Advances in Mechanical and Materials Engineering

Volume 41, 2024, Pages 183-193
https://doi.org/10.7862/rm.2024.16

THE FACULTY OF MECHANICAL ENGINEERING AND AERONAUTICS
RZESZOW UNIVERSITY OF TECHNOLOGY

Original Research

The Effect of the Drawing Die Radius in the Bending Under Tension Test on the Frictional Behaviour of AISI 430 Steel and AW-1100 Aluminium Alloy Sheets

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Received: 22 October 2024 / Accepted: 5 December 2024 / Published online: 16 December 2024

Abstract

Friction is an unfavourable phenomenon in sheet metal forming processes because it increases the forming force, reduces the surface quality of the drawpieces and affects the increased wear of the forming tools. This article presents the results of experimental studies on friction occurring due to the drawing die radius. The test materials used were 0.8-mm-thick strip samples made of AISI 430 steel and AW-1100 aluminium alloy sheets. A special bending under tension friction-test simulator was used to carry out the tests. Countersamples (pins) with different radii in the range of 1.5 mm to 13.5 mm were used. The tests were carried out at room temperature under mineral-based oil lubrication conditions. The friction tests were supplemented by determining the hardness and measuring the surface roughness (parameters Ra, Rq and Rt) of the samples. Based on the results, it was found that the coefficient of friction increased with a decrease in the bending pin radius, however, this behaviour changed above a critical radius (4.5 mm), after which the coefficient of friction increased with an increase in the pin radius. Furthermore, the AW-1100 aluminium alloy strip had a higher coefficient of friction than the AISI 430 steel strip.

Keywords: AW-1100 aluminium alloy, AISI 430 steel, coefficient of friction, bending under tension test, sheet metal forming

1. Introduction

Deep drawing is one of the most widely used manufacturing processes in sheet metal forming, making it is possible to manufacture products with very complex geometry in contrast to other processes, such as machining and casting. During the deep drawing process, a flat sheet called a blank is plastically deformed to achieve its final shape (Pereira et al., 2024). However, this deformation is not uniform and the surface of the sheet is subject to the occurrence of phenomena caused by friction and wear, such as scratches, debris, cracks, delamination and plastic deformation of the asperities (Arinbjarnar & Nielsen, 2023). One way to reduce the unfavourable impact of friction is to use lubricants in liquid, gaseous or solid forms (Semiatin, 2006). Traditionally, petroleum-based lubricants are used in the metal forming industry. However, in the last decade there has been an interest in edible and non-edible green oils (Carcel et al., 2005; Więckowski et al., 2020). The use of environmentally friendly lubricants with a high degree of biodegradability is consistent with the concept of sustainable industry (Antonicelli et al., 2024). Efficient lubrication is necessary to mitigate the deleterious effects of friction and wear. Current literature on this subject argues that friction-related aspects are of great concern, as they have a considerable influence on productivity, product quality and die wear, because during material processing, friction and lubrication are influenced by many factors, such as sheet properties, temperature, surface finish, contact pressure, sliding speed, lubricant characteristics, die radius, among others (Luiz et al., 2023; Trzepieciński & Lemu, 2020). The main parameters influencing the physico-mechanical phenomena in the contact zone in sheet metal forming are shown in Fig. 1.

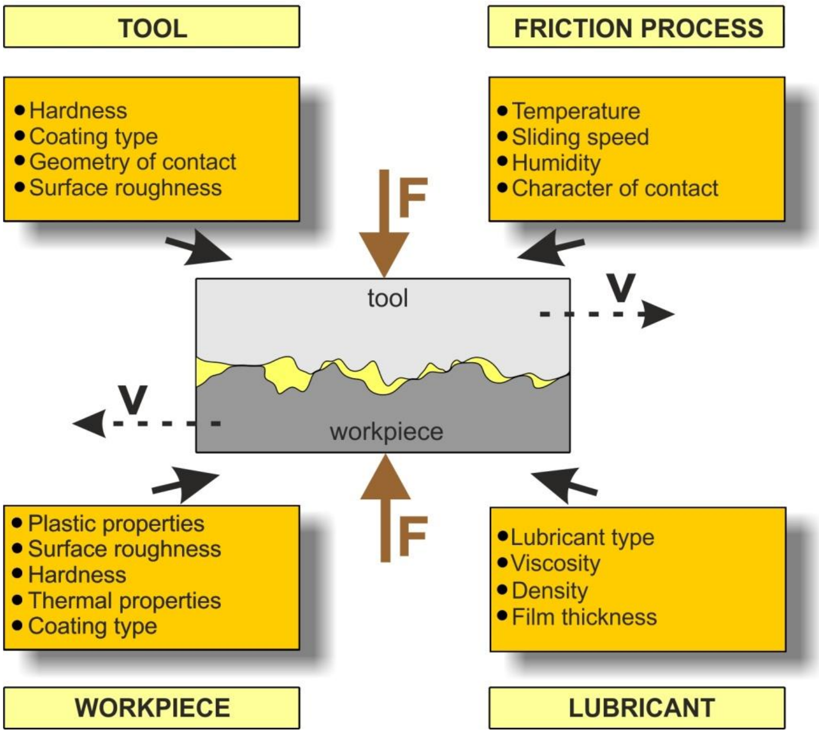

Fig. 1. The main elements of the tribological system in sheet metal forming.

