

Effect of Sandblasting on Low and High-Cycle Fatigue Behaviour after Mechanical Cutting of a Twinning-Induced Plasticity Steel

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Abstract. In the last years, car bodies are increasingly made with new advanced high-strength steels, for both lightweighting and safety purposes. Among these new steels, high-manganese or TWIP steels exhibit a promising combination of strength and toughness, arising from the austenitic structure, strengthened by C, and from the twinning induced plasticity effect. Mechanical cutting such as punching or shearing is widely used for the manufacturing of car body components. This method is known to bring about a very clear plastic deformation and therefore causes a significant increase of mechanical stress and micro-hardness in the zone adjacent to the cut edge. To improve the cut edge quality, surface treatments, such as sandblasting, are often used. This surface treatment generates a compressive residual stress layer in the subsurface region. The monotonic tensile properties and deformation mechanisms of these steels have been extensively studied, as well as the effect of grain size and distribution and chemical composition on fatigue behaviour; however, there is not so much documentation about the fatigue performance of these steels cut using different strategies. Thus, the aim of this work is to analyse the fatigue behaviour of a TWIP steel after mechanical cutting with and without sandblasting in Low and High-Cycle Fatigue regimes. The fatigue behaviour has been determined at room temperature with tensile samples tested with a load ratio of 0.1 and load amplitude control to analyse High-Cycle Fatigue behaviour; and a load ratio of -1 and strain amplitude control to determine the Low-Cycle Fatigue behaviour. Samples were cut by shearing with a clearance value of 5%. Afterwards, a part of the cut specimens were manually blasted using glass microspheres of 40 to 95 microns of diameter as abrasive media. The results show a beneficial effect of the sandblasting process in fatigue behaviour in both regimes, load amplitude control (HCF) and strain amplitude control (LCF) tests, when these magnitudes are low, while no significant differences are observed with higher amplitudes.

Abstract. low-cycle fatigue, high-cycle fatigue, mechanical cutting, sandblasting, high manganese steel, TWIP steel

1 Introduction

Nowadays, lightweight construction is one of the major concerns in automotive industry to meet the increasing demands towards environment and safety related issues. A large part of body-in-white (BiW) components is currently manufactured using ultra high-strength steels (UHSS), with fracture strengths from 1000MPa upwards.

The cold forming of pieces of complex geometry is not an easy task with this type of steels, thus, there has been a growing interest for High Mn Steels (HMnS). The main characteristic of these steels is high Ultimate Tensile Strength (UTS) values, around 1000MPa, combined with high ductility, above 50%, and high strain hardening coefficient. This combination of properties is the result of the activation of specific deformation mechanisms such as TRIP and/or TWIP effects.

Currently, the industrialization of the production of HMnS and the reliability of their in-service properties have led to the first applications of HMnS for automotive components. Despite this, there are still aspects related to the performance of HMnS produced parts that need further evaluation in order to extend the implementation of these steels for industrial applications. In particular, there are still some concerns regarding the fatigue performance of components' cutting zones and the methodologies to improve it.

Regarding fatigue, failures are mainly triggered by pre-existing defects at the surface or inside the material. Internal defects are usually associated to non-metallic inclusions generated during steel manufacturing. Surface defects can be produced during cold rolling or part processing. Among the defects produced during forming, trimming produces surface irregularities at the cut edge, which may act as preferential sites for fatigue crack initiation and propagation. Several authors have assessed

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the effect of cutting technologies on fatigue properties for different sheet steel grades: carbon and micro-alloyed steels [1]; UHSS with UTS up to 1400MPa [2] and deep drawing, high strength dual phase, austenitic and duplex stainless steels [3]. In all cases, it is concluded that the cut edge makes the fatigue strength of the metal decrease because of the roughness that the cutting process generates. It is also observed that the magnitude of the clearance was of minor importance, being more critical the tool wear.

If the effect of the different cutting methods is analyzed, the specimens with milled edges showed higher fatigue limit than mechanically cut edges. These authors also concluded that there were no significant differences between milled and water jet cutting, while the lowest fatigue behaviour was observed in laser cut specimens. Thus, the main conclusion of this and other works [4, 5] is that lower strength steels were less sensitive to the cutting method than the higher strength steels and that in most cases, shearing produced lower fatigue strengths than other cutting methods due to the presence of larger surface defects at the edges.

