Original Article

Evaluation of the flange stretching capability of a 780 MPa class multiphase advanced high strength steel

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Abstract

Advanced High Strength Steels or AHSS (Advanced High Strength Steels) have superior properties to conventional steel are widely used in the automotive industry, they provide weight reduction and at the same time, increase vehicle safety in the event of collisions. Flangeability is an essential element for forming automotive components such as chassis and suspension components. Research is ongoing into the development of forming techniques that can improve the performance of AHSS during industrial operations, particularly flange drawing. Therefore, there is great interest in investigating the extensibility of the pre-cut cutting edge and determining the factors that significantly influence the formability of the product. The test used to evaluate flangeability is the Hole Expansion Ratio (HER). In this research, the objective was to evaluate the influence of the conditions of four edge cutting methods on the hole expansion test of advanced multiphase high-strength steel class 780 MPa through four methods: Machining, LASER and punching with expansion of the hole in the direction of the punch (burr downwards) and in the opposite direction (burr upwards). The results of this study corroborate the literature that indicates that the state of the edge after cutting directly influences the expansion capacity of the hole.

Keywords: Hole expansion; Edge condition; flange stretching; Machining; LASER.

1 Introduction

Multiphase steels such as Euronorm HDT780C grade CP800 rolled by ArcelorMittal, have a homogeneous microstructure of fine bainite, ferrite and martensite (Figure 1) and are less sensitive to edge cracking than Dual Phase (DP) steels. DP steels exhibit lower hole expansion ratio (HER) values, as they have a greater hardness gradient between the martensite and ferrite phases, which is considered by literature to be one of the main causes of the greater propensity to failure [1].

This study focuses on evaluating the hole expansion capacity of 780 MPa multiphase steel (Complex Phase – CP800) and the different drilling methods with the aim of identifying the mechanisms and factors that lead to the occurrence of premature failure of CP800 steels in stamping operation.

2 Development

During the punch cutting operation, the blade/punch penetrates the metal until the pressure exerted by the tool is greater than the shear strength of the material, at which point fracture of the metal occurs. The characteristic aspect of the section of a surface cut by shearing includes 4 regions (Figure 2): Roll over zone, Burnish zone, fracture zone, and burr [2].

A critical factor influencing both the visual appearance and residual ductility of the sheared cutting edge is the distance between the cutting blades or between the punch and the cutting die. This dimension is traditionally referred to as gap or clearance and is usually stated as a percentage of the cut material thickness.

The opening used determines the relative length of each of the three regions and the height of the burr [3]. The

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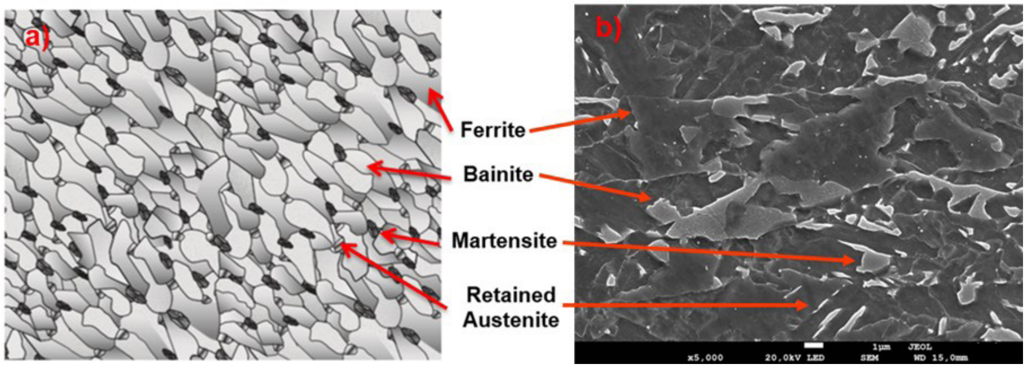

Figure 1. a) Scheme of a complex-phase steel microstructure showing martensite and austenite retained in a ferrite-bainite matrix. b) Microstructure of CP800 observed in SEM after Nital 2% attack.