Due to the complexity of the friction phenomenon in deep drawing processes, many tribological tests have been developed that reproduce friction in specific areas of the stamping tool in sheet metal forming. In addition to the commonly known strip drawing test, the bending under tension (BUT) test simulates friction conditions on the drawing die radius. In recent years, many scientists have been extending the knowledge about the influence of the tool radius, tool preheat temperature and sliding speed on the drawing die radius on the force parameters of the forming process, sheet metal formability and surface quality of the drawpieces. Andreasen et al. (2006) developed a sensitive torque transducer in which friction around the tool radius can be directly measured. The effect of the drawing speed on the tribological performance of AISI 316 stainless steel was studied. It was found that increasing the drawing speed from 10 mm/s to 50 mm/s significantly reduced friction stress. Ayllón et al. (2017) used the BUT test to model material deformation during the single-point incremental forming (SPIF) process of Ti-6Al-4V (Grade 5) titanium alloy. Both experimental and finite element-based approaches reproduced a realistic situation from the point of view of the lubrication regime occurring in SPIF. Vega et al. (2017) investigated ammonium-based protic ionic liquids as lubricant fluids for sheet metal forming. They found that protic ionic liquids showed a performance similar to that of the mixed lubrication regime. Folle and Schaeffer (2016) proposed a method for measuring the contact pressure in the BUT test using a pressure sensitive film. The results revealed that the area of contact between the sheet and the pin will always be smaller than the area calculated geometrically. Similar results were obtained by Kim et al. (2004) and Pereira et al. (2009). Coubrough et al. (2002) evaluated the contact pressure using a film of piezoelectric material in the BUT test. The change in the electric current voltage was proportional to the pressure value on the pin. Ceron et al. (2014) proposed the tribometer for analysing the effect of temperature on the frictional behaviour of DP800 steel in the BUT test. It was concluded that the proposed methodology can effectively predict the interface temperature in the test tool.

In recent years, there has been an increasing application of stainless steel and aluminium alloys in situations where corrosion resistance and weight reduction are desired. However, friction between the sheet metal and the die during stamping has also had a major impact on the formability of these materials (Gao et al., 2024). Although the influence of contact pressure and sliding speed on the coefficient of friction (CoF) has been intensively investigated, the study of the influence of the die geometry in terms of curvature is limited (Evin et al., 2014). Some authors (Dilmec & Arap, 2016; Kim et al., 2012; Zhao et al., 2021) have reported different coefficients of friction between flat and curved surfaces, but have not analysed the causes of this behaviour in depth. For this, several tribological tests have been used to simulate friction phenomena in specific regions of stamped parts, for example, the BUT test, which simulates the contact region of the deep drawing die radius. In this region, the mutual effect of the bending and stretching forces dominates the tribocontact (Luiz et al., 2023; Luiz & Rodrigues, 2022). Therefore, this study aims to investigate the influence of the radius of the stamping die on the tribological behaviour of AISI 430 steel and AW-1100 aluminium alloy sheets, both of 0.8 mm thickness. Eight different bending pin radii (1.5–13.5 mm) were used in the BUT test, the coefficient of friction was determined and the experimental results were compared with each other. In addition, variations in the hardness of the sheets and the roughness parameters (Ra, Rq and Rt) were also analysed.

2. Materials and methods

2.1. Test material

In this study, 0.8-mm-thick metal strips with a width of 25 mm and a length of 770 mm, cut from AISI 430 ferritic stainless steel and AW-1100 aluminium alloy sheets along the rolling direction, were used as test materials. The test materials can be strengthened by the work hardening phenomenon. Both materials have high electrical conductivity, thermal conductivity, corrosion resistance, and workability. Uses include decorative panels and household utensils. The quality requirements for the chemical composition of these metal sheets are presented in Tables 1 and 2.

The basic mechanical properties of the metal strips (Table 3) were determined using a universal tensile testing machine (Emic, model DL30000 with capacity of up to 300 kN) at room temperature, according to the American Society for Testing and Materials (2021) standard. Flat dog-bone specimens with dimensions as specified in the American Society for Testing and Materials (2021) standard, with 50 mm gauge length, were used in the tests.

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

C	Ni	Si	Mn	Cr	S	P	Fe
≤0.12	≤0.75	≤1.0	≤1.0	16-18	≤0.03	≤0.04	balance

Table 2. Chemical composition of AW-1100 aluminium alloy sheets (wt.%).

Mn	Zn	Si+Fe	Cu	Other	Al
0.05	0.10	0.95	0.05-0.2	0.15	balance

Table 3. Mechanical properties of test materials.

