UDK 539.42:621.77.014.2
Professional article/Strokovni članek

ISSN 1580-2949
MTAEC9, 47(3)385(2013)

INFLUENCE OF SAMPLE DIRECTION ON THE IMPACT TOUGHNESS OF THE API-X42 MICROALLOYED STEEL WITH A BANDED STRUCTURE

VPLIV USMERJENOSTI VZORCEV NA UDARNO ŽILAVOST MIKROLEGIRANEGA JEKLA API-X42 S TRAKAVO MIKROSTRUKTURO

Ahmadreza Salimi[1], Hossein Monajati Zadeh[1], Mohammad Reza Toroghinejad[2], Davod Asefi[1], Amir Ansaripour[1]

[1]Department of Materials Engineering, Najafabad Branch, Islamic Azad University, P.O. Box 517, Isfahan, Iran
[2]Department of Materials Engineering, Isfahan University of Technology, Isfahan, Iran
salimy.ahmadreza@gmail.com

Prejem rokopisa – received: 2012-08-13; sprejem za objavo – accepted for publication: 2012-10-23

The layering of a microstructure parallel to the direction of the material flow during the hot working process is called banding. In the present paper, the severity of ferrite-pearlite banding in the API-X42 microalloyed steel and its effects on the impact energy are studied. Specifically, the impact toughness is examined in the cases of banded and non-banded samples along two directions, perpendicular and parallel to the rolling, and the obtained results are compared. Metallographic examinations, together with the Charpy impact tests at 0 °C and –18 °C, were done for both directions, parallel and perpendicular to the rolling. The results showed a dependence of the impact energy on the sample direction relative to the rolling to be larger with the banded than the non-banded sample. The difference between the impact energies for the directions parallel and perpendicular to the rolling was also noticed to be caused by the increasing anisotropy index.

Keywords: API-X42 steel, pearlite-ferrite banding, impact energy

Usmerjanje mikrostrukture vzporedno s smerjo vročega preoblikovanja se imenuje trakavost. V članku je predstavljena študija preprostosti feritno-perlitnih pasov v mikrolegiranem jeklu API-X42 in njihov vpliv na udarno energijo. Specifično je primerjana udarna žilavost med vzorci s trakavo in netrakavo mikrostrukturo vzdolž dveh smeri, pravokotno in vzporedno s smerjo valjanja. Opravljene so bile metalografske preiskave in udarni preskusi Charpy pri 0 °C in –18 °C vzporedno in pravokotno na smer valjanja. Rezultati so pokazali odvisnost udarne energije glede na usmerjenost vzorca pri valjanju, relativno bolj v trakavih kot v netrakavih vzorcih. Pri naraščajočem indeksu anizotropije je bila opažena razlika med energijo udarca pri vzporedni in pravokotni smeri valjanja.

Ključne besede: jeklo API-X42, perlitno-feritni trakovi, udarna energija

1 INTRODUCTION

The layering of a microstructure parallel to the direction of the material flow during the hot working process is called banding. Generally, banding is classified into two major categories. The microscopic bands include deformation bands, transformation bands and shear bands, and the macroscopic bands include carbide banding in tool steels, layered ferrite-pearlite structure of rolling in low-carbon alloy steels and martensite banding in heat-treated alloy steels.[1–4] Because of these various micro and macro features, there is no universally accepted definition of banding. Moreover, there are clearly various mechanisms that can cause these structures.

Ferrite-pearlite banding may occur due to a segregation of some alloying elements during solidification after casting and hot-working processes.[5] When steel is slowly cooled from the austenite region, the pro-eutectoid ferrite is formed initially in the areas with a relatively low number of austenite-stabilizing elements, whereas pearlite is formed in the areas with more austenite-stabilizing elements after being cooled down to the temperatures below the eutectoid line, creating a banded microstructure containing successive pearlite and ferrite areas.[6]

There have been several studies on the effect of banding on mechanical properties[7–9]. Working on heavily banded 0.3 % carbon steel, Jatczak et al.[10] found little or no effect on the anisotropy of tensile properties, while a significant anisotropy of the reduction in area and impact properties was discovered. They also observed a very small change in mechanical properties in longitudinal direction as well as in impact properties and ductility in transverse direction due to homogenization.

Grange[11] found that both banding microstructure and longitudinally directed inclusions cause anisotropy in the mechanical properties of 0.025 % C and 1.5 % Mn steel, eliminating the decrease in anisotropy caused by banding; however, this decrease is trivial if numerous inclusions are elongated in longitudinal direction. In some studies, the effect of banding and specimen orientations on the fracture toughness has been investigated and it has been shown that banding has a significant effect on the rolling-plane anisotropy.[12–14] However, little has been done to examine the differences between banded and non-banded samples in different directions.

