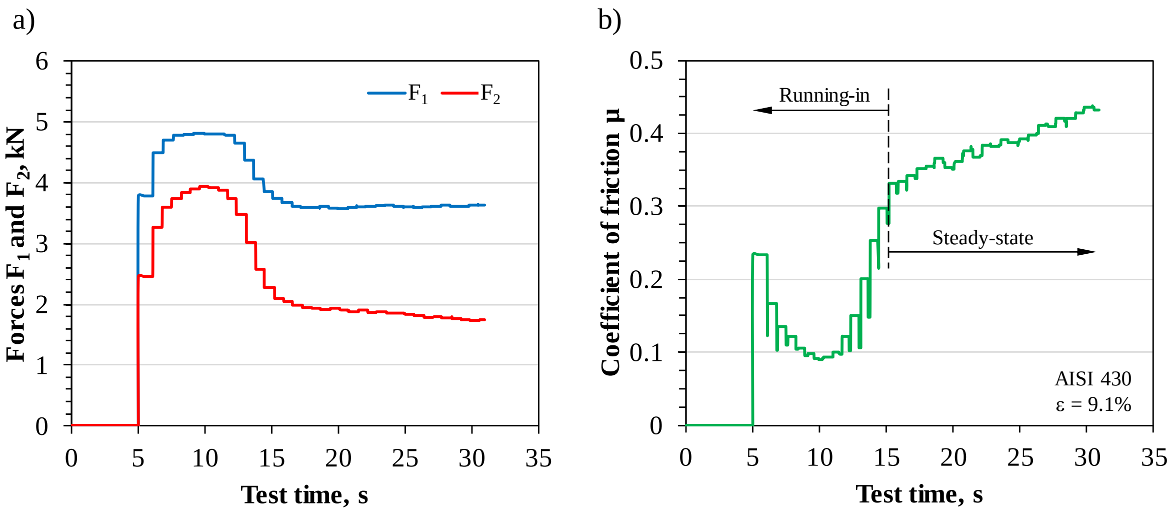

Fig. 5. Characteristic curve of AISI 430 steel strips subjected to the BUT test: a) applied forces (F_1 and F_2) and b) coefficient of friction.

Coefficient of friction as a function of the pre-strain level is shown in Fig. 6. It is observed that the value of the friction coefficient increased almost linearly (R^2 = 0.969) with the increase in pre-strain. This behaviour evidence that the previous deformation of metal sheets exerts a significant influence on their tribological properties, especially during multi-pass forming processes. The direct relationship between pre-strain and friction coefficient can be attributed to microstructural and topographic changes on the material surface, such as increased roughness, strain hardening and changes in residual stress distribution.

Luiz and Rodrigues (2021) tested AISI 304 steel sheets in bending under tension conditions. Microstructural analysis revealed that the steel strip exhibited two different phases during the BUT test, γ-austenite and α'-martensite, indicating that a phase transformation occurred during the plastic deformation process. Under these conditions, the level of work hardening and residual stresses of the material tend to increase, influencing the tribological behavior of the metal sheet.

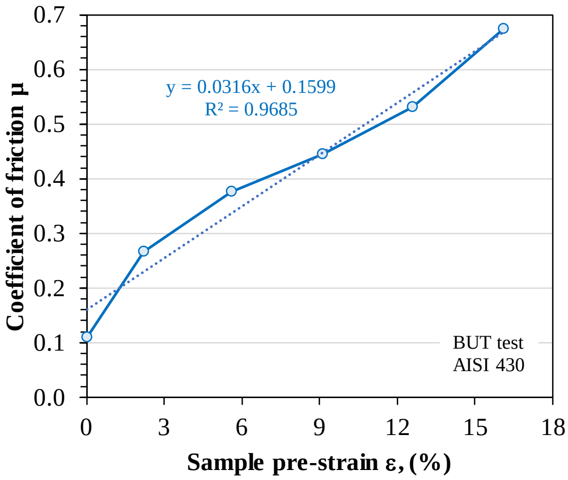

Fig. 6. Effect of sample pre-strain on the value of the coefficient of friction of AISI 430 steel strips subjected to the BUT test.

It can be seen in Fig. 7 that the roughness parameters also increased almost linearly with increasing pre-strain. Figure 8 clearly shows that the surface topography of the AISI 430 steel strips underwent variations as the level of pre-deformation also increased. During the deformation of metals, especially in processes such as rolling, drawing and stretching, the crystalline planes close to the surface suffer stresses that can cause irregular sliding, resulting in a rougher surface topography. Under these conditions, there is an increase in the interaction between the asperities of the sheet and the tool, which increases resistance to friction and wear during the BUT test. Unlike to Ra and Rq, the surface roughness parameter Rt is calculated using peak values. Therefore, its value is significantly affected by contamination, deep scratches, and measurement noise. This supports the premise that the increase in deformation, even under lubricated conditions, causes variations in the contact interface.

