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The effect of microstructure on the sheared edge quality and hole expansion ratio of hot-rolled 700 MPa steel

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Abstract. The effects of microstructure on the cutting and hole expansion properties of three thermomechanically rolled steels have been investigated. The yield strength of the studied 3 mm thick strip steels was approximately 700 MPa. Detailed microstructural studies using laser scanning confocal microscopy (LCSM), FESEM and FESEM-EBSD revealed that the three investigated materials consist of 1) single-phase polygonal ferrite, 2) polygonal ferrite with precipitates and 3) granular bainite. The quality of mechanically sheared edges were evaluated using visual inspection and LSCM, while hole expansion properties were characterised according to the methods described in ISO 16630. Roughness values (R_a and R_z) of the sheet edge with different cutting clearances varied between 12 µm to 21 µm and 133 µm to 225 µm, respectively. Mean hole expansion ratios varied from 28.4% to 40.5%. It was shown that granular bainite produced the finest cutting edge, but the hole expansion ratio remained at the same level as in the steel comprising single-phase ferrite. This indicates that a single-phase ferritic matrix enhances hole expansion properties even with low quality edges. A brief discussion of the microstructural features controlling the cutting quality and hole expansion properties is given.

1. Introduction

Increasing demands for safety, reduced fuel consumption and emissions in the automotive and transportation industry have led to the increased use of high performance materials in the last two decades. The most used solution has been high strength steels (HSS) as they provide an excellent combination of weight saving potential and cost efficiency. Higher strength allows the use of thinner wall thicknesses and lighter designs. High strength steels are also advantageous price-wise compared to alternative material choices like aluminum or composites, which provides cost efficiency in part production. However, increasing strength usually means lower ductility and huge efforts have been made to develop the formability of HSS.

In this paper, the research has been concentrated on thermomechanically rolled 700 MPa yield strength steels, which are often applied to the suspension parts of automobiles. These parts are usually cold formed and the manufacturing process includes shear cutting and flanging. Problems often arise when the sheared edges are stretched during pressing as they are prone to crack formation. The edge crack sensitivity is affected by the microstructure [1-2] and the cut edge quality [3-5]. It is well known that dual phase steels have poor stretch flanging properties while single-phase ferritic steels show better local deformation ability [1],[6]. On the other hand, hot-rolled single-phase precipitation hardened steels in this strength level often show a tendency to splitting in the sheared edges, which decreases the edge formability [7].

This paper reports the cut edge quality and stretch flangeability of three different hot-rolled 700 MPa steels and discusses the metallurgical factors affecting them.

2. Experimental

The three investigated thermomechanically rolled steels consist of 1) essentially single-phase polygonal ferrite (steel SP1), 2) essentially single-phase ferrite containing precipitates (steel SP2) and 3) a multiphase microstructure containing ferrite, bainite and martensite (steel MP). Tensile tests were carried out at room temperature in accordance with the European standard EN 10002 with the tensile axis in the rolling direction (RD).

2.1. Microstructure

General characterization of the microstructures was performed on Nital etched specimens with a laser scanning confocal microscope (LSCM) and a field emission scanning electron microscope (FESEM) (Ultra plus, Zeiss). Electron backscatter diffraction (EBSD) measurements were used to generate texture and grain size data using the Oxford HKL acquisition and analysis software. The FESEM for the EBSD measurements was operated at 15 kV and the step size was 0.3 μm.

2.2. Cutting

Cutting tests were carried out at room temperature in an Aliko mechanical cutting machine with the knife-edge parallel to both the transverse and rolling directions. The cutting clearances (i.e. percent of the sheet thickness) were 0.1 mm (3.3%), 0.3 mm (10%), 0.4 mm (13.3%) and 0.6 mm (20%). After cutting, the quality of the cut edge surface was examined visually and roughness measured by using LSCM ISO 4287:1997.

2.3. Hole expansion

Stretch flangeability is typically measured by conducting hole expansion (HE) tests. Tests were carried out in Lapland University of Applied Sciences with an Erichsen formability research testing machine (model 145-60) according to ISO 16630:2009. The HE test consists of two steps. The first step is punching a pre-hole at 10 mm/min punch speed using a tool with the correct clearance (inside diameter 10.7 mm) according to the standard. The second step is the forcing of a conical expanding tool into the pre-punched hole at 15 mm/min until any crack extends through the test piece thickness. The test operator stops the test the instant this occurs by continually following the progress of the test. The sheet holder force was 200 kN in both steps. The limiting hole expansion ratio is obtained by measuring the expanded hole in two perpendicular directions and expressing the increase in hole diameter as a percentage of the original hole diameter as described in the standard.