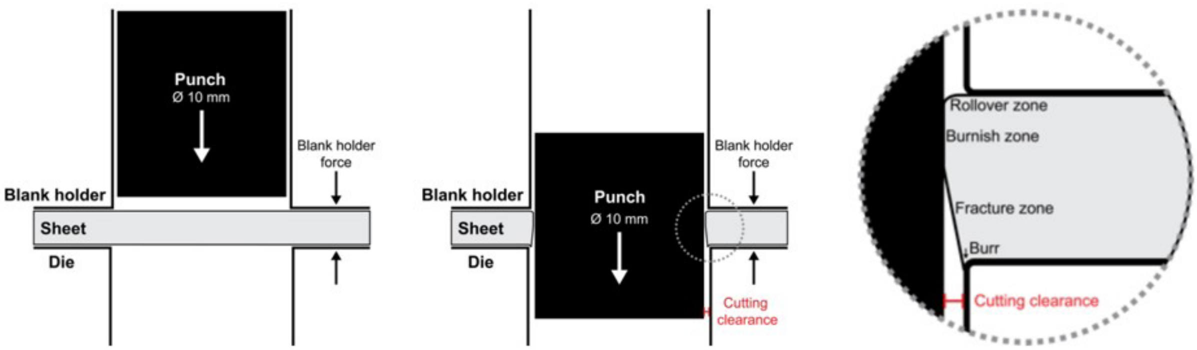

Figure 2. Schematic representation of regions normally formed on a cut edge surface [2].

study carried out was based on the ISO 16630 [4] standard, in which the cutting is performed by punching circular holes (10 mm in diameter) and the applied cutting gap is approximately 12%, calculated by half of the difference between the diameters of the matrix (dm) and punch (dp), divided by the thickness of the material (e), Equation 1.

$$\text{Cutting clearance } (\%) = \frac{(dm - dp)}{2e} \text{ x } 100 \quad (1)$$

Three factors have a direct influence on the edge stretching capacity - the condition of the hole edge, the steel microstructure and the non-metallic inclusions. They influence the flanging of the cut edge and consequently the expansion of the hole in steel plates [5]. The drilling process reduces ductility in the region adjacent to the edge, as it induces local hardening, micro voids, cracks and notches. The presence of inclusions such as titanium-rich particles and complex oxides (Al2O3-CaO) are detrimental to edge stretching resistance, as they act as micro-void nucleation sites during cutting and facilitate crack propagation. To reduce edge cracks, it is recommended to have a good steel cleanness, a homogeneous microstructure with equiaxed grains, the reduction of the segregation zone, the control of the morphology/amount of second phase and the evaluation of anisotropy of the material with Lankford coefficient (r) and the exponent work hardening (n) [6].

3 Materials and methods

The evaluation of the hole expansion capacity was carried out in Complex Phase steel of the resistance class of 800 MPa (CP800) with a nominal thickness of 3.3 mm with the following chemical specification (Table 1) and mechanical properties (Table 2) according to the standard. Considering that the minimum size of a specimen for the tensile and hole expansion tests is 100 mm^2, 5 samples of coils were taken with dimensions of 1500 x 500 mm.

3.1 Tensile test

To evaluate the mechanical properties, the tensile test was carried out in accordance with ISO 6892-1 [7] using a test specimen with a measuring base equal to 80 mm and a width of 20 mm and oriented at 15° by 15° from the longitudinal of the rolling direction (Figure 3). The tensile tests were carried out in the ArcelorMittal Tubarão mechanical testing laboratory, on a Zwick Roell Z250 universal mechanical testing machine, with 25 tf of capacity.

Table 1. Chemical composition of CP800 Steel

Steel Grade	Max. C (%)	Max. Si (%)	Max. Mn (%)	Max. P (%)	Máx. S (%)	Al (%)	Max. Ti + Nb (%)	Max. Cr + Mo (%)
HR CP800	0.18	1.0	2.2	0.05	0.01	0.015 -1.2	0.25	1.0

Table 2. Mechanical properties of hot-rolled grade CP800

Steel Grade	Yield Stress 0.2% (YS) (MPa)	Ultimate tensile strength (UTS) (MPa)	Elongation min (%)
HR CP800	600 - 820	760 - 960	13

Table 3. Summary of hole expansion test conditions performed in this study

Hole Expansion Test	Hole geometry	Type of hole	Direction of HE Test	Cutting Clearence	Steel Grade	Number of test	Total
HER	Circular 10 mm	Punching	Cutting direction (Burr Up)	12%	CP800	10	10
		Punching	Inverted cutting direction (Burr Down)				10
		Machined	Cutting direction	NA			10
		LASER	Cutting direction				10
						HER Test	40