Regarding TWIP steels, there is relatively little work reported on their fatigue behaviour. High cycle fatigue [6, 7], as well as low cycle and extremely low cycle fatigue life [8], have been evaluated in some works. In general, the fatigue limit of TWIP steels correlates to their high ultimate tensile strength, with a ratio of fatigue limit to tensile strength around 0.4, similar to the one of stainless steels, but far from that obtained with other UHSS steels such as Dual or Complex Phase steels, around 0.5 or even higher [4, 9].

There is not much information on the effect of the cut edge in the fatigue life of these steels. Only Mateo et al. [10] evaluated the effect of the laser cutting on fatigue behaviour of two metastable steels, one of which was a TWIP steel, applying the staircase method. According to these results, TWIP steel is less sensitive than stainless steel to defects at the cut edge. However, no studies have been found on how the mechanical cutting affects the fatigue behaviour of these type of steels.

On the other hand, there are some works that report the negative effect of mechanical cut on forming and post-forming operations, such as hole expansion, due to the high amount of deformation introduced to the hole edge [11]. Thus, it is expected that this high degree of deformation introduced at the cutting edge could negatively affect fatigue behaviour.

In this sense, it has been demonstrated that some surface treatments can improve fatigue behavior through the retardation of fatigue crack initiation or propagation. These treatments, such as sandblasting or shot peening, are effective methods to enhance the fatigue properties, by inducing a compressive residual stress in the subsurface of the material [12, 13]. In sandblasting, the sample surface is blasted repeatedly by high-speed sand particles, leading to reduce the surface roughness, removal of surface scale and generation of local plastic deformation in the surface layer. In addition, a compressive residual stress layer is formed in the subsurface region. Microstructural changes due to

sandblasting have also been reported in austenitic steels [14].

The aim of the present work is to increase the knowledge about the effect of the mechanical cutting on the fatigue performance of High Mn Steels (HMnS) and, propose industrial treatments to improve their fatigue behaviour. To achieve these objectives, after mechanical cutting, a part of the cut specimens have been manually blasted using glass microspheres of 40 to 95 microns of diameter as abrasive media. Materials with polished cut edges have been used as a reference in this study.

2 Materials

Two grades of TWIP steel were analysed: TWIP1.5 and TWIP3.0. The chemical compositions of these steels are shown in table 1 and table 2.

Table 1. Chemical composition of TWIP1.5 steel.

Element	C	Mn	Al	Si
Weight %	0,35	19,9	1,0	0,2
	P	N	S	Fe
	0,015	0,0126	0,0003	Balance

Table 2. Chemical composition of TWIP3.0 steel.

Element	C	Mn	Al	Si
Weight %	0,38	18,3	1,2	0,29
	P	N	S	Fe
	0,018	0,0104	0,0005	Balance

Then, samples of these steels were polished and etched following standard methods. Their microstructures can be seen in figure 1 and figure 2.

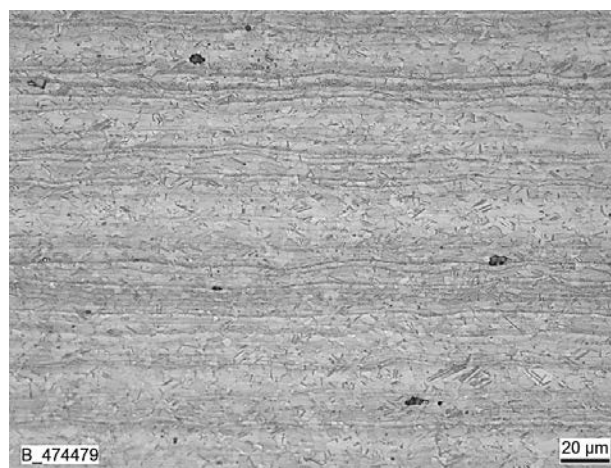


Fig. 1. Microstructure of TWIP1.5 at the centre (Nital etched).



Fig. 2. Microstructure of TWIP3 at the centre (Wallner etched).

As seen in the previous figures the two TWIP steels shows a homogeneous austenite matrix. The grain size is the only notable difference.

Conventional axial tensile tests were performed according to EN-ISO6892-1 with the specimens oriented transverse to the rolling direction. Table 3 shows the results.

Table 3. Mechanical properties of analysed TWIP steels.