3. Results and discussion

Tensile properties of the studied steels are presented in Table 1. It can be seen that the strength level is extremely similar for all steels while total elongation is slightly higher in single-phase steels than the multiphase steel.

Table 1. Tensile properties of investigated steels.

Steel	Yield strength (MPa)	Tensile strength (MPa)	Total elongation (%)
SP1	724	805	23
SP2	738	853	19
MP	729	876	17

3.1. Microstructure

Steels SP1 and SP2 consist of mainly polygonal ferrite and small cementite carbides (Figures 1a-b). Steel MP shows a more complex microstructure including ferrite, bainite and martensitic islands (Figure 1c). The effective grain sizes (i.e. grains contained within high-angle grain boundaries (>15°)) were 2.3 (±0.06) μm, 3.1 (±0.11) μm and 1.8 (±0.06) μm in SP1, SP2 and MP, respectively. The same relative coarseness of the microstructures is apparent from the FESEM micrographs in Figure 1. The grain morphology is equiaxed in SP2 and convex-like in SP1 while in steel MP it is elongated into pancaked grains.

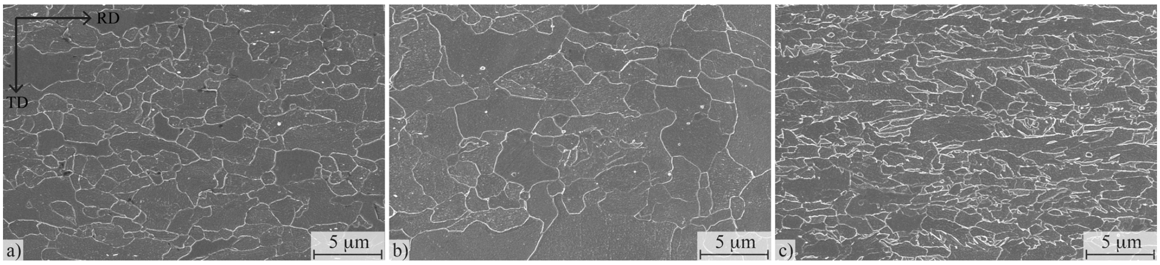

Figure 1. Typical FESEM micrographs of steels a) SP1, b) SP2 and c) MP.

The transformation texture at the sheet centrelines are shown in Figure 2. Strong {113}<110>, {112}<131> and {554}<225> components are present due to ferrite forming from heavily pancaked austenite with the strongest intensities in steel MP, Figure 2c. Although lower than can be found in cold-rolled materials, the texture component intensities are relatively high for hot rolled sheet.

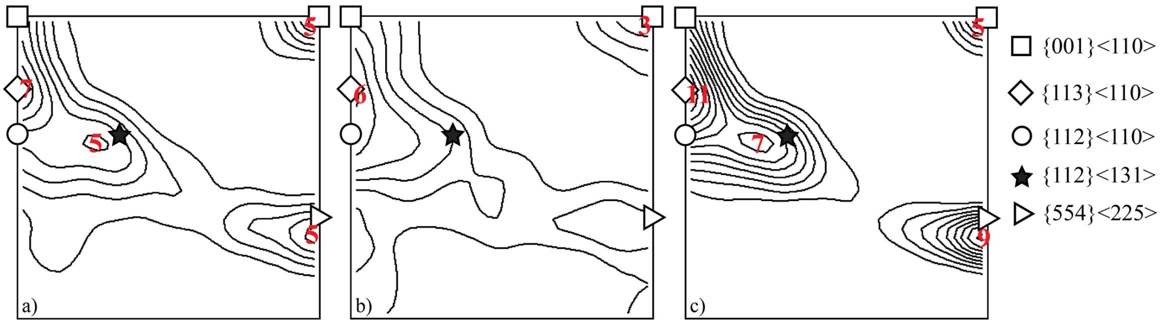

Figure 2. ϕ_2=45° ODF sections illustrating the centerline texture of the a) SP1, b) SP2 and c) MP steel. (Levels: 1, 2, 3…)