In the previous researches, the samples with a banded structure were selected, and after the study of structural and mechanical properties, the same steel was heat treated, by normalizing or annealing it, to remove microstructural banding.[2–15] The potential problem of this method is that this treatment makes it possible to prepare samples of the same steel in a virtually non-banded versus severely banded conditions; however, the differences in the chemical-composition distribution, grain size and inclusion morphology during heat treatment are inevitable. So, they can affect the accuracy of the results. In this study, the impact properties of several API-X42 steel samples with different bandy degrees of the ferritic-pearlite structure after hot rolling have been investigated. No heat treatment was done on the samples to reduce the banding phenomenon.

2 EXPERIMENTAL PROCEDURE

In this study, the initial production data of 50 samples of the API-X42 steel were obtained. Among them, 16 samples with the same chemical composition were selected. The chemical composition in mass fractions (%) is 0.12 C, 0.905 Mn, 0.21 Si, 0.007 P, 0.003 S and 25 N (μg/g). The samples were investigated with optical metallography.

Metallographic specimens were prepared in accordance with the guidelines and recommended practices given by ASTM-E3 Methods. Their images provided by an optical microscope at the magnification of 100 and 500 were also taken.

To investigate just the banding effects and remove the other effects of metallurgical variables, samples with the same grain size and chemical composition and with very low amounts of inclusions have been selected.

The banding in API-X42 is the ferrite-pearlite banding. Hence, the banded samples and non-banded ones were separated from each other by using the Assessing the Degree of Banding or Orientation of Microstructures standard (ASTM-E1268). The anisotropy index *(AI)* was estimated from the following equation:

$$AI = N_{L\perp}/N_{L\parallel} \tag{1}$$

where $N_{L\perp}$ and $N_{L\parallel}$ are the mean numbers of the feature interceptions with the test lines respectively perpendicular and parallel to the deformation direction per length unit of the test lines. For a randomly oriented, non-banded microstructure, *AI* has a value of one. As the degree of orientation or banding increases, *AI* increases, too.

For the impact testing (according to the ASTM-E23 standard), three samples from each plate in a direction perpendicular to rolling and three samples in parallel with the rolling direction were prepared as shown in **Figure 1**. (At the state *A*, the test piece is perpendicular to the rolling direction and the notch is parallel to rolling. At the state *B*, the test piece is parallel to the rolling direction and the notch is perpendicular to rolling and the pendulum strikes the test piece in the direction parallel to rolling).

The Charpy impact tests at 0 and –18 °C were done. The amount of the absorbed energy was determined for each test piece. Finally, the mean of the three results for each temperature was reported as the final result. The fracture surface was coated with nickel to be prepared for examining the crack-propagation path in normal view of the fractured face. Nickel prevents damaging the studied fracture surface. Then the back of the broken test-piece notch was investigated with SEM microscopy.

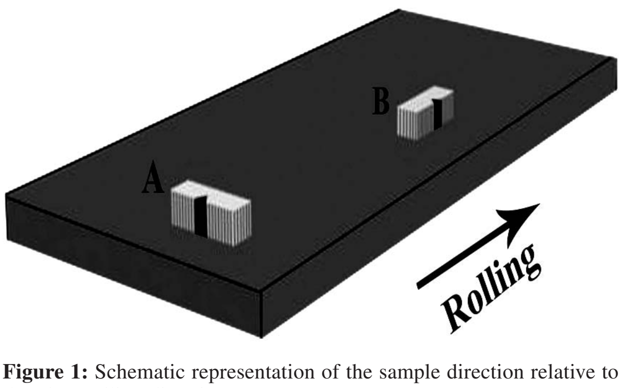

Figure 1: Schematic representation of the sample direction relative to the plate rolling direction
Slika 1: Shematski prikaz smeri vzorčenja in usmerjenost plošče glede na smer valjanja

3 RESULTS AND DISCUSSION

Figure 2 shows two metallographic images used for determining *AI* for the two cases of highly and poorly banded microstructures. The results for the classified specimens after the metallography, the anisotropy index and the impact energy, are shown in **Table 1**.