Steel	YS [MPa]	UTS [MPa]	Elongation [%]
TWIP1.5	564	947	48.3
TWIP3.0	369	802	56.5

Table 3 shows, as would be expected, a higher Ultimate Tension Strength (UTS) and Yield Strength (YS) with a decreasing of grain size; whereas the uniform elongation and total elongation become smaller.

3 Experimental procedure

In order to evaluate the influence of the cutting process on the fatigue behaviour of these steels, the calibrated zone of specimens was cut using different strategies:

- Spark erosion (EDM) and polished, with a first grinding and a polishing with two types of abrasive pastes to get clean and shiny surfaces, identified as [REF] condition.
- Shearing using a cutting clearance of 5% of the sheet thickness and a punch radius of 30 microns, identified as [CUT] condition
- Shearing as previously commented and manually blasted using glass microspheres, identified as [SAN] condition.

Figure 3 shows the tool employed for cutting a part of the specimens tested.

The geometry of the edges was evaluated by cutting a specimen of each strategy in cross section and analysing them by optical microscopy, figure 4 and figure 5.

Vickers micro-hardness profiles were also performed to assess the effect of each cutting methodology and are shown in figure 6.

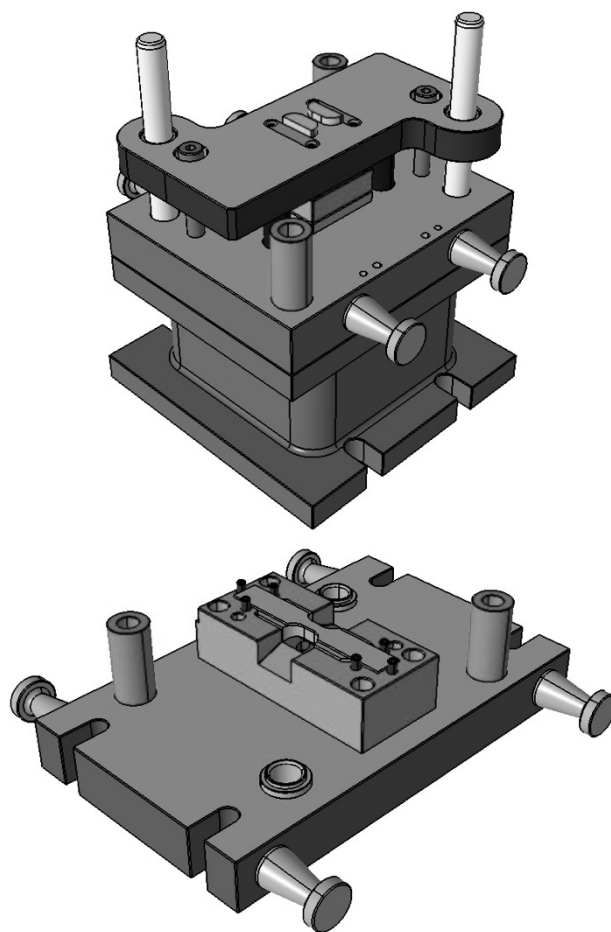


Fig. 3. Tool employed for cutting fatigue specimens.

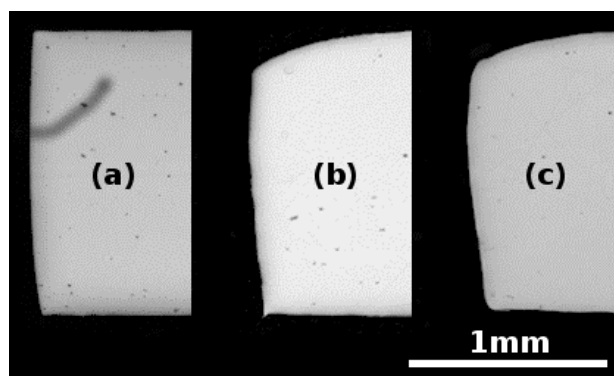


Fig. 4. TWIP1.5 cut edges: (a) REF, (b) CUT and (c) SAN.