3.2. Cutting

Figure 3 shows the effect of cutting clearance on the quality of the longitudinally cut edges. There were insignificant differences in the quality of the cut edges between the longitudinal and transverse cuts so the results in Figure 3 are applicable irrespective of cutting direction. Cut edges typically show several zones on the edge face known as rollover, shear zone, fracture zone and burr [8]. It can be seen that the roughness of the fractured zone of steel MP is less sensitive to changes in cutting clearance than steel SP. The profiles of the fractured zones were mapped with a laser scanning confocal microscope in order to form 3D maps (Figure 3) and evaluate surface roughness values R_a and R_z, which are presented in Figure 4. The results in Figure 4 confirm the visual observations that steel MP is more robust than the SP steels with regard to the effect of clearance on fracture surface roughness. One factor which might affect the edge surface quality is the grain size, which is very small in steel MP that has the finest cut edges. The robustness of edge quality against variations in tool clearance can be very important in industrial practice as the cutting clearance tends to change due to tool wear in the workshop.

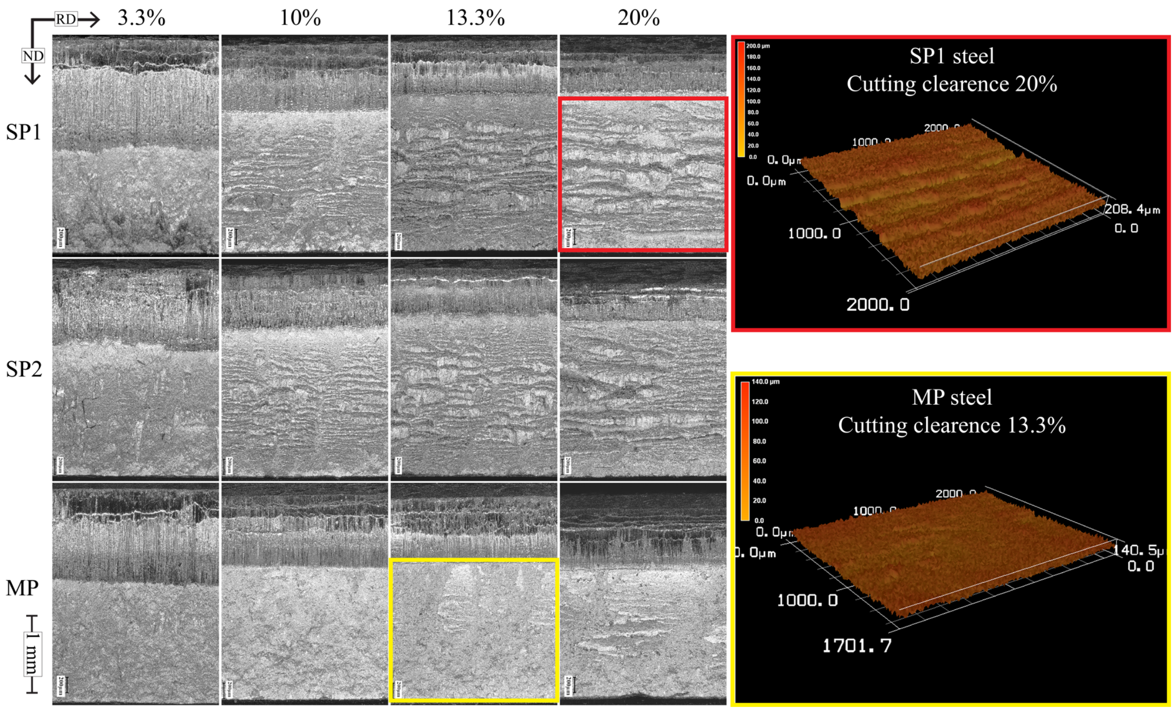

Figure 3. LSCM images of the longitudinally sheared edges and 3D maps of fractured zone surfaces.