Material	Yield stress $R_{p0.2}$, MPa	Ultimate tensile strength R_m, MPa	Elongation after fracture A_{50}, %
AISI 430	316	465	33
AW-1100	93	115	5

The hardness of the metal strips in the as-received state was measured using a Vickers microhardness meter (Shimadzu, model HMV-2T), with a test load of 1.96 N for a time of 15 s. The average hardness found for the AISI 430 steel and AW-1100 aluminium sheets was 120.6 and 44.1 HV, respectively. Furthermore, with the aid of a portable surface roughness tester (Tesa Rugosurf 20), the basic height parameters of the geometric structure of the strip surfaces were determined: the arithmetic mean roughness Ra, the root-mean-square roughness Rq and the total height of the roughness profile Rt. The surface roughness parameters were determined according to the International Organization for Standardization (2021) standard. The average values found for these parameters on the surface of the AISI 430 steel strip, in the as-received state, were 0.09, 0.15 and 1.08 µm, respectively. For the AW-1100 aluminium sheet, these were 0.76, 0.93 and 5.70 µm, respectively. The bending pins (countersamples) were machined from VND steel (DIN: 1.2510) and heat treated (quenching at 800°C + oil cooling + 2 consecutive tempering passes at 260°C) to increase wear resistance. VND steel is typically used to produce woodworking tools, cutting tools, measuring instruments, and guide pins as well as tools and dies in general.

The quality requirements for the chemical composition of VBD steel are presented in Table 3. The requirements for the basic mechanical properties are equal to (ABNT VND, 2024): $R_{p0.2} \geq 681$ MPa, $R_m \geq 779$ MPa, $A = 32\%$. After being treated and polished, the hardness was on average 760 HV and the roughness parameters were Ra = 0.27 µm, Rq = 0.36 µm and Rt = 2.28 µm, respectively.

Table 3. Chemical composition of VND steel (wt.%), prepared on the basis of ABNT VND (2024).

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

2.2. Bending under tension test

The friction simulation test used in this study was the BUT test. This test is capable of 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). It consists of bending and sliding a metal strip with a certain thickness *t* over a pin with a predetermined radius *R* (Fig. 2b). During the kinematics of the movement, a front tension force F_1 is applied to one end of the metal strip, while the other and is subjected to a back tension force F_2. Figs. 3a and 3b show the friction test stand, as well as the tool holder (die) and some of the bending pins used during the tests, respectively.

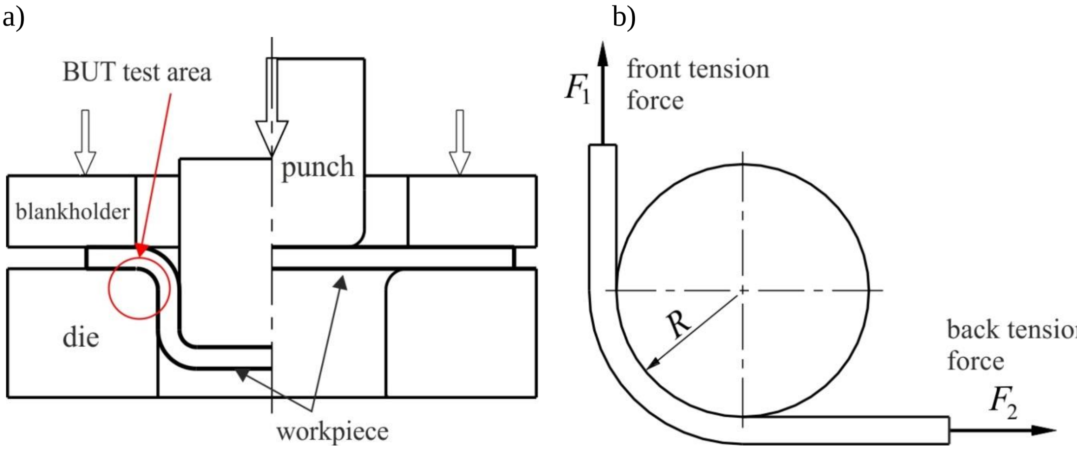

Fig. 2. a) BUT test area and b) the forces acting on the strip sample in the BUT test.

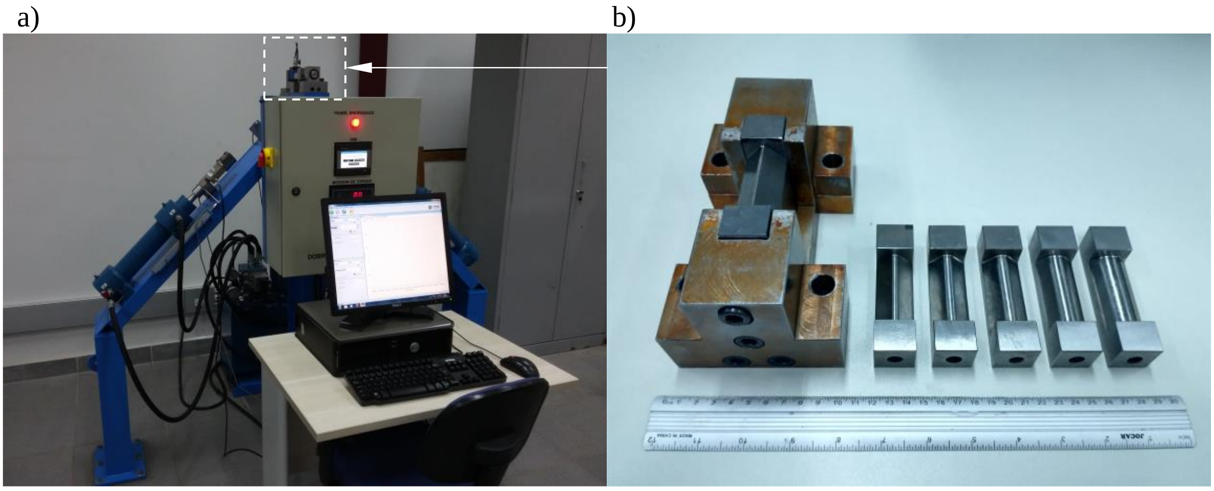

Fig. 3. a) the friction simulator and b) the tool holder and the bending pins.