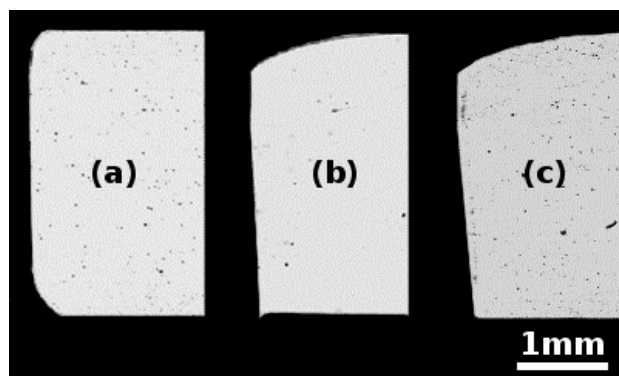


Fig. 5. TWIP3.0 cut edges: (a) REF, (b) CUT and (c) SAN.

Residual stresses were also evaluated on the surface of the samples by means of instrumented indentation using the methodology developed by Wang and Bao [15, 16]. In order to perform indentation tests, a Berkovich indenter was used with an applied penetration depth of 10 μm . Results of residual stresses, shown in figure 7, correspond to an average value from at least 20 indentations.

Regarding fatigue behaviour, tests were conducted in dual column servo-hydraulic testing machine. Low Cycle Fatigue (LCF) tests, to obtain $\epsilon\text{-N}$ curves, were performed according to ISO12106 standard [17] using an axial contact extensometer. Total strain versus number of cycles curves were then used to determine the Basquin and Coffin-Manson relationships. High Cycle Fatigue (HCF) tests, to obtain SN curves up to 2×10^6 cycles, were obtained according to ISO1099 standard [18], using a load ratio (R) of 0.1. All tests were performed at room temperature. After these tests, some fracture surfaces were inspected by means of field emission scanning electron microscopy (FE-SEM).

4 Results

Sheet cut edges present different geometry depending on the cutting methodology employed. As shown in figure 4 and 5, polished samples present rounded edges without asperities, as expected (figure 4(a) and 5(a)). Sheared samples show the typical features of a sheared edge with rollover, smooth, fracture zones and burr in two materials (figure 4(b) and 5(b)). Once samples are submitted to the sandblasting operation, the roughness of the cutting edge is reduced and the burr removed.

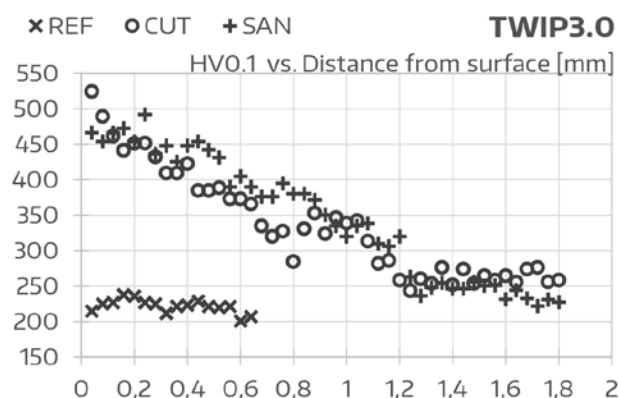
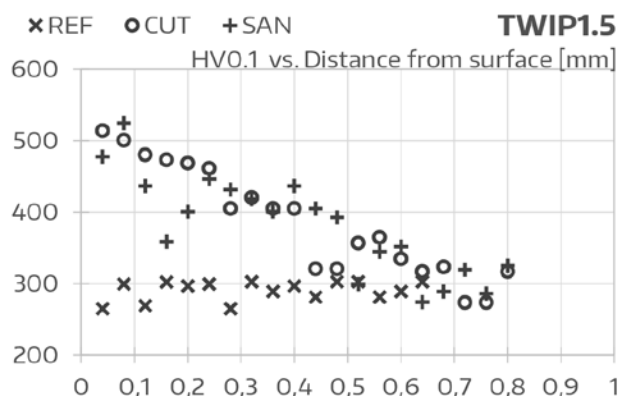


Fig. 6. Micro hardness profiles at the near cut edge.

Micro-hardness profiles shown at figure 6 show that the shearing process increases hardness near the cut edge, an increase that is not observed in polished specimens, for which the cut were done by EDM. The length of the cut-hardened area is deeper in the thicker steel, while no clear differences of hardness are observed between the sheared samples with and without sandblasting treatment.