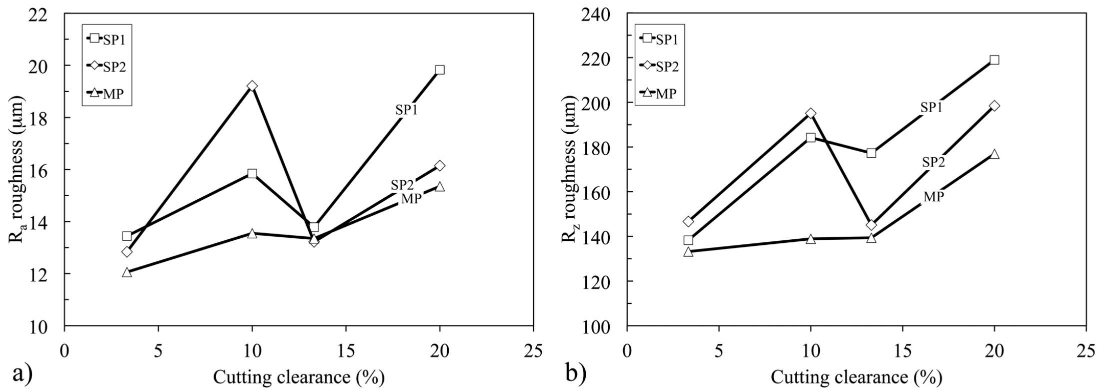

Figure 4. Roughness a) R_a and b) R_z values of fractured zone using LSCM ISO 4287:1997.

It should be noted that the cut edges of steel SP1 contained severe local splits (Figure 5) that were not located within the 3D surface roughness measurement areas. Edge splitting can deteriorate formability significantly. Splitting has been noticed in ferritic steels, for example when carbides are located on grain boundaries and the ferrite grains are elongated [7]. The splits propagate very easily along the weakened carbide enriched grain boundaries. Steel SP1 has carbides on the ferrite grain boundaries and a somewhat elongated convex-like grain morphology which can together lead to splitting. In comparison, steel SP2 has an equiaxed grain morphology which can prevent severe splitting [7].

Figure 5. Splitting of the sheared edge in steel SP1

In addition to the above mentioned zones on the cut edge surface, the punching and shearing processes also generate plastic deformation and work hardening in the steel beneath the edge face. This deformed, shear affected zone (SAZ) can affect the stretching properties of the edge [9]. According to Mori et al. [3] the hole expansion ratio decreases as the maximum hardness of the cut edge is increases. Figure 6 shows hardness profiles as a function of distance below the cut edge faces. It is evident that work-hardening takes place close to edge face increasing the hardness from 330 HV0.1 to 400-475 HV0.1. Steel SP2 has lower maximum hardness than SP1 and MP. The width of the SAZ is about 0.8 mm and 0.45 mm for steels MP and SP, respectively. Also steel MP has generally higher hardness values in the SAZ than the SP steels indicating overall more work-hardening in the SAZ of steel MP even though the maximum hardness is smaller than that shown by steel SP2. When comparing steels SP1 and SP2, it is evident that close to edge face steel SP2 has a smaller hardness gradient than SP1.

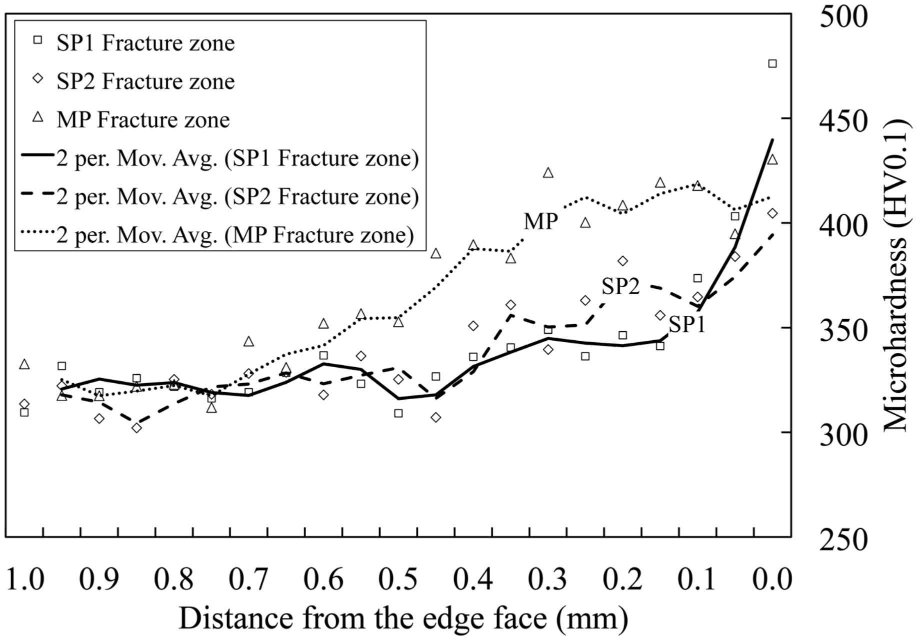

Figure 6. Microhardness values behind the sheared edge face.