Table 1: Relationship between the impact energy and the anisotropy index for the two temperatures of 0 °C and –18 °C
Tabela 1: Odvisnost med udarno energijo in indeksom anizotropije za dve temperaturi, 0 °C in –18 °C

No. of piece	AI	Impact energy, J	
		(–18°C)	(0°C)
1A	2.07	46.4	63.0
2A	2.18	55.4	67.5
3A	1.57	67.9	72.3
4A	1.55	67.4	74.0
1B	2.07	84.0	87.9
2B	2.18	88.8	89.7
3B	1.57	78.6	83.0
4B	1.55	79.6	85.0

In accordance with the banding standard, the optimal state is achieved when *AI* is equal to 1. It means that the

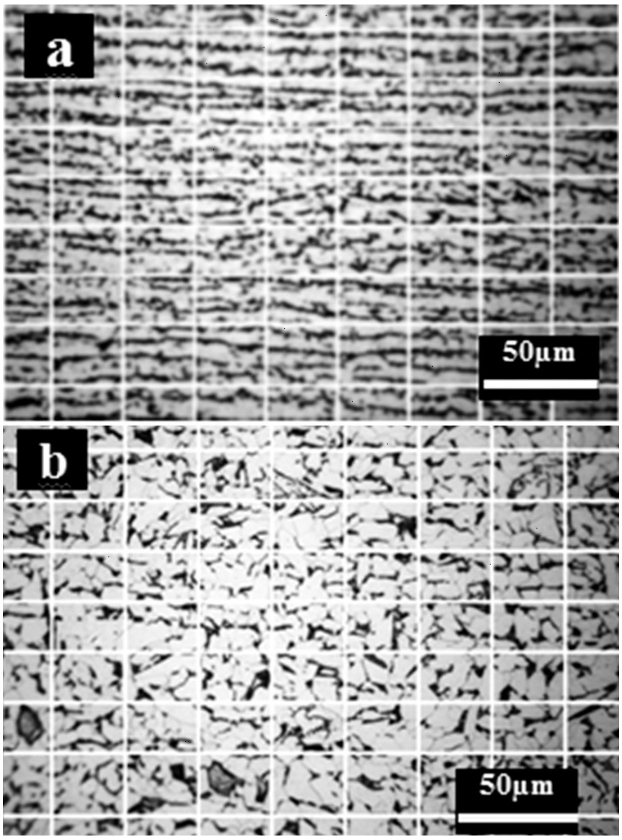

Figure 2: Two examples of a: a) banded structure and b) non-banded structure, for which the anisotropy index was determined

Slika 2: Primer: a) trakave mikrostrukture in b) mikrostrukture brez trakavosti, za katero je bil določen indeks anizotropije

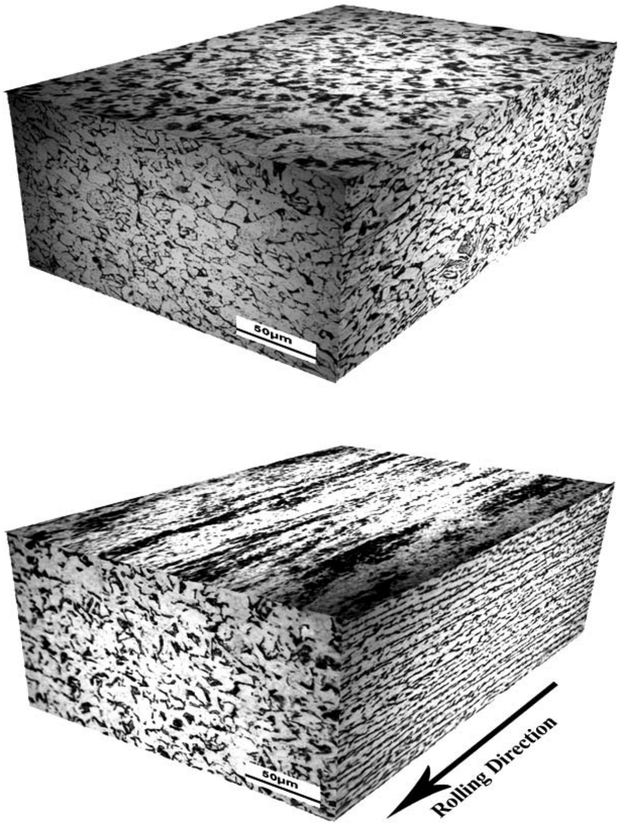

Figure 3: Three-dimensional images of metallographic samples 4A and 2B as the two samples with a low and a high *AI*

Slika 3: Tridimenzionalna slika metalografskega vzorca 4A in 2B kot dva vzorca z nizkim in visokim indeksom anizotropije *AI*

number of $N_{L\perp}$ must be equal to the number of $N_{L||}$. By increasing it to a number higher than 1, $N_{L\perp}$ is higher than $N_{L||}$, and the microstructure becomes more banded.

