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A Characterization of the Impact Toughness of Hot-rolled HSLA Steel

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Abstract

Due to the wide use of HSLA steels in difficult conditions, e.g. at low temperatures, it is extremely important to test the impact strength of these steels. This is equally important because most of those structures are made by welding these steels, and the welding process itself has a significant impact on the properties of joints and welding zones. In this work, the authors analyzed two selected representative HSLA steels rolled in the Krakow branch of ArcelorMittal Poland S.A. – the only place in Poland where HSLA steels in the form of hot-rolled strips can be produced on an industrial scale. Impact tests were performed in accordance with technical acceptance standards, and then the fracture surfaces after impact tests were characterized using light and scanning microscopy. In the next part of the work, a set of previously gathered data were analyzed to determine the influence of thermomechanical rolling process parameters on the level of impact strength and the influence of chemical composition on it.

Keywords:

HSLA steel, thermomechanical rolling, impact toughness, mechanical properties, microstructure

1. INTRODUCTION

High-strength low-alloy steels (HSLA) are well-known and widely used in a variety of structures such as automotive components, transmission pipelines, and marine structures. These structures often operate in severe weather conditions or at sub-zero temperatures. It is therefore essential that these steels have high impact strength and a ductile to brittle transition temperature at low temperatures. These structures are very often created with the use of welding, which also has a significant impact on the properties of the steel [1–4]. Impact tests for HSLA steels are therefore used very frequently in industrial practice as technical acceptance tests. One of the most common impact tests is the Charpy test [5].

From a scientific point of view, the study of impact toughness is equally important, with researchers often attempting to determine what influences the amount of impact. The authors [6, 7] pointed out that the impact strength of HSLA steel type S460 is not uniform but depends on the material microstructural anisotropy and texture. Technical acceptance tests are carried out according to the standard in one direction only and usually at the temperature of −20°C, sometimes −40°C. In order to get a broader characterization of the material, it is useful to carry out tests at the temperature of 0°C and other rolling directions, for example. The paper [6] shows that impact strength decreases with decreasing temperature, but the decrease in impact strength is very testing direction dependent – the difference between the impact strength of the material tested in rolling direction (RD) and the transverse direction (TD) can be as high as 40 J.

The strength of the steel depends largely on the microstructure, as discussed in papers [8–10]. It has been pointed out that the same HSLA steel, but with a variable final microstructure – ferritic, bainitic or martensitic – has different strength properties and therefore a different level of impact strength. Moving from ferrite to bainite to martensite, the grain size becomes finer and finer, and the yield strength increases by up to 100%, but the steel becomes more brittle – the impact strength can drop by up to 150 J for a similar chemical composition at the same testing temperature.

From an industrial point of view, it is not only the microstructure that has a strong influence on the impact strength of steel. As shown in [11, 12], the thermomechanical process parameters are also important. Particular attention was paid to the finish rolling temperature (FRT). In this study, the authors showed that the best results in terms of impact toughness can be obtained by rolling just above the Ar_3 (austenite to ferrite transformation) temperature, which in that case was about 820°C. Additional normalization after the process helped to achieve the best impact properties of the several variants analyzed. In [10], attention was also paid to the occurrence of MnS. The effect of these inclusions on the upper shelf energy (USE) of the steel was found to be pronounced. However, a well-chosen deformation path (FRT + normalization) makes it possible to practically neglect the influence of these harmful inclusions. Attention to MnS inclusions and their influence on impact toughness was also described in [13]. The authors pointed out that the presence of these sulphides is the main reason for the resulting impact anisotropy in HSLA steels.

The only place in Poland where HSLA steels can be produced in the form of hot-rolled strips is the rolling mill of ArcelorMittal Poland S. A. in Krakow. In this study, the authors decided to characterize two selected representative HSLA steels rolled in the Krakow rolling mill from the point of view of impact toughness, and then analyze the set of previously gathered data. Based on this information, it would be possible to check whether the process parameters and the basic composition have an influence on the impact strength of the investigated steels.

2. MATERIALS AND METHODS

Two representative steel grades were chosen to characterize hot rolled HSLA steel. The grades were given the working codes S1 and S2. The chemical compositions of these two grades are shown in Table 1. The chemical composition was analyzed using atomic emission spectroscopy (AES). Charpy impact test specimens were prepared from both selected steels. The specimens were cut in the rolling direction (RD) and transverse to the rolling direction (TD) according to the scheme presented in Figure 1. A V-shaped notch was cut on the surfaces of selected specimens. The tests were carried out on a Charpy hammer with an initial energy of 450 J and a hammer rounding radius of 2 mm. The tests were performed at the temperatures of 0°C, −20°C and −40°C, with a series of tests for each temperature to have the average of the results.