Trzepieciński and Lemu (2020a) used the BUT test to investigate the CoF of low-carbon steel sheet under different lubrication conditions. The authors concluded that the CoF value increased with increasing strip elongation. A similar conclusion was found by Masters et al. (2013) based on strip drawing tests of pre-strained AlMgSi aluminum alloy sheets. They found that the pressure at the strip-tool interface is significantly affected by changes in sheet metal roughness, causing changes in friction characteristics. Trzepieciński and Fejkiel (2017) investigated the effect of sample pre-straining and lubrication conditions on the CoF and surface roughness of deep drawing quality steel sheets in strip drawing test. It was found that sample pre-straining causes an increase in the values of Ra, Rq and Rz parameters and the CoF decreases with increasing contact pressure. Therefore, the surface roughness of metal sheets plays a crucial role in the performance of the stamping process. Parameters such as Ra, Rq and Rt directly influence aspects such as friction, the quality of the final part and the durability of the tools. Understanding these parameters is essential to optimize the process and avoid common problems, such as excessive tool wear, part failures or surface defects.

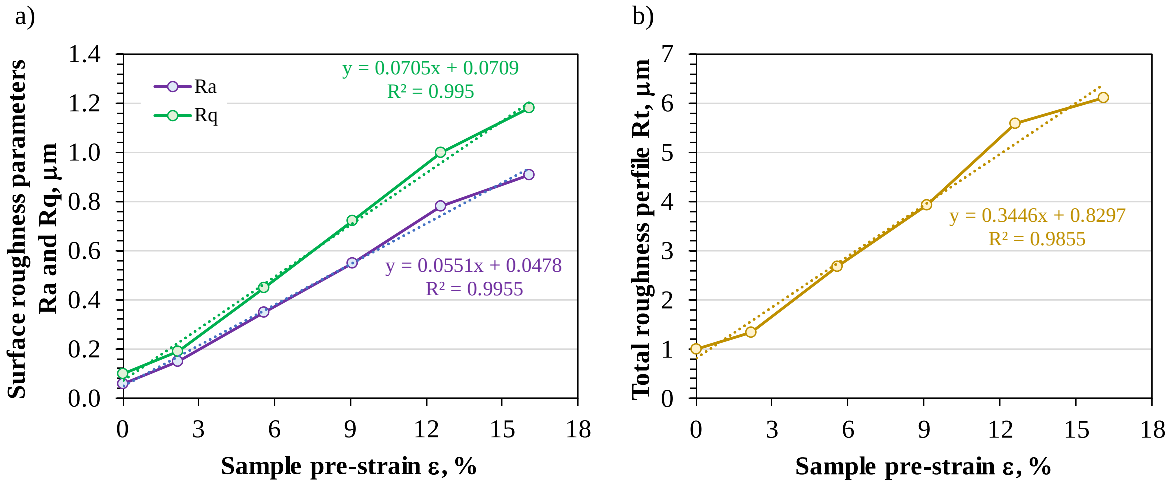

Fig. 7. Effect of sample pre-strain on the roughness parameters of AISI 430 steel strips subjected to the BUT test: a) Ra and Rq; b) Rt.