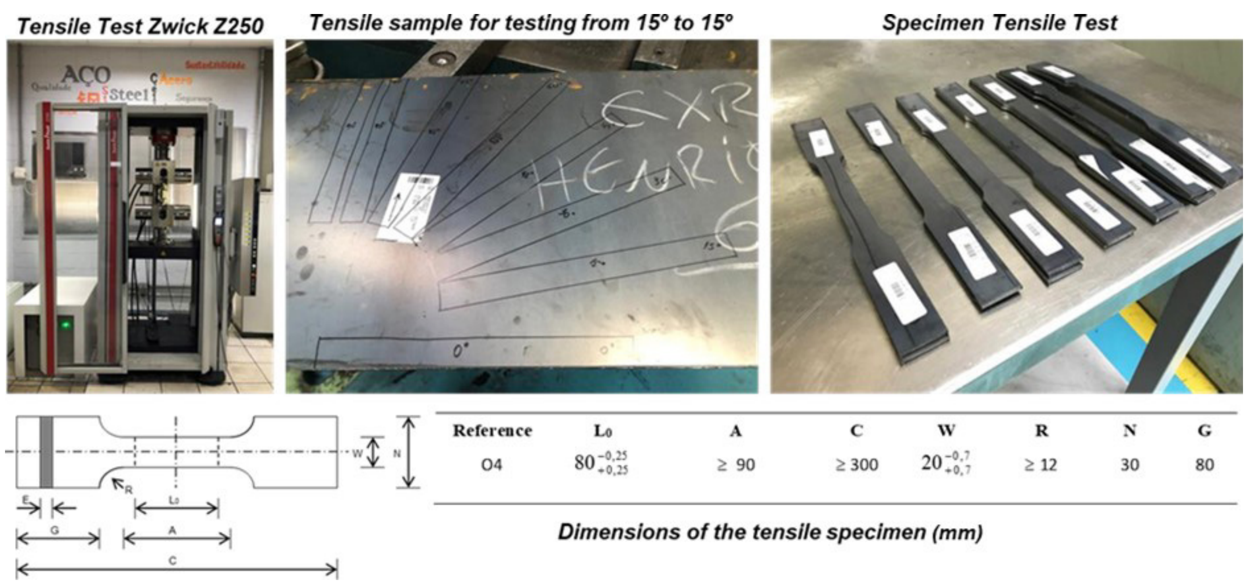

Figure 3. Duplicate tensile tests with angle variation every 15° to study hardening (n) and anisotropy (r) properties and coefficients.

In the tensile tests, the values of yield strength (YS) at 0.2% strain, ultimate tensile strength (UTS), total elongation (E) and the hardening coefficient (n) and anisotropy (r) were determined.

The hole making methods used were punching, LASER cutting and machining. The expansion of the hole was carried out in the cutting direction. However, for punching cutting, the evaluation was also carried out by reversing the cutting direction. In Table 3 is the description of the cutting procedure by these four methods and the conical expansion direction of the hole.

3.2 Punching

For the hole punching process, the punch cross section geometries will be circular as shown in Figure 2. The cutting gap will be defined by Equation 1 to reach 12% ± 2%. The quoted gap is stipulated for carrying out a hole expansion test according to ISO 16630 [4] for circular holes.

3.3 Laser cut and machined

The hole was LASER cut using a 3 kW Fiber Optic machine. For this cut, a cutting power of 700 W, frequency of 500 Hz, with O_2 as assistance gas for cooling the sample (Figure 4a). The cutting advance to be used was 6 m per minute. The machining cut was performed by the milling operation, with a hard metal end mill (Figure 4b). The hole was drilled in just one stage with a 10.0 mm diameter cutter, using a cutting speed of 360 revolutions per minute and feed of 75 mm per minute. The purpose of machining at low feed speed is to provide a cutting edge with a good finish and with as little hardening as possible.

3.4 Hole expansion test

To evaluate the flanging capacity, the Hole Expansion Ratio (HER) test was used, using a conical head punch (60°) to promote the expansion of the 10 mm diameter hole, Figure 5. The tests were carried out in an Erichsen 120/20 hydraulic press, using the description of ISO 16630 [4] as a reference. Each test was interrupted immediately when a crack crossing the entire thickness of the material at the edge of the hole occurred. Test results were expressed according to Equation 2.

$$\text{HER } (\%) = \frac{(\boldsymbol{\emptyset d} - \boldsymbol{\emptyset d}0)}{\boldsymbol{\emptyset d}0} \text{ x}100 \qquad (2)$$

4 Results and discussion

4.1 Test results - tensile, anisotropy & hole expansion ratio

The tensile tests carried out in the rolling direction demonstrated convergence with the appropriate values for the CP800 grade (Table 4).The occurrence of fracture, through the thickness of the material during hole expansion tests, may also be associated with the anisotropy of the material [7]. To this end, tensile tests were carried out in duplicate on 7 samples divided into 15º and 15°, starting from 0º in reference to the longitudinal direction of rolling and 90º in reference to the transverse direction. The anisotropy (r) results can be seen in Figure 6.