Table 1
Chemical composition of the investigated steels

Steel	C_{avg} [wt.%]	Mn_{avg} [wt.%]	Nb_{avg} [wt.%]	Ti_{avg} [wt.%]	V_{avg} [wt.%]
S1	< 0.07	< 0.90	< 0.04	< 0.01	< 0.01
S2	< 0.08	< 1.00	< 0.06	< 0.04	< 0.01

After the test, the analyses of the fracture surfaces of the samples were also carried using SEM. In addition, specimens for metallographic observations were prepared from the selected steels to characterize the microstructure of the material. The samples were embedded in resin, etched with 2% Nital solution and the microstructures were then analyzed using a Leica metallographic optical microscope.

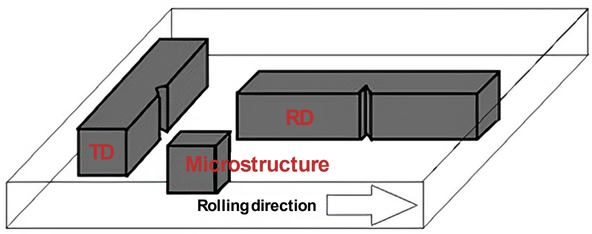


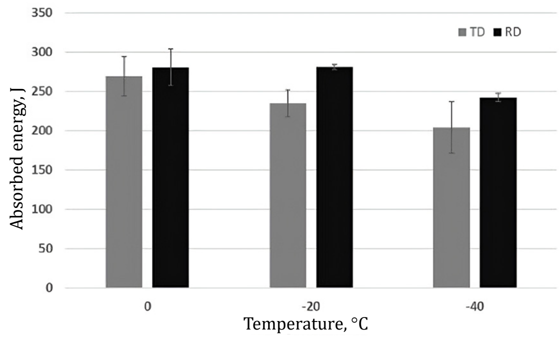
Fig. 1. Scheme of sampling in relation to the rolling direction

The second part of the study focused on the statistical analysis of data from the real, industrial process. Several sets of industrial impact tests performed according to the acceptance standards were analyzed. The samples were correlated with the chemical composition of the individual melts and also with the basic parameters of the thermomechanical rolling process – austenitizing temperature, average end-of-rolling temperature and average coiling temperature. Also analyzed were the influence of the chemical composition on the impact strength of selected HSLA steels and the influence of selected rolling process parameters.

3. RESULTS AND DISCUSSION

A series of Charpy impact tests were carried out for both of the analyzed steels. The results are shown in Figure 2a, b for S1 and S2 steels respectively. For both steels, specimens cut out along the rolling direction show higher fracture work than for the TD direction. For S1 steel, the differences in this parameter between the RD and TD directions are slightly smaller than for S2 steel. In the temperature range investigated, a decrease in impact toughness is observed for both S1 and S2 steels, but there is no sharp decrease in properties and thus it can be concluded that these steels do not exhibit brittle fracture in the temperature range investigated and the ductile to brittle transition temperature is below −40°C. For S2 steel tested at the TD direction at the temperature of −20°C, a slight increase in absorbed energy can be observed, but the scatter of results is considerable, and it can be concluded that there is a downward trend in impact strength here as well, as discussed above. The significant difference in absorbed energy between steel S1 and S2 is due to the geometry of the sample. Full-sized test pieces, i.e. with a cross-section of 10 mm × 10 mm, were made from S1 steel. Reduced test pieces, i.e. with a cross-section of 10 mm × 5 mm, were made from S2 steel due to its manufactured thickness.

a)



b)

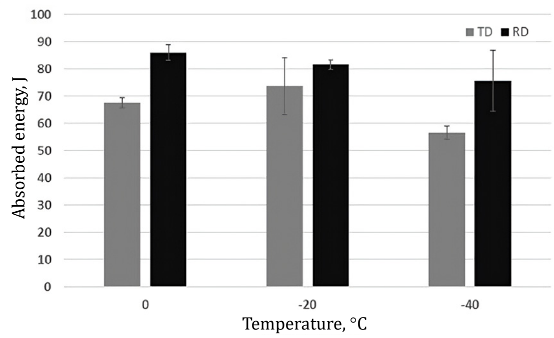


Fig. 2. Charpy impact test results for: a) S1 steel; b) S2 steel

The analysis of the fracture surfaces performed on SEM showed that the surfaces have the characteristics of ductile fracture with small areas of brittle ones. The areas of brittle fracture increase with decreasing temperature and with increasing Ti content in the steel. The fracture surfaces for both steels have characteristic dimples with manganese sulphide beads in them (see Fig. 3). The microstructures of two steels were also analyzed (Fig. 4). Both are ferritic-pearlitic, with finer grain in the S2 steel. Fainer grain size appears in the steel containing more Ti, because titanium parts block grain growth during recrystallisation. This structure is conducive to higher strength properties, but also results in a decrease in impact strength, which can be seen both in the case of the tests carried out and in the observed fracture surfaces.