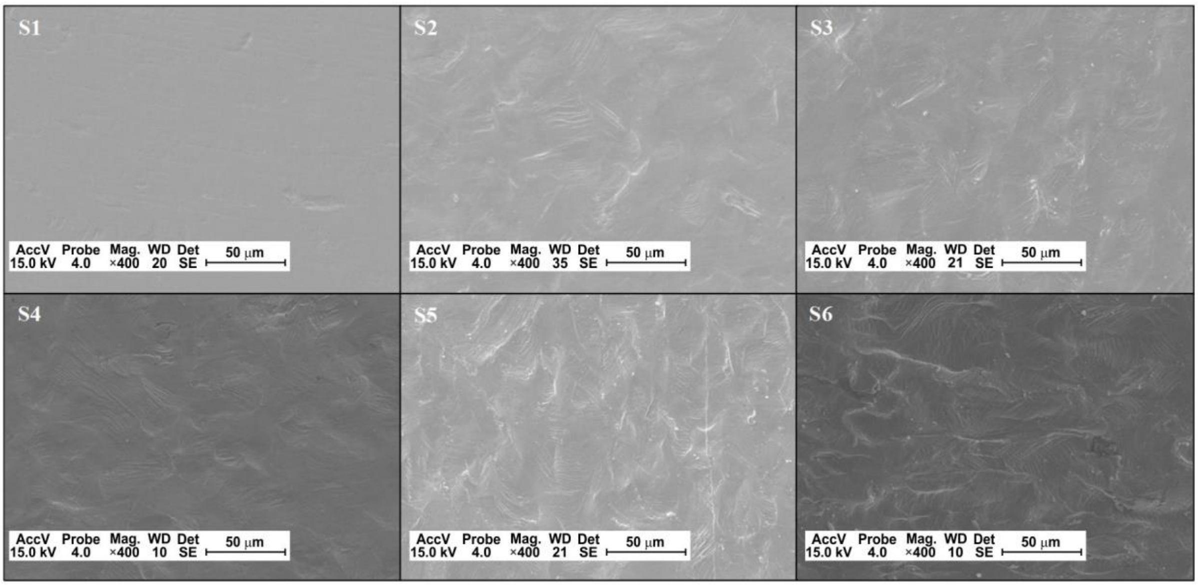

Fig. 8. SEM image of the surface of the as received sample (S1) and the pre-deformed samples after BUT tests: S2 (ε = 2.1%), S3 (ε = 5.6%), S4 (ε = 9.1%), S5 (ε = 12.6%) and S6 (ε = 16.1%).

Corroborating the previous analysis, it can be observed in Fig. 9 that there was a significant increase in the hardness of the pre-deformed metal strips due to the work hardening effect. However, this increase tended to decrease as the deformation level approached the uniform elongation. This behavior is a consequence of the material's intrinsic nature, where its chemical composition includes a stabilization relationship among Nb, N, and C, forming stable carbides and nitrides that directly influence the creep properties of the material (Gordon & van Bennekom, 1996). Under these conditions, the material exhibits a low work hardening rate, as evidenced in its mechanical properties. Thus, it can be inferred that the applied force and material deformation during the BUT test result in an additional hardening pass, which leads to different hardness values.

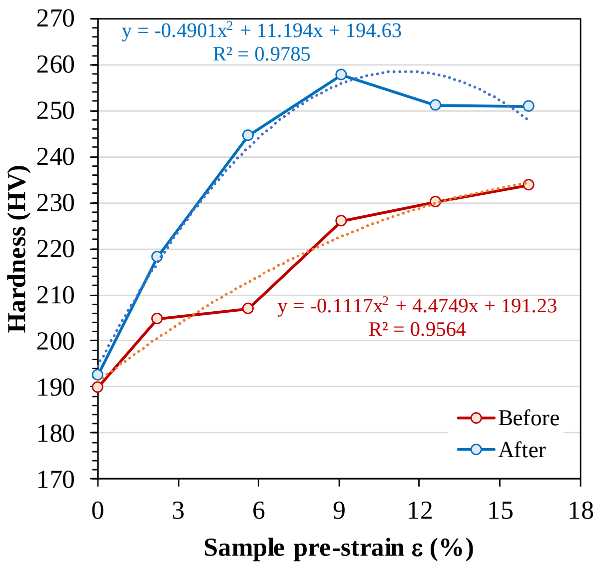

Fig. 9. Effect of sample pre-strain on the hardness of AISI 430 steel strips before and after the BUT test.

In Fig. 10, it is observed that the intensity of the scratches on the strips surface increased progressively with the increase in deformation, resulting in severe ploughing. The increase of surface roughness and strip hardness evidenced in Fig. 7 and Fig. 9, respectively, intensified this friction mechanism. The hardened asperities with a high peak value break the lubricant film more easily and the hardened sheet particles act as a third body at the contact interface, increasing abrasive wear.

In the context of multi-pass forming, these changes play a critical role, as an increase in the coefficient of friction can result in greater resistance to sliding between contact surfaces, directly impacting process efficiency, final part quality and tool wear. These factors reinforce the importance of understanding the interaction between tribological conditions and processing parameters, so that it is possible to optimize system performance and minimize premature failures.