The final crack generally appears in the region of the minimum anisotropy coefficient (r_{min}), where the resistance

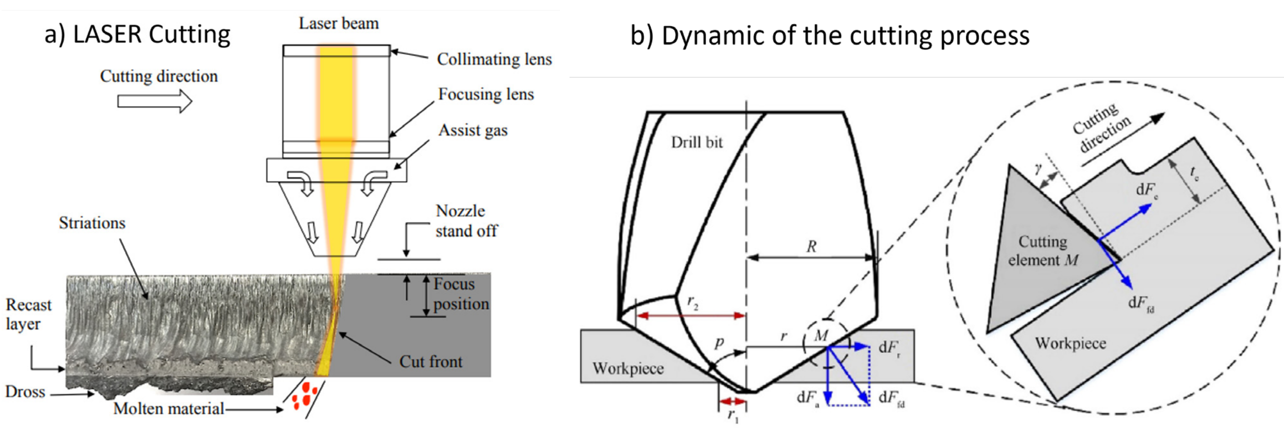

Figure 4. Representation of making the hole by LASER and drilling cutting. a) Schematic of the mechanisms during LASER cutting [8] and b) Representation of making the hole by Drilling cutting [9].

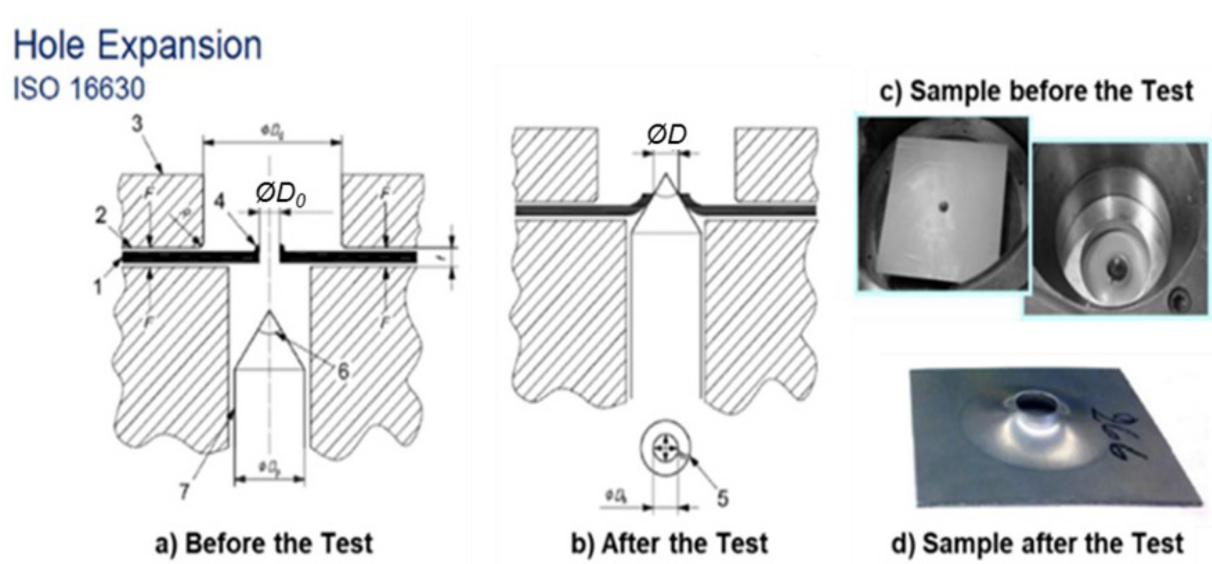

Figure 5. Representation of Hole Expansion Test [2].

Table 4. Mechanical properties of CP800 steel analyzed in rolling direction

YS 0.2% (MPa)	UTS (MPa)	Elongation (%)	Strain hardening (n)	Anisotropy (r)
806	866	13.3	0.095	0.856

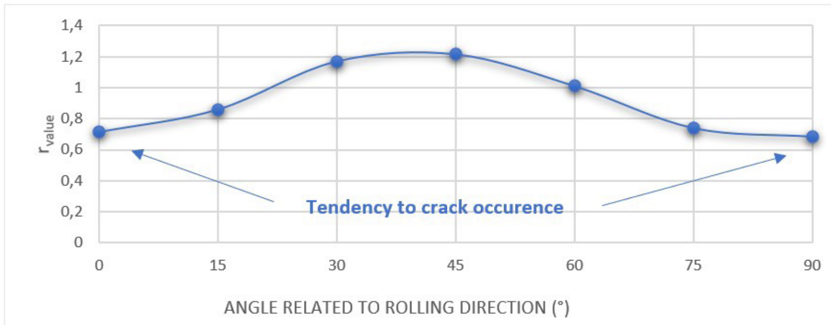

Figure 6. Graph of anisotropy value (r) versus rotation direction angle obtained after tensile tests on samples divided into 15º and 15°.