According to **Table 1,** all the measured values of *AI* are greater than 1. This indicates that all the samples are banded. But two series of more banded specimens containing the test pieces *1A, 2A, 1B, 2B* and two series of less banded specimens containing the test pieces *3A, 4A, 3B*, *4B* can be singled out.

Three-dimensional metallographic microstructure images of samples 4A and 2B are shown in **Figures 3a** and **3b,** respectively, as the samples with a poorly and a highly banded microstructures.

As can be seen, the banding phenomenon is more visible in the direction parallel to the rolling cross-section. The relationship between the impact energy and *AI* for the eight test pieces examined in the directions of *A* and *B*, is shown in **Figure 4**.

According to **Figure 4**, in the samples of series *A*, the impact energy is reduced with an increase in *AI*. As the samples of series *B* behave differently, an increase in *AI* causes an increase in the impact energy. About a 40 % increase in *AI* results in about a 10 % increase in the impact energy of *B* samples and about a 25 % decrease in *A* samples.

This increasing and decreasing of the impact energy caused by the increasing banding can be attributed to the crack-growth path in the banding layers of the impact sample. Schematic representations of the crack-growth paths from samples *A* and *B* are shown in **Figure 5**. According to this figure, in the *A* sample the crack

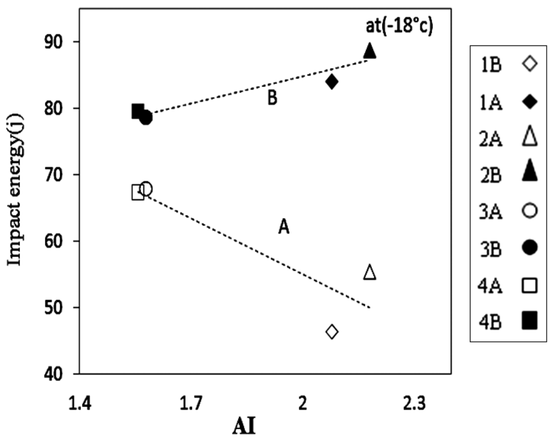

Figure 4: Dependence of the impact energy on the sample direction (A and B according to **Figure 1**) and *AI* at –18 °C

Slika 4: Odvisnost udarne energije od usmerjenosti vzorca (A in B na **sliki 1**) in indeksa anizotropije *AI* pri –18 °C moves along the path of the layers placed on each other, while in the *B* sample the crack movement is perpendicular to the layers and is encountered by different layers on its path. So, a stronger banding is more harmful for the *A* sample and more useful for the *B* sample. This is because more layers on the crack-growth path can absorb more energy.

According to **Table 1** and **Figure 3**, the *1B* and *2B* test pieces that have a high AI, absorbing more energy before the fracture, while the 3B and *4B* test pieces that have a low *AI* absorbing less energy and allowing the fracture to occur. In addition, the minimum value is related to the *3B* sample having the lowest *AI*. It means that banding can be useful to impact properties if the pendulum impact on the test piece is in the direction perpendicular to the rolling. A crack can deviate from its main path due to grain boundaries, flow lines, inclusions and banding. It can be seen in **Figure 2** that in the banded samples the distance between the ferrite and pearlite is smaller than in the non-banded samples and the crack is forced to encounter many more phases on its path. Also, the phase continuity is a more important factor in the case of highly banded samples than in the case of poorly banded samples. The reason for this is the fact that when phases are continuous, a crack is forced to encounter many more phases on its path. On the other hand, due to the discontinuity of the phases in the poorly banded samples, a crack may follow a longer path before encountering another phase. This can be better seen in **Figure 6**, which shows a SEM image of the section perpendicular to the fracture surface of sample 2. This figure implies that the crack path has been serrated while crossing the ferrite-pearlite banded structure.

The crack path on this figure is perpendicular to the plate. So, during the crossing, it has been involved with the structures of ferrite and pearlite. This caused a change in the path and can be the reason for an increase in the absorbed impact energy in *B* similar to the banded samples.