The tests were carried out under lubricated conditions with a sliding speed of 5 mm/s. Pins with the following radii were used: 1.5, 3.0, 4.5, 6.0, 7.5, 9.0, 10.5, 13.5 mm. All countersamples had the same surface roughness as defined in Section 2.1. It is worth noting that for each new test, the contact surfaces were cleaned with acetone and then a mineral-based lubricating oil (kinematic viscosity of 120 mPa·s and density of 0.894 g/cm^3) typical for cold forming was applied abundantly to the strip/pin contact interface. The coefficient of friction (CoF) was determined according to Eq. (1) (Sulonen et al., 1981):

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

where F_b is the bending force, which is determined by Eq. (2) (Swift, 1948):

$$F_b = \frac{R_{p0.2} \cdot t^2 \cdot w}{2R} \quad (2)$$

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

3. Results and discussion

Figure 4 shows the behaviour of the CoF of the AISI 430 steel and AW-1100 aluminium alloy strips as a function of the bending pin radius during the BUT test. It was found that for both materials, the value of the CoF decreased with the increase in the radius of the bending pin. However, this behaviour changed after a critical radius (4.5 mm), at which the value of the coefficient of friction increased. Nanayakkara et al. (2005) observed a similar behaviour for galvanised steel sheets subjected to the BUT test, concluded that after a critical bending radius, the tribosystem changed its lubrication regime from mixed to hydrodynamic. Current literature explains that this change may be related to the variation in contact pressure and increased surface roughness of the sheet metal due to plastic deformation by stretching. Deformation of the sheet metal causes a change in its mechanical properties due to the work hardening phenomenon (Parsa & Ahkami, 2008). Generally, contact pressure tends to increase as the radius of the pin decreases and, furthermore, it is not uniformly distributed on the contact surface (Andreasen et al., 2006; Kim et al., 2012). Under these conditions, the ability of the lubricant to separate the contact surfaces and stabilise friction is reduced.