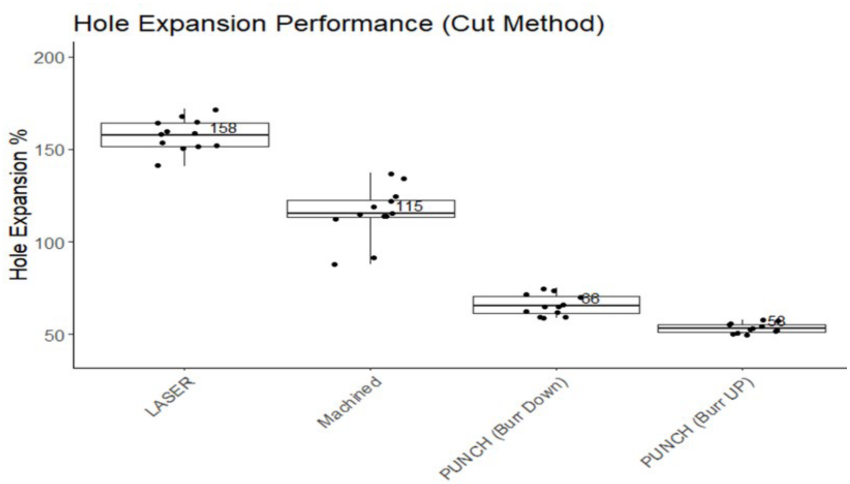

Figure 7. Results of HE tests for different cutting methods.

to thickness reduction is lowest. Therefore, the higher the r_{value} of the material, the greater its hole expansion capacity, as can also be seen in the graph. The anisotropy coefficient (r) has an interesting behavior when evaluating the angle x lamination direction relationship, having lower values at angles 0º and 90º, among others. According to these studies, these angles are considered to have a greater tendency for the occurrence of cracks, as highlighted in Figure 6.

The hole expansion tests with the 4 different types of cuts showed cracks only at angles of 0º and 90º, with the greatest incidence at 0º, that is, along the longitudinal face of the material. These results are corroborated by the literature [1] and can be used to some extent to predict failures during stamping.

Figure 7 shows the results obtained in the hole expansion tests with the different cuts. Two sequences of five samples were analyzed and the result is an average of these tests. The results showed the expected behavior for each type of cut, however the LASER showed a significantly higher HER value.

4.2 Critical analysis of results

According to Worswick et al. [10], a factor that can explain the great difference in performance between the expansion capacity of holes manufactured by machining in relation to holes manufactured by LASER and also by punching is the orientation of the finish left on them by each manufacturing technique.

While the orientation of the manufacturing marks is parallel to the surface of the plate in holes made by machining, it is perpendicular to the surface of the plates in holes made by LASER or punching. This causes the concentration of stresses, favorable to the opening and propagation of cracks, to be greater in holes manufactured by punching, reducing their expansion capacity when compared to machined holes, however the results showed that the LASER is less susceptible to this effect. obtaining the best HER result.

In relation to holes/flanges made by punching, a high degree of deformation is expected in this region, resulting from the load required to separate the material. This localized strain hardening deteriorates the possibility of material deformation under stamping stresses (Figure 8). The inversion of the hole expansion direction (Burr Up and Burr Down) influences the final result due to the hardening of the edge in the shear region as shown in Figure 9.

In relation to LASER-cut holes, thermal input is suggested as one of the factors that can deteriorate the stretching capacity of high-strength steel flanges, as it promotes the formation of high-strength constituents in the layer adjacent to the edge, resulting from the high input heat applied during physical separation.

It is likely that the presence of these constituents can induce a reduction in local ductility and promote the premature occurrence of cracks. However, what was observed in the tests was that the formation of higher hardness constituents promoted a region of high concentration of stress and resistance, with the remainder of the material having a ductile microstructure, which favored the material's stretching capacity during the tests.