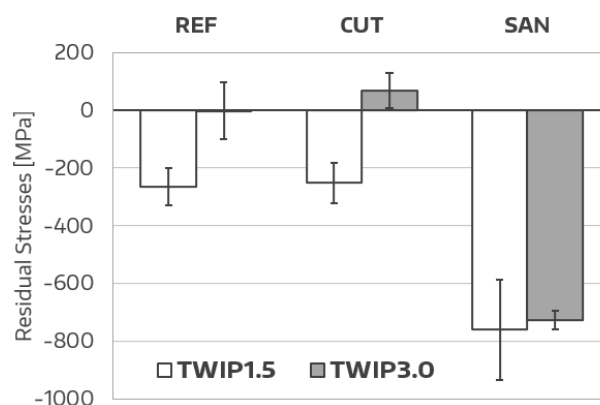


Fig. 7. Residual stresses obtained on the TWIP steels surface.

As can be seen in figure 7, sandblasting process induces high compressive stresses measurable even at penetration depth of 10 microns with instrumented indentation. The magnitude of these compressive stresses does not differ much from those reported by other authors that performed shot peening process with different TWIP steels, although the depth of the compressive layer was higher [19], 100 to 300 microns for a shot peening versus 25 to 75 microns for a sandblasting [20].

The main strain and stress-life fatigue results are summarized in figure 8 and 9, defined here as the strain and stress amplitude leading to 50% survival probability (experimental values).

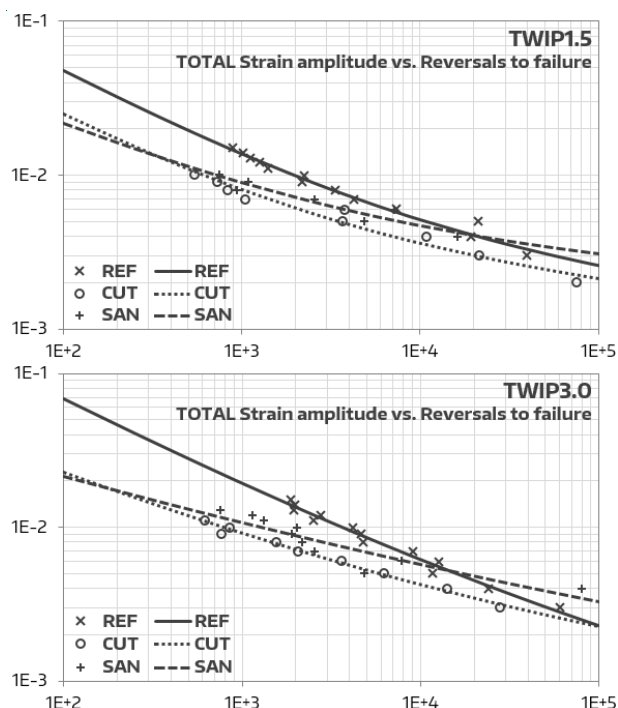


Fig. 8. ϵ N curves obtained with TWIP steels

As shown in figure 8 and 9, fatigue performance depends on the cutting strategy employed. At low and high number of cycles (LCF and HCF tests), both strain and stress that can be applied for a given number of cycles, is higher for polished specimens compared with the sheared ones.

Concerning sandblasting specimens, the effect of this surface treatment on the fatigue performance depends on the applied stress level. Thus, the sandblasting process significantly increase the strain and stress-life behaviour when the stress level is low (low strain in LCF tests and low stress in HCF tests). On the contrary, at higher stress levels (high strain in LCF tests and high stress in HCF tests) sandblasting treatment does not introduce any noticeable improvement in the fatigue behaviour of this type of steels, since the fatigue results of sheared specimens are similar with and without sandblasting, at high stress levels.