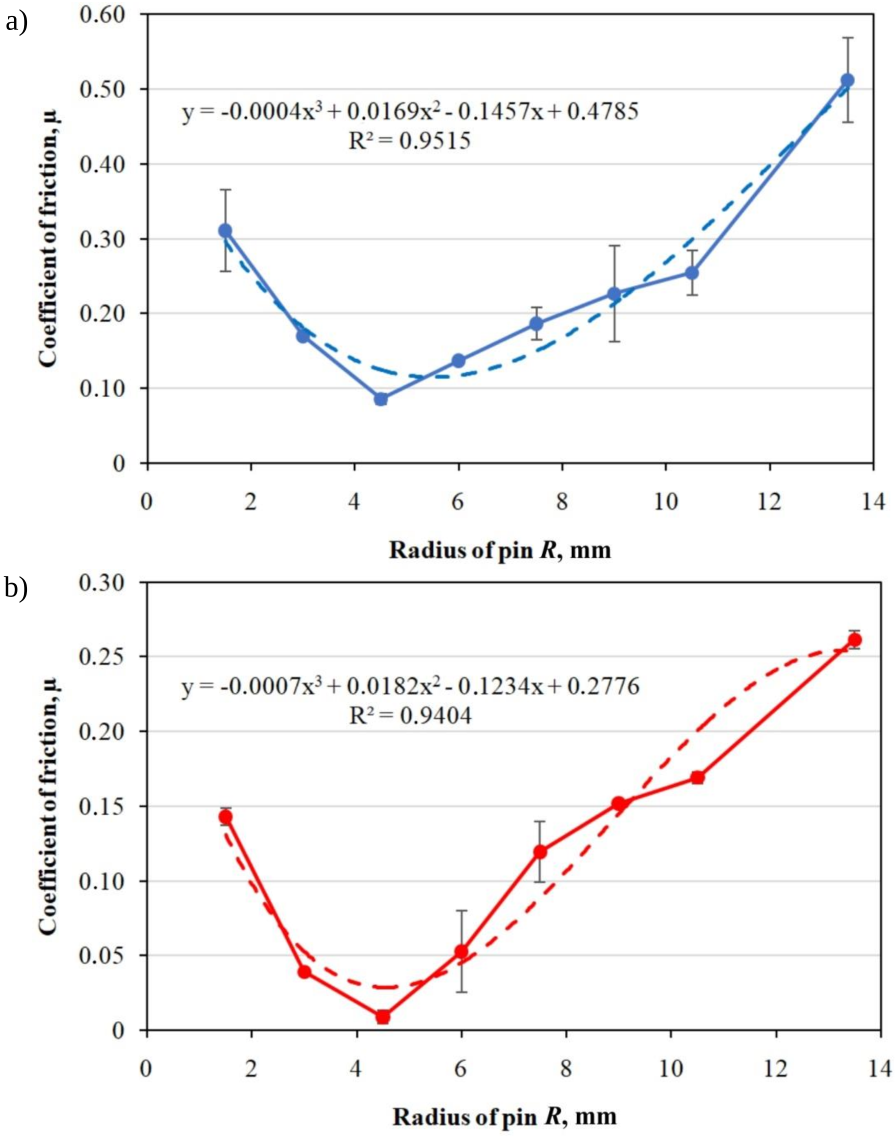

Fig. 4. Effect of the bending pin radius R on the value of the coefficient of friction (μ) of a) AW-1100 aluminium alloy and b) AISI 430 steel strips subjected to the BUT test.

At higher pressures, the lubricant film may be expelled from the contact zone or rupture, which increases the mechanical interaction between the surface asperities through flattening and ploughing mechanisms and, consequently, the resistance to friction is increased (Roizard et al., 1999). Increased frictional resistance on the drawing die radius can cause premature cracking of the drawpiece due to increased sheet metal deformation resistance in the punch impact area. Such cracking most often occurs in the area of the punch drawing radius (Seo et al., 2018).

In addition, it is possible to observe in Fig. 4a that the value of the friction coefficient of the AW-1100 aluminium strip was higher compared to that of the AISI 430 steel strip. This behaviour can be attributed to the greater surface roughness of the aluminium strip, as shown in Fig. 5. However, it can be observed in Fig. 5 that, from a radius of approximately 7.5 mm, the difference in surface roughness parameters tended to decrease. Most likely, the lower intensity of the mutual effect of bending/stretching at larger radii and the more uniform lubrication regime were the cause of this behaviour. The surface roughness parameters of the samples were measured in the middle section of the sample in the area of contact with the pin surface, in the direction transverse to the strip pulling direction. In fact, it can be seen in Fig. 4 that for larger radii the difference between the values of the CoF for the metal strips was ~1.5–2.0 times greater, while for smaller radii it was ~2.2–9.6 times greater, supporting the discussions above. For the AW-1100 sheet with pin radii greater than 7.5 mm, and for the AISI 430 sheet with pin radii greater than 10.5 mm, both parameters Ra and Rq increase rapidly. Probably, for the small pin radii, the increase in surface roughness caused by sample elongation is compensated for by the phenomenon of the flattening out of the surface asperities.

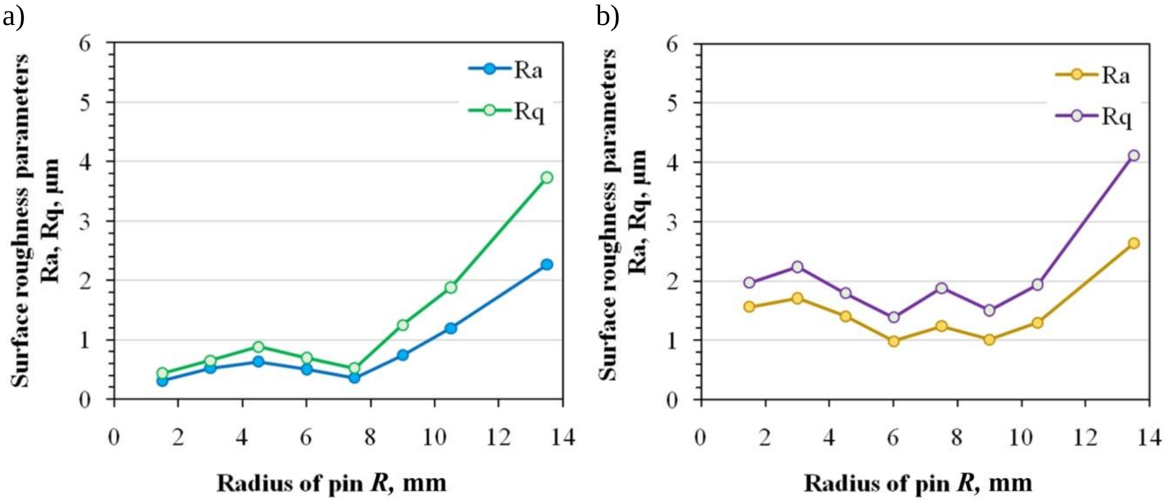

Fig. 5. Effect of the bending pin radius (*R*) on the Ra and Rq parameters of a) AW-1100 aluminium alloy and b) AISI 430 steel strips subjected to the BUT test.