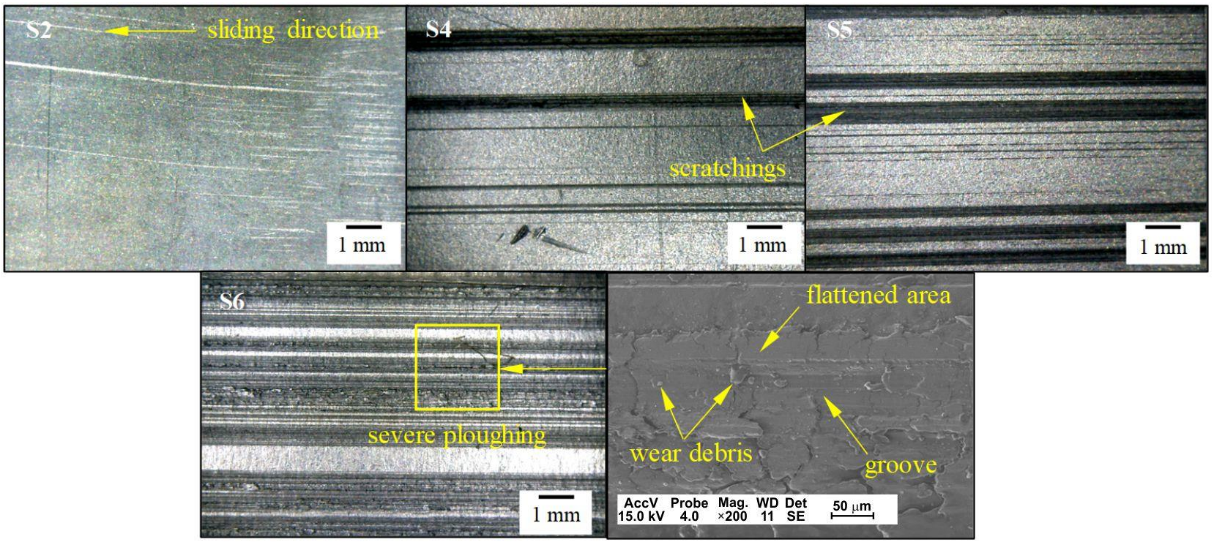

Fig. 10. View of the AISI 430 steel strips surface after BUT test. S2 (ε = 2.1%), S4 (ε = 9.1%), S5 (ε = 12.6%) and S6 (ε = 16.1%).

Furthermore, detailed analysis of tribological behavior under different levels of pre-strain can offer valuable insights for developing more efficient lubricants or adjusting forming strategies, such as modifying surfaces, speeds and process trajectories. Thus, the study of the friction coefficient under these conditions proves to be fundamental not only for improving tribological performance, but also for sustainability and industrial competitiveness.

4. Conclusions

Based on the experimental results obtained with the pre-deformed AISI 430 steel sheet subjected to the BUT test, the following conclusions can be drawn:

- The coefficient of friction increased (~0.11–0.674) almost linearly (R^2 = 0.9685) with increasing pre-strain.
- The values of the roughness parameters (Ra, Rq and Rt) tended to increase with increasing pre-strain, this is because the crystalline planes close to the surface suffer stresses that cause irregular sliding, resulting in a rougher surface topography.
- The hardness value of the pre-deformed strips also increased with increasing pre-strain; however, after tended to show a constant increase for deformations close to the uniform elongation.
- Scratches and severe wear occurred on the surface of the strips and intensified with increasing roughness.

Therefore, in industrial applications, more efficient lubrication will be required in multi-pass deep drawing with the use of AISI 430 steel stabilized with Nb, mitigating the detrimental effects of friction and wear, ensuring that parts with higher surface quality are produced and adding value to the final product. Finally, it is concluded that these results can be used as input data in the computational numerical simulation of drawing processes, as well as in design guidelines and failure prevention criteria through the use of AISI 430 steel sheet stabilized with Nb, leading to cost reduction, improved drawing process performance, and surface quality of products.

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Wpływ Wieloetapowego Formowania na Właściwości Tribologiczne Blachy Stalowej AISI 430 w Procesie Głębokiego Tłoczenia

Streszczenie

W artykule przedstawiono wyniki badań wpływu wstępnego odkształcenia blachy na zmianę parametrów chropowatości powierzchni i wartości współczynnika tarcia. Próbki w postaci pasów ferrytycznej blachy stalowej nierdzewnej AISI 430 o jakości wymaganej do głębokiego tłoczenia o wymiarach 0,8 × 25 × 500 mm zostały wstępnie odkształcone metodą jednoosiowego rozciągania dla pięciu różnych wartości odkształcenia rzeczywistego. Zbadano korelację między parametrami chropowatości powierzchni próbek i twardością z warunkami tarcia badanych pasów w teście zginania z rozciąganiem. Wyniki wykazały, że współczynnik tarcia określony dla wszystkich wstępnie odkształconych pasów zwiększał się wraz ze wzrostem poziomu odkształcenia rzeczywistego. Wzrost odkształcenia plastycznego blach w stanie jednoosiowego rozciągania powoduje prawie liniowy wzrost wartości podstawowych parametrów amplitudowych chropowatości powierzchni, jednak twardość wykazała tendencję do stałego wzrostu dla odkształceń bliskich wydłużeniu równomiernemu. Ponadto na powierzchni pasów zaobserwowano zarysowania i intensywne zużycie, które nasilały się wraz ze wzrostem chropowatości blach.

Słowa kluczowe: odkształcenie wstępne, stal nierdzewna ferrytyczna AISI 430, próba zginania z rozciąganiem, współczynnik tarcia