3.3. Hole expansion

Hole expansion ratios for steels SP1, SP2 and MP were 28.7%, 40.5% and 28.4%, respectively. It is well known that the ISO HE test can have large scatter between the test results even with the same material and machine [10]. Therefore, the 95% confidence interval was analyzed with Minitab® software, which gave the interval plot shown in Figure 7. It can be seen that the SP steels show larger scatter than steel MP. This is probably due to the enhanced robustness of sheared edges of steel MP. However, it is clear that steel SP2 has a statistically significantly better HE ratio than steels SP1 and MP.

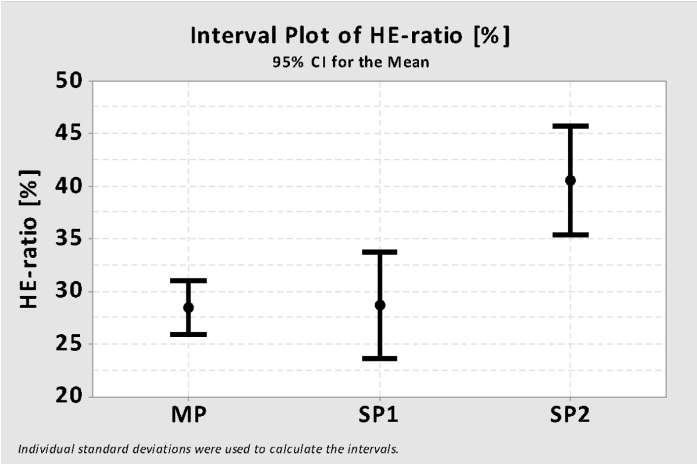

Figure 7. Mean HE ratios with 95% confidence intervals for the means.

3.4. Factors affecting hole expansion ratio

When considering the tensile properties, it is evident that total elongation does not correlate with HE ratio: while steel SP1 has the highest total elongation, it has the lowest HE ratios.

Mean surface roughness R_a (Figure 4) does not seem to give a very good estimate of hole expansion properties, as has also been observed by Mori et al. [3]. On the other hand, Mori et al. [3] suggested that maximum surface height difference in the cut edge gives better correlation to stretch flangeability. Hence, the R_z values are also presented in Figure 4, however no correlation is apparent. This is most probably due to the fact that while Mori et al. [3] made the surface measurements over the whole cut edge, including the boundary of the sheared and fractured zones where the largest height differences were found, in this study only the fractured zone was measured for R_z.

The highest HE ratio of steel SP2 might be explained by the fact that, despite having the same base material hardness, its SAZ has the lowest maximum hardness of all the studied steels. This should leave more work-hardening and deformation capacity to accommodate the straining occurring during the edge forming. This is also in line with Mori et al. [3] who also found a correlation between maximum hardness and HE ratio. Furthermore, the hardness profile in the SAZ of steel SP2 changes gradually away from the edge face. This is important during localized deformation preventing strain "hot spots" and delaying cracking.

FESEM investigations were carried out for the expanded samples in order to understand the cracking mechanisms and the most critical factors in the steel microstructure during stretch flanging. As is well known, void formation during deformation is controlled by microstructural factors like carbides, inclusions and phase boundaries [11-12]. Especially DP steels show only moderate HE properties due to decohesion of the soft ferrite and hard martensite phases during the local deformation generated by the HE test. On the other hand, single-phase ferrite or bainitic ferrite is known to perform well in hole expansion due to its high local deformation capacity [1-2].

Microstructures in the deformed area near the punched and expanded hole are shown in Figure 8. It is evident that steels SP1 and SP2 show a very high degree of deformation in the ferrite matrix and small void formation in the vicinity of cementite particles (Figures 8a-b). Steninger and Melander [13] have also seen that cementite particles nucleate voids in ferritic steels.