The AW-1100 alloy sheet showed a greater increase in the Rt parameter compared to the AISI 430 sheet (Fig. 6). It is worth noting that this parameter represents the sum of the maximum peak height and the maximum valley depth of the profile along the evaluation length. In contrast to the Ra and Rq parameters, it should be taken into account that the Rt parameter is significantly affected by scratches, contamination and measurement noise due to its use of peak values. The increase in the CoF due to contact pressure, even under lubricated conditions, causes changes mainly in the surface topography of the aluminium sheet, which is softer compared to the tool hardness. Moreover, AW-1100 sheet metal is a material with much lower hardness than the steel countersample, therefore its surface tends to show greater topographic changes, such as greater wear and deeper scratches. The hard tool asperities cause ploughing of the surface of the soft aluminium strip, creating deep scratches, which increases the Rt parameter value. At larger radii, the real contact area between the strip sheet and the pin is larger, which usually results in a larger increase in the Rt value compared to smaller radii. The influence of the radius of the pin on the change in the total height of the roughness profile for steel (Fig. 6b) is not as stable as shown in Fig. 6a. Due to the complex influence of pressure, the radius of the pin, the sheet metal properties and the lubrication regime on the change in the sheet surface topography at pin radii of 9 and 10.5 mm, a beneficial reduction in the real pressures could have occurred. A larger pin radius, with the same cross-section of the strip sheet, causes a reduction in the real contact pressures.

The behaviour of the hardness values shown in Fig. 7 supports the aforementioned statements, where, on average, a lower hardness value is noted for the aluminium strip, even though it presents an approximately constant increase in hardness throughout the range of radii tested (Fig. 7a). In contrast, for smaller radii, it is observed that the AISI 430 steel strip tended to present a smaller increase in hardness. Since the metal strips are subjected to bending and stretching during the BUT test, at larger radii, the mutual effect of these stresses is less intense, attenuating the effect of work hardening and, consequently, the hardness value. Furthermore, it is observed that the AISI 430 steel strip tended to present a hardness very similar to its hardness in the as-received state (Fig. 7b), which indicates that its asperities did not undergo such a significant variation in mechanical properties. In addition, a larger pin radius causes less of a bending effect on materials compared to smaller radii. This produces smaller deformations in the thickness of the strip sample.

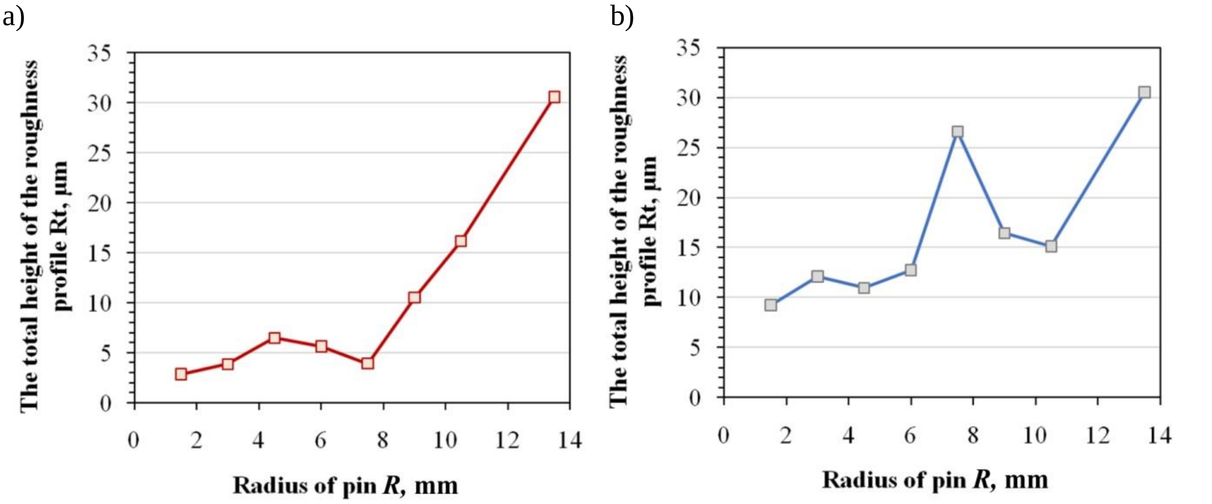

Fig. 6. Effect of the bending pin radius *R* on the Rt parameter of a) AW-1100 aluminium alloy and b) AISI 430 steel strips subjected to the BUT test.