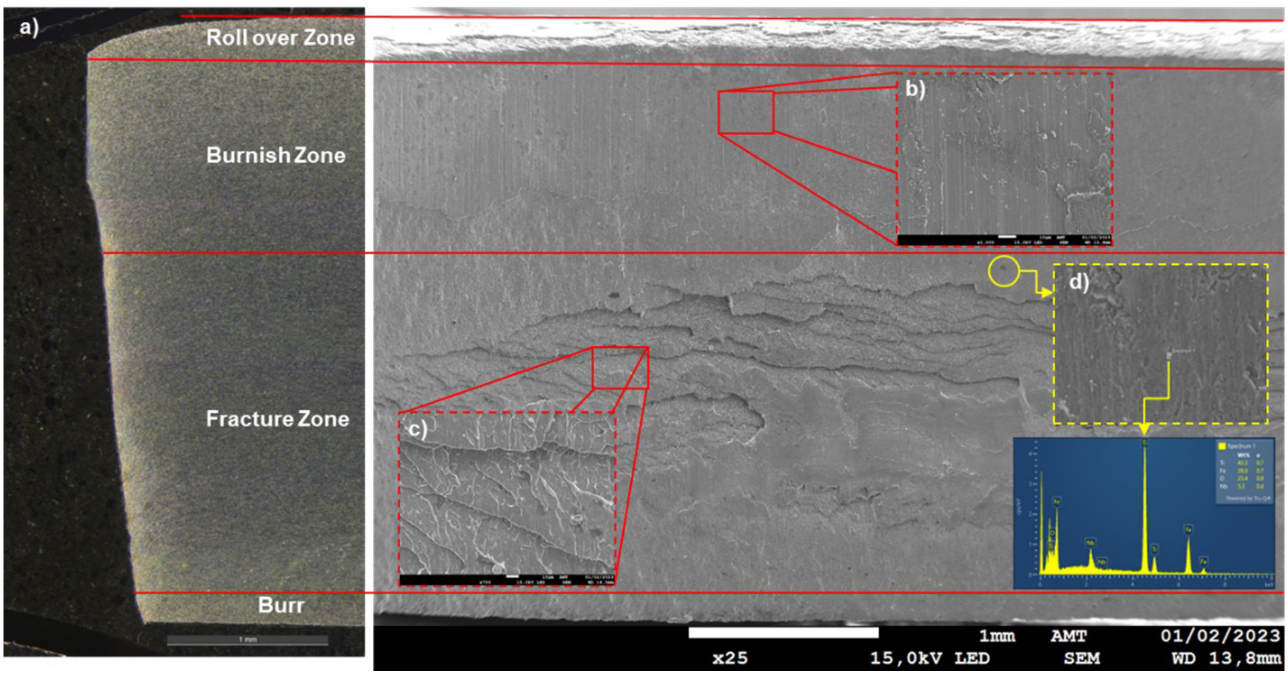

Figure 8. Evaluation of the punch cut. a) Image of the cut profile observed in the stereoscope; b) Cut marks in the direction of the punch; c) formation of flaws on the surface due to the high load of the cut; d) observing the presence of a titanium nitride on the cutting edge.

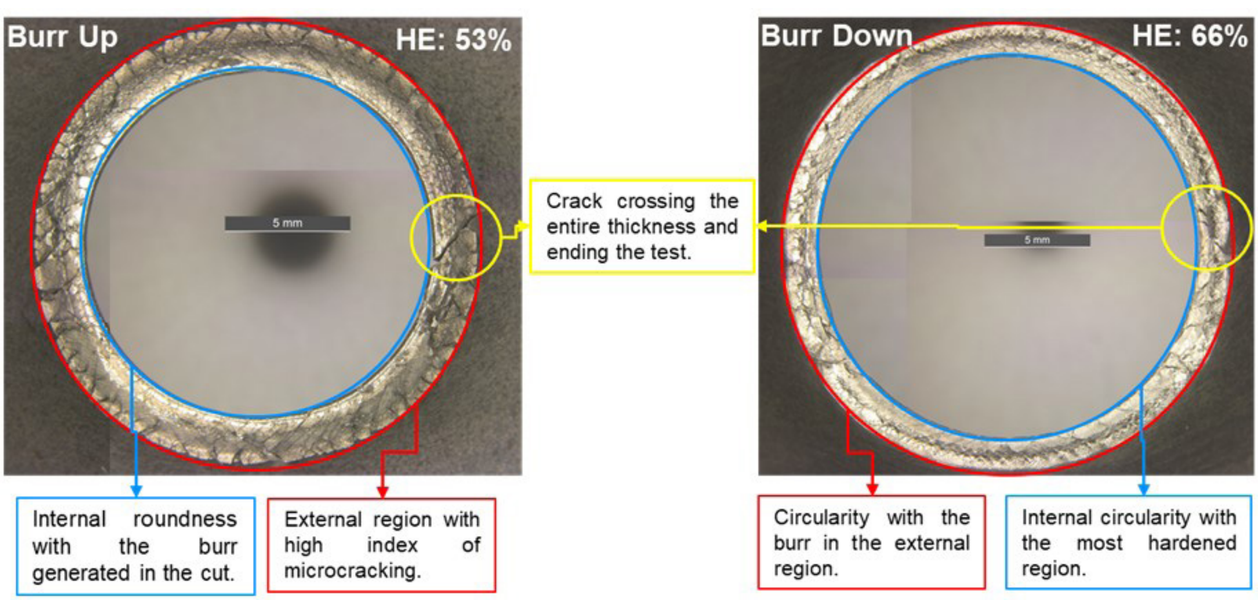

Figure 9. Evaluation of the edge generated by punch cutting (Burr Up and Burr Down) after the hole expansion test.