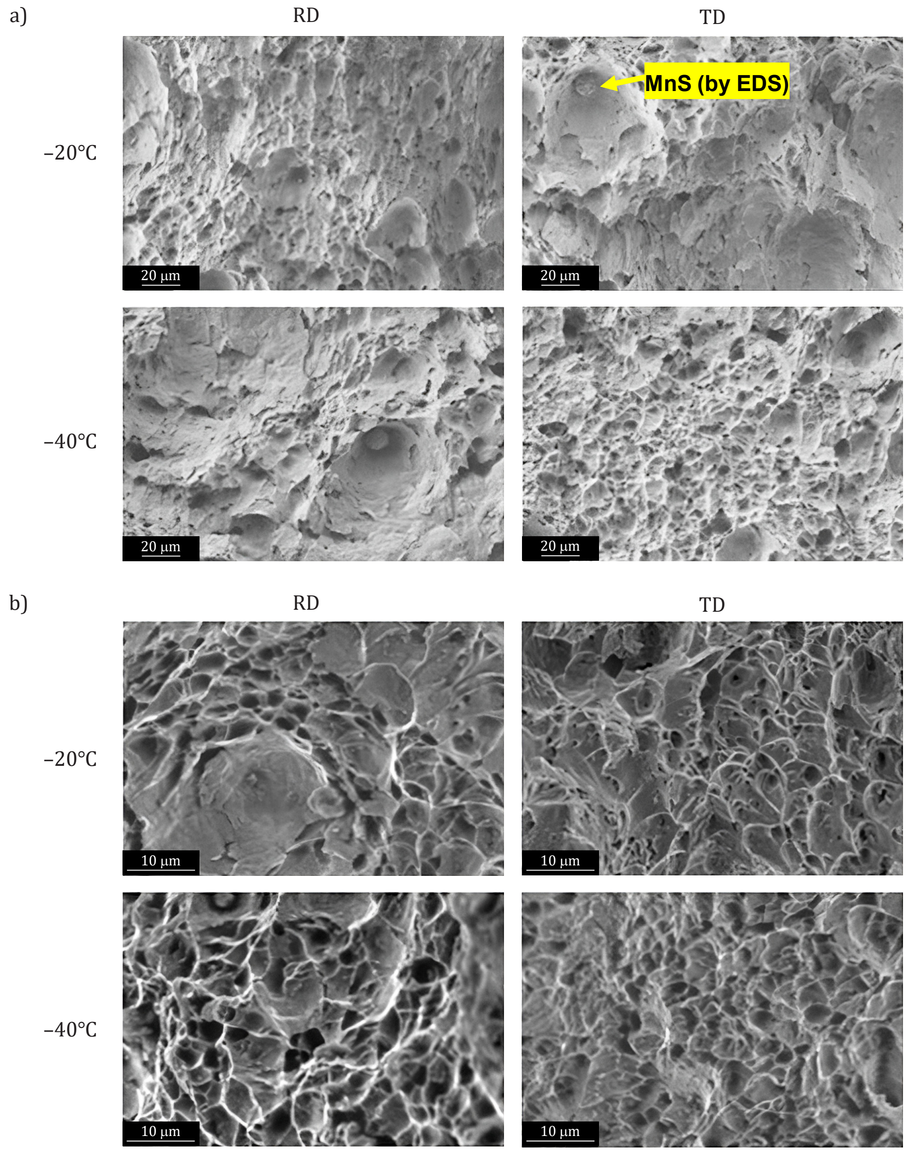


Fig. 3. Representative images of fracture surfaces taken using SEM for: a) S1 steel; b) S2 steel