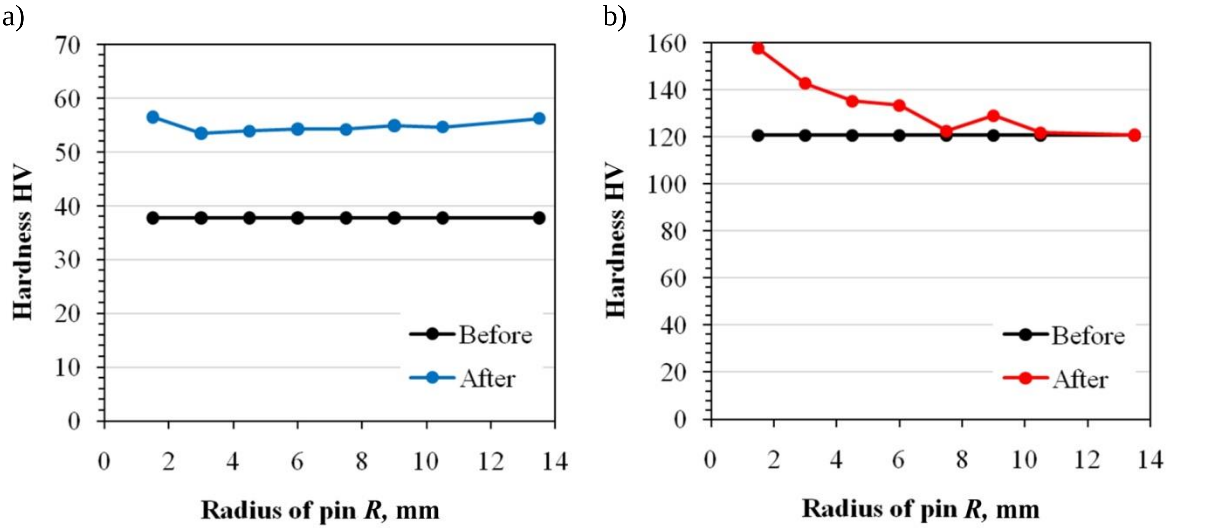

Fig. 7. Effect of the bending pin radius *R* on the hardness HV value of a) AW-1100 aluminium alloy and b) AISI 430 steel strips subjected to the BUT test.

In addition to the aspects discussed above, two important friction mechanisms most likely occurred at the contact interface of the solid surfaces (strip/pin) during the BUT test: frictional adhesion and interaction between the asperities of the hard tool and the relatively soft workpiece. Current literature explains that the first mechanism is caused by microwelding (Fig. 8a), that is, due to interatomic forces at the contact interface (Folle et al., 2022). The second is caused by a mechanical interaction of both asperities of the materials in contact (Fig. 8). In the first case, the material with the lower hardness (strip) is usually pulled out, and this debris ends up functioning as interface material, causing abrasive wear and, consequently, scratches on the surfaces of the formed parts. In the second case, there is closer contact between the solids, such that the asperities end up penetrating each other, also producing scratches on the soft surface (strip) caused by the harder one (pin).

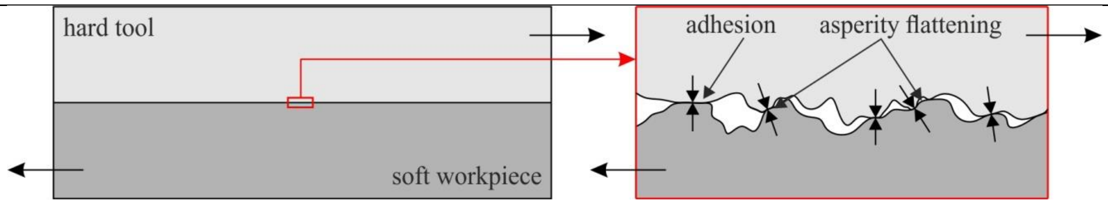

Fig. 8. Schematic illustration of the friction mechanisms presents in the stamping of metal sheets: frictional adhesion and asperity flattening.

In this case, it is also very likely that the material torn off the strip surface has increased the effect of abrasive wear at the contact interface (Devenport et al., 2023). Wear products can be suspended in the lubricant as a so-called third body and interact with the rubbing surfaces through a three-body abrasion mechanism (Chen & Li, 2022). In this way, this layer contains the lubricant and its tribological transformation products and wear products.

Another mechanism that may also have influenced the variation in the lubrication regime is the plastic deformation of the asperities of the softer material as its slides over the bending pin. The normal load exerted by the hard asperity of the tool increases on the soft asperity of the metal strip causing the latter to deform plastically when its yield limit is exceeded. As a result, it flattens, which increases the real contact area and, consequently, friction. However, when the flattening of asperities happens at the closed lubricant pockets (Wang et al., 2021), that is, the oil reserve that remains in the valleys of the metal strip, this improves the efficiency of the lubrication at the contact interface, attenuating the effect of friction and, as a result, the roughness parameters Ra and Rq also tend to be smaller, as observed in Fig. 4 for smaller radii. It is important to emphasise that Ra and Rq provide more stable results, that is, they are not as significantly affected by scratches, contamination and measurement noise as the Rt parameter. Generally, in the sheet with less roughness, the dominant mechanism is surface adhesion, while in the rougher sheet, the asperity flattening mechanism dominates the tribocontact, and the intensity of this mechanism increases with the increase in the surface roughness of the deformed sheet which has a much lower hardness than the tool material. Under specific conditions of contact pressure and properties of the rubbing bodies, the ploughing mechanism may occur. It is important to emphasise that these different friction mechanisms do not occur in isolation, but through a superposition of mechanisms that are difficult to quantify and control. In this regard, the tribological literature explains that the adhesion and plastic deformation mechanisms are strongly influenced by the increasing of the real contact area and work hardening of the surface asperities, respectively. This superposition occurs in undetectable proportions and varies over time and place, making it almost impossible to calculate the real CoF as well as wear (Bowden & Tabor, 1986). However, simulated friction tests provide very interesting results, which can be used, for example, as input data in computational numerical simulation of manufacturing processes.