Steel MP also exhibits a very high degree of deformation in the multiphase structure. Also the carbon enriched islands can be seen to have taken up significant plastic strain, although some secondary small voids were found at the phase boundaries (Figure 8c), like those found in DP steels. However, the void formation and decohesion is not as severe as that seen in DP steels as the carbon enriched islands can be seen to have a large deformation capacity without void formation. Presumably, this is because the hardness difference between the matrix and the carbon enriched islands is smaller than that in DP steels [14]. This implies that the ferrite phase is more bainitic in character with a higher hardness than polygonal ferrite. Alternatively, or additionally, the martensite or MA islands are softer than those typically found in DP steels [15].

In all the studied steels, severe voids were found in the vicinity of TiN inclusions (Figures 8d-f). These voids occur as a result of decohesion between the ferritic matrix and the hard nitrides (Figure 8d). Decohesion takes place because the hard TiN does not deform, which leads to shear localization and void formation in the boundary area [11]. It is also evident that voiding intensifies when TiN inclusions crack into smaller fragments (Figures 8e-f).

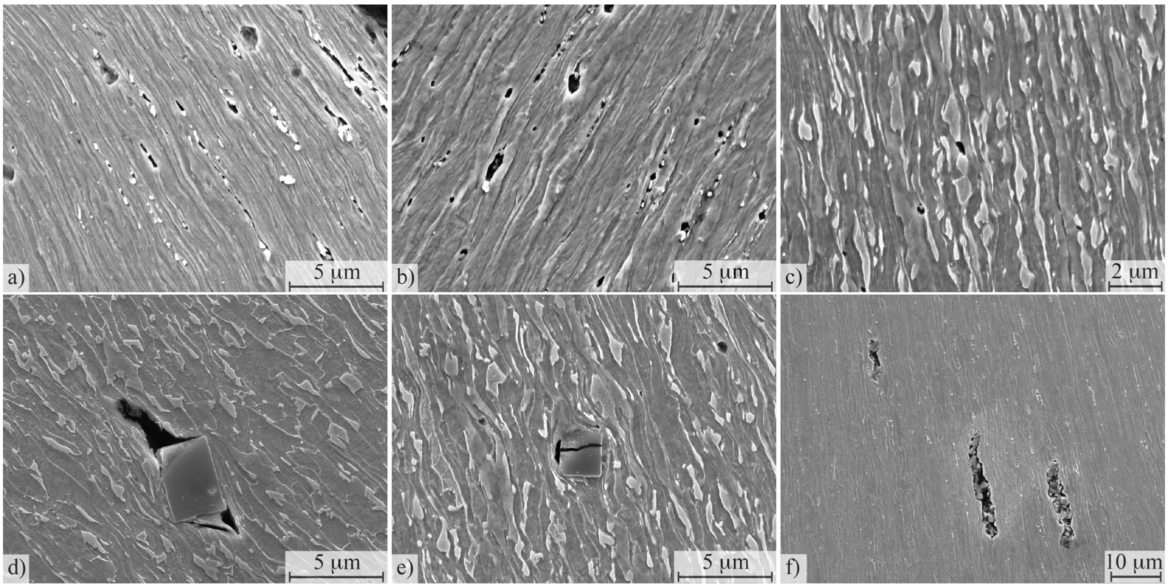

Figure 8. FESEM micrographs from deformation area of expanded samples a) SP1, b) SP2, c) MP, d) MP TiN, e) MP cracked TiN and f) SP1 fractured TiN.

4. Summary

When targeting as good stretch flangeability as possible, it is important to understand the factors affecting edge formability. In this paper three different thermomechanically hot-rolled steels with yield strengths of 700MPa were investigated. Mechanical shearing and hole expanding tests were carried out in order to find out the effect of microstructure and cut edge quality to stretch flangeability.

According to the results, it is preferable to have an equiaxed single-phase ferritic microstructure, which can withstand large local strains. Additionally, it is important to eliminate secondary particles like TiN inclusions and cementite, which act as void nucleation sites. Therefore, precipitation strengthening should be done with small homogeneously distributed precipitates, which are not concentrated in the grain boundaries in order to prevent splitting tendency. Furthermore, work hardening of the SAZ during mechanical shearing should be as little as possible to ensure enough remaining deformation capacity for edge forming, as in the case of steel SP2. It has been found that the quality of the sheared edges affects the scatter of the HE test results and the robustness of the material to changes in cutting clearance: the finest edge quality and robustness was achieved with steel MP, which implies that a very small grain size is beneficial in shearing.

Acknowledgements

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