Another preponderant factor was the quality of the edge cutting with the LASER, which presented an infinitely higher level of finish than the other cuts used in the study, as highlighted in Figure 10.

Figure 11 shows the cutting profile and the quality of the cut after machining and before expansion, where we can observe the generation of hardening points in the material and the formation of "teeth" due to the cutting or sharpening of the tool used. These small imperfections tend to reduce the stretching capacity of the material edge, which could justify the lower value than that obtained by LASER cutting as seen in Figure 12.

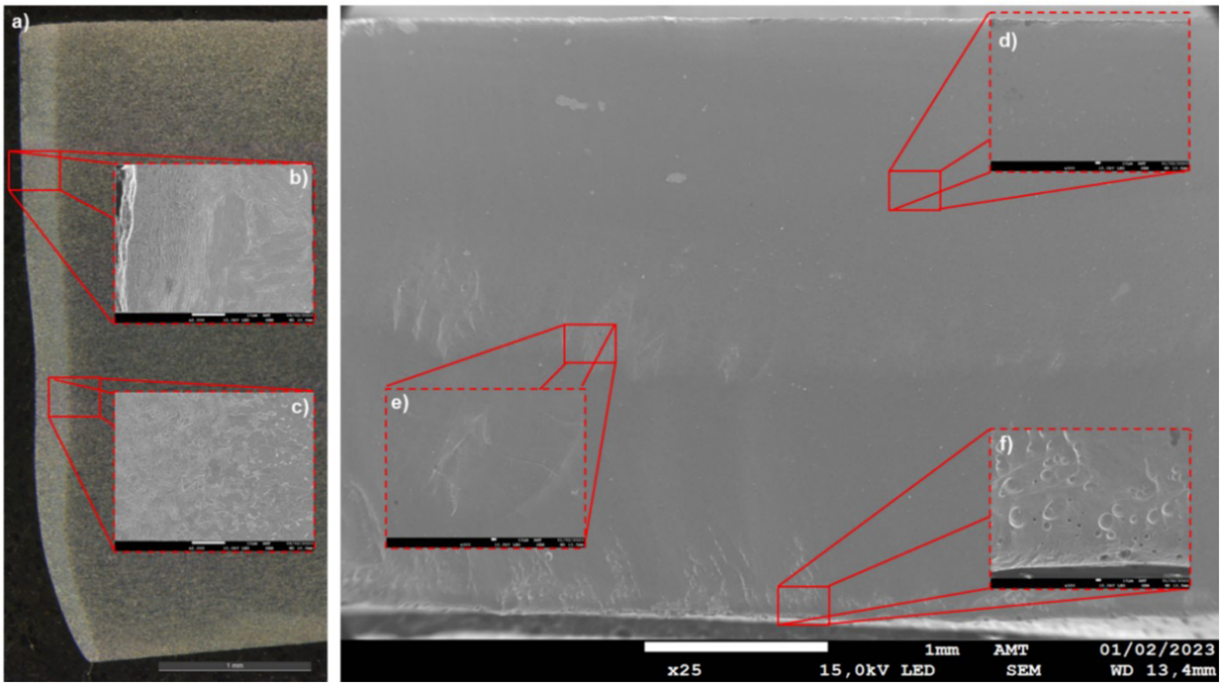

Figure 10. Evaluation of LASER cut. a) Image of the cut profile observed in the stereoscope; b) formation of the high hardness martensite constituent; c) the thermal input generated an HAZ of around 250µm; d) region with excellent cutting finish; e) marks of the hot cut with the shape of dendrites and f) presence of bubbles in the region of the end of the cut due to the melting of the material.