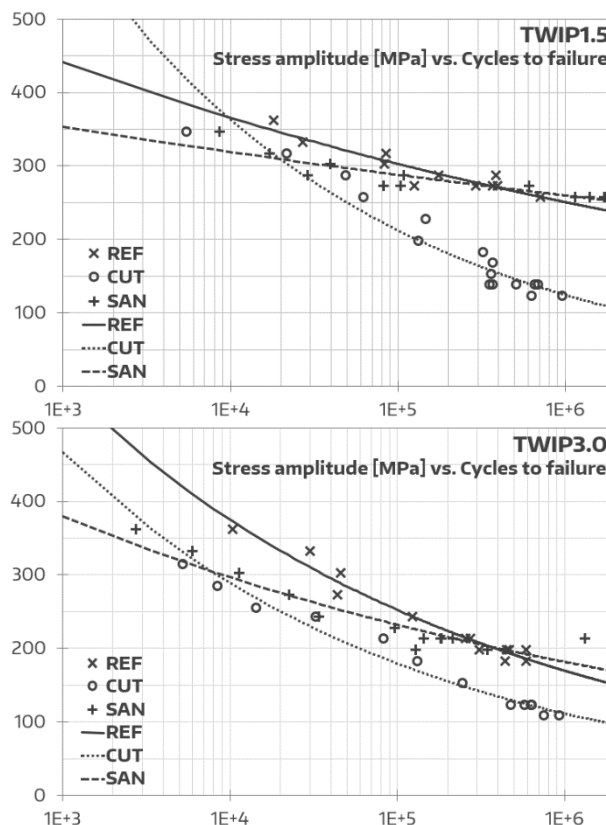


Fig. 9. SN curves obtained with TWIP steels.

These results may be explained as follows: sandblasting process to sheared specimens generates a compressive residual stress layer which is expected to influence the fatigue life. At low cyclic stresses, the favourable effects of the compressive residual stress layer results in life enhancement. As the cyclic stress increases, the residual stresses will relax quickly and the extent of life enhancement will decrease, as some authors support [21].

5 Discussion

Fatigue properties are extremely sensitive to the presence of pre-existent surface defects in the material, such as non-metallic inclusions, irregularities, asperities or even cracks originated during cutting or forming processes, because the crack nucleation step is then shortened, or even removed.

It is well accepted that materials with high ductility, or toughness, as TWIP steels, have a high crack propagation resistance and the fatigue life is mainly spent in the crack growth regime. Thus, tough materials are usually referred to as high defect tolerant since the crack nucleation step does not control the fatigue life. On the contrary, high strength materials have a low crack propagation resistance because of their limited toughness. In that case, crack nucleation may take an important part of the total fatigue life, because the fatigue crack growth rate is relatively high. Thus, high strength materials are more sensitive to pre-existent defects, and they are usually referred to as low defect tolerant materials.

Thus, to rationalize the origin of failure in each case, a detailed SEM investigation of one specimen of each cutting strategy was done. These SEM fractographies are shown in figures from 10 to 12 for TWIP1.5 and 13 to 15 for TWIP3.0.

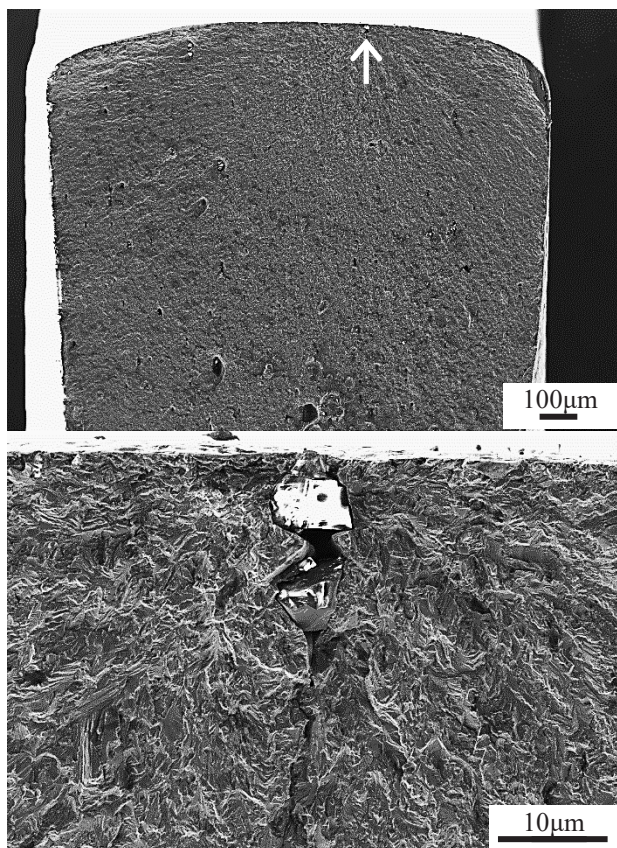


Fig. 10. Fractography of failed TWIP1.5 polished sample, showing the fatigue initiation site.

The fatigue failure surfaces in most cases show a failure origin independent of the cutting strategy, with no clear differences between the polished, sheared and sandblasted specimens. In most of the surface specimens analysed by SEM, the failure origin occurs in non-metallic inclusions located near the edge of the specimens.

Thus, as discussed above, the important differences in fatigue performance observed are not conditioned by the nucleation stage, but by the propagation stage.