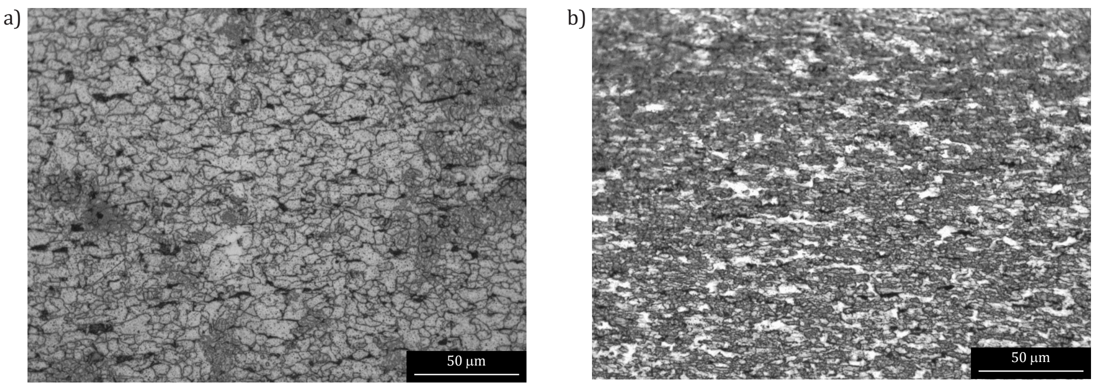


Fig. 4. Microstructures of the investigated steels: a) S1 steel; b) S2 steel

The first part of the study was aimed at characterizing the impact toughness for two selected representative steels produced at the Krakow rolling mill. The study was based on technical acceptance tests and was carried out in accordance with the technical standards for thermo-mechanical steels. In the second part, however, the focus was on process analysis through statistical data. Several hundred results from technical acceptance tests carried out over several recent years were collected. In order to focus on specific, selected steel grades and thicknesses, the data was limited to the previously discussed S1 and S2 steels of selected thicknesses. First, it was investigated whether the basic parameters of the thermo-mechanical rolling process have an influence on the level of impact strength. The effects of austenitizing temperature, average rolling end temperature and average coiling temperature were analyzed. For S1 steel – a steel based on micro Nb additives – no high correlation between process parameters and impact strength was found. For S2 steel, no strong correlation was found, but here it can already be seen that the austenitizing temperature or the average coiling temperature have a greater influence on impact strength. For S2 steels, a reduction in austenitizing temperature was found to increase the level of impact strength. The R^2 value is about 0.22, which is not high, but has the highest impact of the analyzed parameters (see Fig. 5).

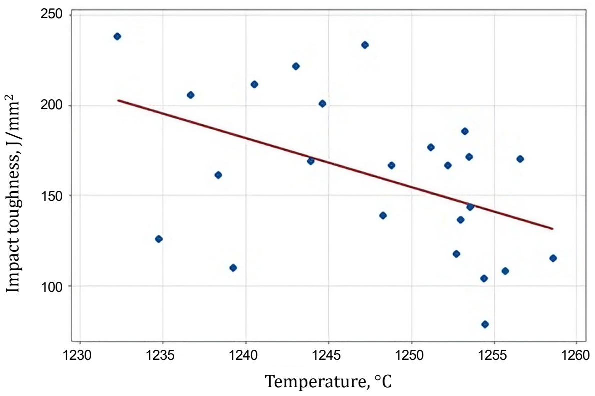


Fig. 5. Correlation between austenitizing temperature and impact toughness for S2 steel

A greater influence of process parameters on the level of impact strength could be expected. However, the small effect found is probably due to the stability of the process. Differences in e.g. average coiling temperature of 10°C do not have a significant impact on impact toughness. To investigate the influence of individual parameters in more detail, the tests would have to be carried out in which the parameters under consideration were varied by more than a few degrees.

Taking into account the analysis of the process parameters, the effect of the individual elements on the impact toughness was also analyzed. For both steels, the influence of basic elements such as C, Mn or Si, micro-additives, other alloying elements or other elements such as S or P, was examined. For both steels analyzed, no clear effect of the elements on the level of impact toughness was found. Here again, this is most likely due to the low variability of the data.

4. CONCLUSIONS

Summarizing the research carried out, the following conclusions can be drawn:

- both steels meet the requirements imposed by the technical standards with regard to the level of impact toughness at negative temperatures;
- both S1 and S2 steels have a ductile to brittle transition temperature below the analyzed temperature of −40°C;
- fracture surfaces after the impact test mainly display their ductile characteristics;
- characteristic globular inclusions of manganese sulphides can be observed on the fracture surfaces, which promote brittleness, but the inclusions are small and strongly dispersed;
- the addition of titanium in these steels favors the refinement of the final microstructure of the product;
- both the basic parameters of the thermo-mechanical rolling process and the chemical composition do not have a significant effect on the level of the impact toughness, at least in the temperature range analyzed.

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