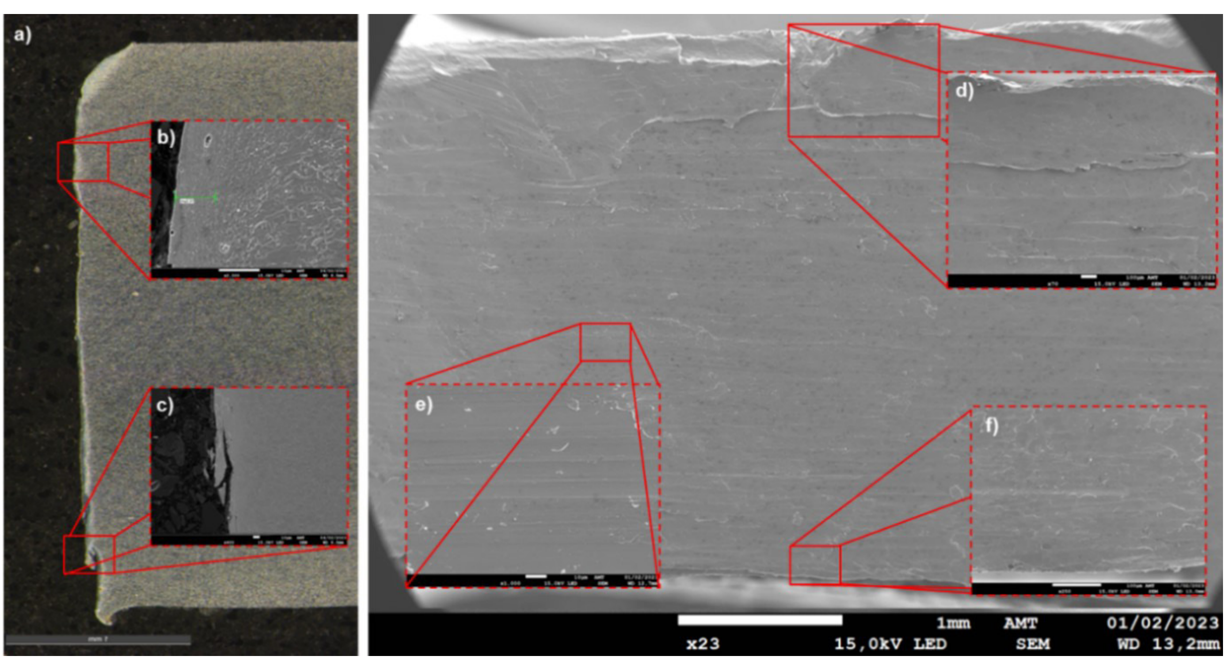

Figure 11. Machining cut evaluation. a) Image of the cut profile observed in the stereoscope; b) presence of regions with a certain level of hardening; c) formation of "teeth" on the cutting edge; d) Machining flaws observed on the cutting edge; e) region with good cutting finish and formation of marks parallel to the surface of the material and f) region with low burr level.

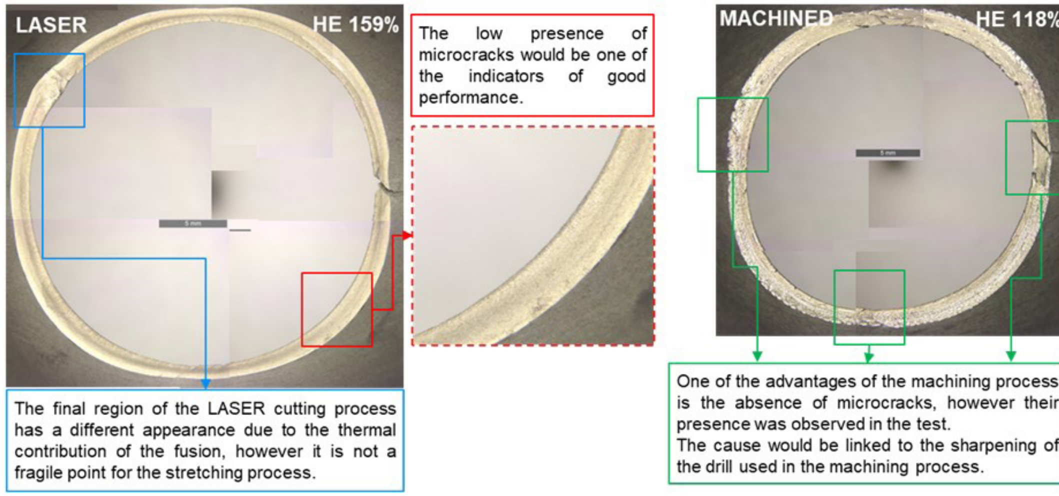

Figure 12. Evaluation of the edge generated by LASER and Drilling cuts after the hole expansion test.

5 Conclusions

- The study demonstrated the potential for the performance achieved by LASER cutting and machined cutting in steel sheets with values of 158% and 115% respectively. For Punching cutting, inverting the plates after cutting, positioning the burr downwards, can generate gains in hole expansion capacity of around 10% for Complex Phase 800 and this value may be higher in other steel classes.
- LASER cutting has gained ground in the processing chain for high-strength steel components, as it can provide a higher productivity advantage than machining cutting and guarantee the quality of the edge finish, as well as the flexibility to deal with complex geometries of parts, in addition to the absence of tool wear from punching and machined cuts.
- The decision to use one of these alternative cutting methods for a specific industrial sheet metal forming operation will depend on many factors, including capital investment, operating cost, and productivity considerations.

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