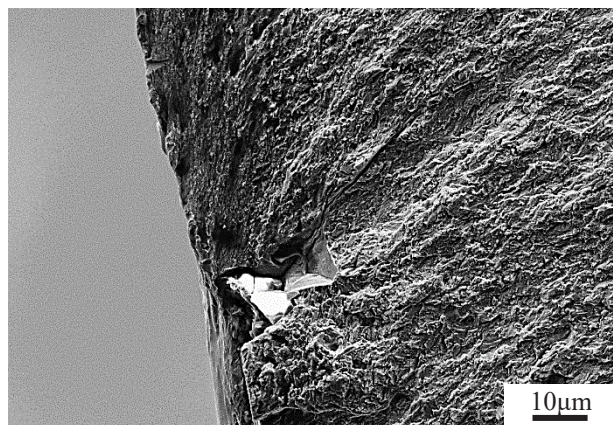
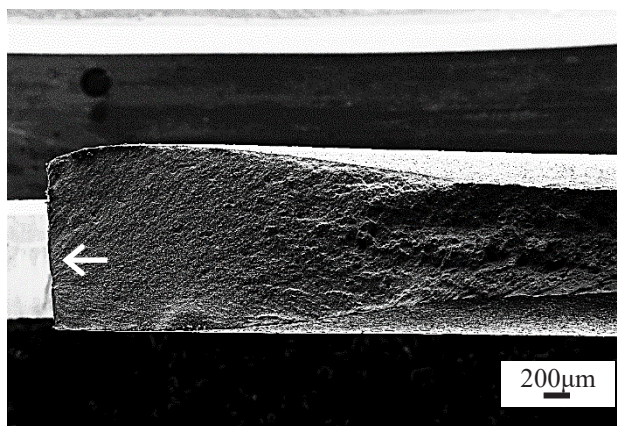


Fig. 11. Fractography of failed TWIP1.5 sheared sample, showing the fatigue initiation site.

Fig. 12. Fractography of failed TWIP1.5 sheared and sandblasted sample, showing the fatigue initiation site.

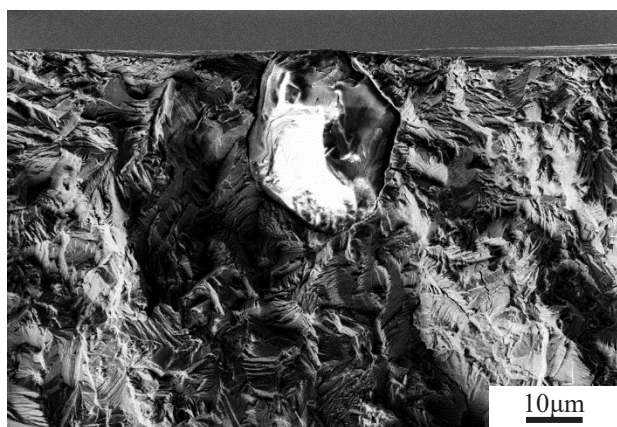


Fig. 13. Fractography of failed TWIP3.0 polished sample, showing the fatigue initiation site.

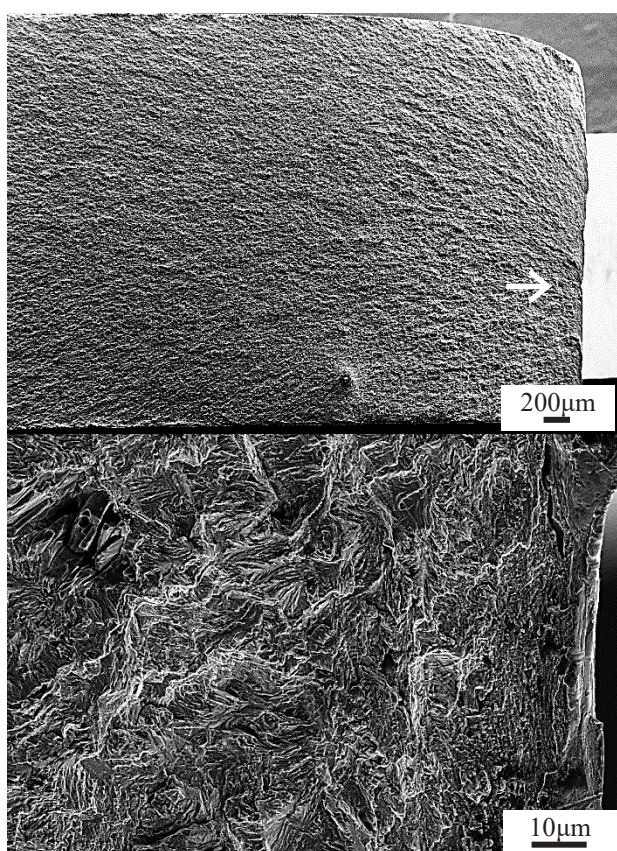


Fig. 14. Fractography of failed TWIP3.0 sheared sample, showing the fatigue initiation site.