The friction coefficients obtained in this work varied from 0.09 to 0.5 for the AW-1100 aluminium alloy and from 0.02 to 0.26 for AISI 430 steel sheets, depending on the pin radius. Luiz et al. (2022) tested the AISI 430 steel sheets in BUT conditions. The results of the CoF for different orientation of samples depending on the rolling direction and sliding speeds revealed that the CoF changes between 0.05 and 0.2, with the increase in sliding speed causing a decrease in the CoF. In another article, Luiz et al. (2023) determined the CoF of an AISI 430 sheet in the BUT test depending on the relative elongation. It was found that the CoF varied between 0.09 and 0.37, respectively, for relative elongation between 0.03 and 0.09. The results for a manganese drawing-quality uncoated steel sheet tested under lubricated conditions with a mineral seal oil revealed a coefficient of friction between 0.16 and 0.17 (Wenzloff et al., 1992), which is consistent with the average value of the CoF in this paper. The CoF of AW-1100 aluminium alloy sheets determined by Folle and Schaeffer (2016) using the BUT test varied between 0.12 and 0.27, depending on the equation used to estimate the CoF. The CoF determined by Azushima and Sakuramoto (2006) for AW-1100 aluminium alloy sheets varied between approximately 0.14 and 0.19 depending on the contact pressure during the BUT test. Thus, the results presented in this paper are consistent with the results of other authors, however, it should be noted that different countersample materials and different surface roughnesses of sheet and countersample were used in the reviewed sources.

4. Conclusions

Based on the experimental tests of friction for the AW-1100 and AISI 430 sheets in the BUT test, the following conclusions can be drawn:

- The values of the roughness parameters (Ra, Rq and Rt) tended to increase with increasing pin radius, this is because variations occurred in the lubrication regime at the contact interface between the strip and the pin.
- The total height of the roughness profile Rt parameter showed a more expressive increase, as it is significantly influenced by scratches, contamination and measurement noise due to its use of peak values.
- For both materials, the CoF increased with decreasing pin radius; however, this behaviour changed at a critical radius (R = 4.5 mm), after which the CoF increased with increasing pin radius.
- In general, the AW-1100 aluminium alloy strip presented a higher CoF (~1.5–9.6) than the AISI 430 steel strip, mainly due to its lower hardness and greater surface roughness.

The results can be used as input data in computational numerical simulations of deep drawing processes as well as in the design guidelines and failure prevention criteria based on the materials investigated, which can result in cost reduction, improvement in process performance and product quality. Commonly, in numerical simulations of sheet metal forming processes, a constant COF value is assumed for the entire contact surface. In reality, in sheet metal forming, the value of the coefficient of friction depends on the contact zone of the sheet metal with the tools and the pressures prevailing there. Moreover, the CoF value is not constant but evolves depending on the changes in contact pressures, sheet metal work hardening and surface topography. The results presented in this article do not exhaust the research topic of friction on the drawing die radius. It seems reasonable to check the lubricant viscosity, friction junctions and different roughness of the countersamples on the co-occurrence of different friction mechanisms at the contact interface.

Acknowledgements

This work was funded by the Minas Gerais State Research Support Foundation – FAPEMIG (Process No. 10359/2022). The authors would like to thank CEFET-MG Campus Timóteo for the support provided for the infrastructure used in the tests, especially the Mechanical Testing Laboratory of the Department of Metallurgy and Chemistry, and also Aperam South America for providing the AISI 430 steel strips.

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Wpływ Promienia Matrycy Ciągowej w Próbie Zginania z Rozciąganiem na Zachowanie Tarciowe Blach ze Stali AISI 430 i Stopu Aluminium AW-1100

Streszczenie

Tarcie jest niekorzystnym zjawiskiem w procesach kształtowania blach, ponieważ zwiększa wartość siły kształtowania, obniża jakość powierzchni wytłoczek i wpływa na zwiększone zużycie narzędzi kształtujących. W niniejszym artykule przedstawiono wyniki badań eksperymentalnych tarcia występującego na promieniu matrycy ciągowej. Materiałami testowymi były próbki w postaci taśm o grubości 0,8 mm wykonane ze stali AISI 430 oraz blachy ze stopu aluminium AW-1100. Do przeprowadzenia testów wykorzystano specjalny symulator testu tarcia zginania z rozciąganiem. Zastosowano przeciwpróbki (sworznie) o różnych promieniach w zakresie od 1,5 mm do 13,5 mm. Testy przeprowadzono w temperaturze pokojowej w warunkach smarowania olejem mineralnym. Testy tarcia uzupełniono o określenie twardości i pomiar parametrów chropowatości powierzchni próbek (Ra, Rq i Rt). Na podstawie wyników stwierdzono, że współczynnik tarcia zwiększał się wraz ze zmniejszaniem się promienia sworznia gnącego, jednak zachowanie to uległo zmianie po osiągnięciu krytycznego promienia (4,5 mm), po którym współczynnik tarcia zwiększał się wraz ze wzrostem promienia sworznia. Taśma ze stopu aluminium AW-1100 charakteryzowała się wyższym współczynnikiem tarcia niż taśma ze stali AISI 430.

Słowa kluczowe: stop aluminium AW-1100, stal AISI 430, współczynnik tarcia, test zginania z rozciąganiem, kształtowanie blach