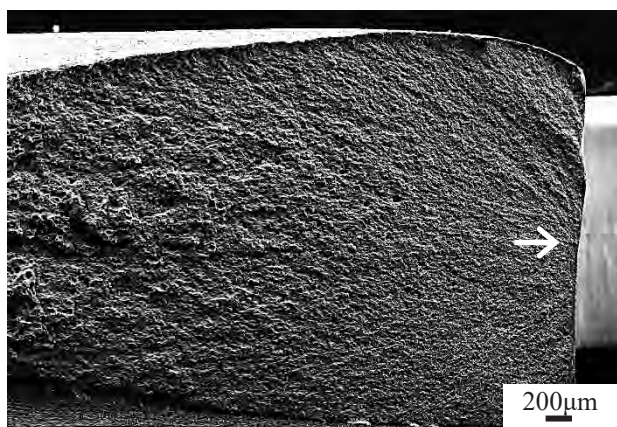


Fig. 15. Fractography of failed TWIP3.0 sheared and sandblasted sample, showing the fatigue initiation site.

These non-metallic inclusions, responsible for the crack nucleation, are probably the ones that cause that the fatigue performance of these two steels is not as high as expected. To know the nature of these non-metallic precipitates, an EDX analysis was performed, showing that most of them were aluminium nitrides.

Regarding fatigue performance between the different cutting strategies, and considering, as already advanced, that these are motivated by different crack propagation rates in each strategy, it seems clear that concerning the specimens sheared and with a sandblasting process after shearing, this different crack propagation ratio is due to the compressive stresses induced by sandblasting, as is shown in figure 7. These surface compressive stresses require greater tensile stresses to propagate the crack, which shifts the strain and stress-life curves to the right. As said before, this improvement is only observed at low strain or stress levels, since if cyclic stress increases, the residual stresses will relax quickly and the fatigue behaviour enhancement will not take place.

Differences between polished and sheared samples, and also with sandblasting specimens submitted at high strains or stresses, cannot be explained by differences in residual stresses, since, as observed with nano-indentation in figure 7, they are practically the same. In this case, this change in crack propagation rate has to be motivated by the microstructural change generated by the mechanical cut in the tool. Thus, in the specimens cut by spark erosion and then polished [REF], no deformation was introduced during cutting process, therefore the original microstructure, tougher, more tolerant to the defects and with a high crack propagation resistance is acting. In contrast, there are many works which support that during specimens shearing a high amount of deformation is introduced on the cut edge [11]. Thus, the microstructure in this region does not tolerate much more deformation and behaves like a material with a limited toughness and with a low crack propagation resistance.

6 Conclusions

Based on the experimental fatigue tests, surface analysis and fractographic observations, the following conclusions can be drawn:

- The fatigue behaviour of the TWIP steels analysed in this work is mainly governed by aluminium nitrides non-metallic inclusions located near the surface. Probably this phenomenon is the reason why fatigue performance of these two steels is not as high as would be expected.
- The presence of these defects near the surface makes the crack propagation step determinant in fatigue behaviour of these materials. Thus, to enhance fatigue performance is necessary to reduce the crack propagation rate.
- As seen above, a strategy to reduce the crack propagation rate is to use a cutting methodology which does not introduce a high amount of deformation on the microstructure, making the steel less defect tolerant because of a toughness reduction.
- Another strategy to reduce the crack propagation rate is the introduction of compressive residual stresses, which requires an increase of the applied tensile stresses to propagate the crack. Sandblasting process has proven to be efficient for this.

Acknowledgments

Part of the research leading to these results has received funding from the European Commission, Research Fund for Coal and Steel, under the grant agreement RFSR-CT-2015-00018 (iCUT project). Authors want to thank all consortium members for their collaboration and expertise.

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