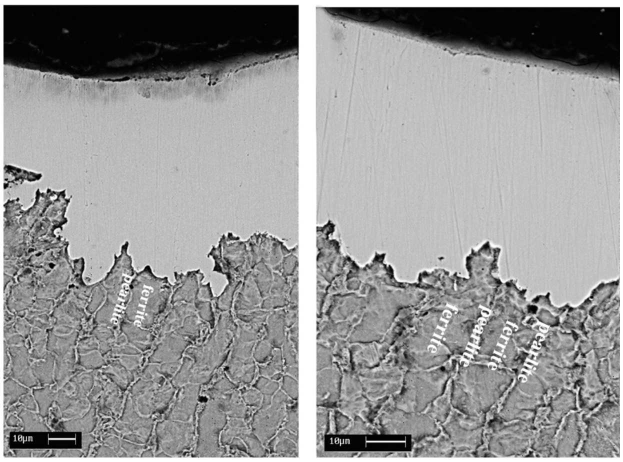

Figure 6: SEM image of a crack-growth path in the cross-section perpendicular to the fracture surface of sample 2B
Slika 6: SEM-posnetek poti rasti razpoke na preseku pravokotno na površino preloma vzorca 2B

The *A* banding structure can also be compared to a fiber composite or a composite with constant reinforcing particles, in which the reinforcing phase is located in the field phase. The fracture in the direction perpendicular to

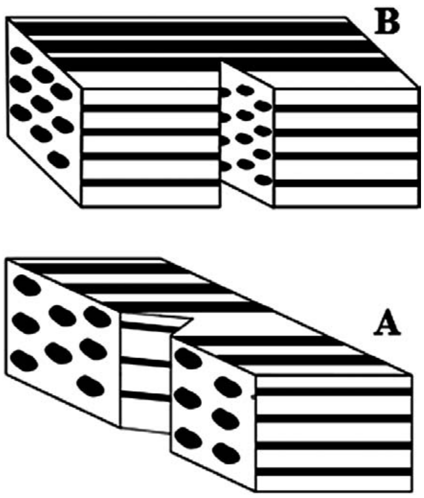

Figure 5: Schematic image representing the crack-growth path in the A and B banded samples
Slika 5: Shematski prikaz poti rasti razpoke v trakavih vzorcih A in B

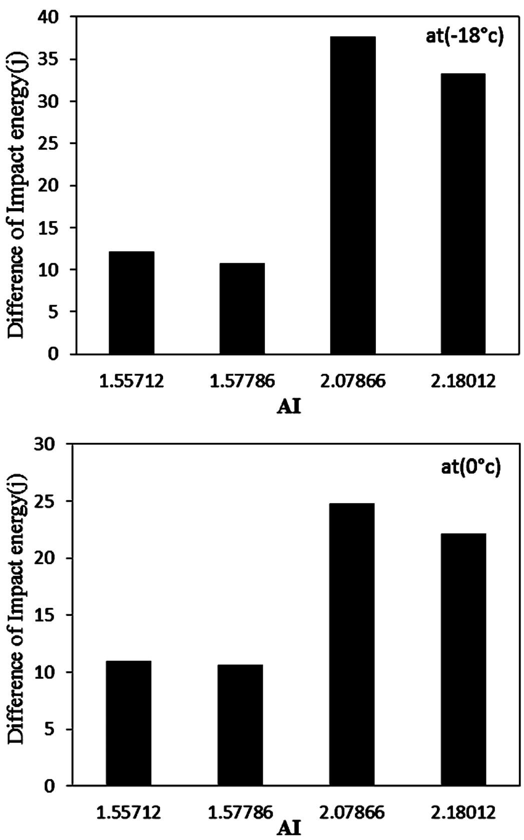

Figure 7: Difference in the impact energies for the A and B samples at –18 °C and 0 °C
Slika 7: Razlika v udarni energiji pri dveh vzorcih A in B pri –18 °C in 0 °C

the fibers is more serious than the one in the parallel direction. **Figure 7** shows the differences in the impact energies for the two directions, perpendicular and parallel, of the rolling.

In a study on an aluminum composite, in which the SiC reinforcing particles are used in two forms, an elongated and a random orientation in the aluminum matrix, the sample with a random distribution showed no difference in the fatigue crack growth in the two directions, the perpendicular and parallel, while the sample with an elongated reinforcement showed an obvious difference.[16]

Also, the repeated impact tests at the zero temperature indicated a similar behavior shown in this diagram, and the diagram in **Figure 4** shows that with the increasing *AI* the differences in the impact energies for the two directions, the perpendicular and parallel, increase from 11 J to 37 J. Therefore, the direction of the samples has a significant effect on the banded samples, reflected in the impact-test results. Due to a more homogeneous microstructure of the non-banded samples or the samples with a lower *AI*, the mechanical properties are not very dissimilar for different directions and are close to the homogeneous state.

However, at the temperature of –18 °C the amount of the impact energy in the banded samples was slightly smaller than at the temperature of 0 °C. This shows that banding has a larger effect on the impact properties at lower temperatures.

4 CONCLUSION

1. Impact energy shows an obvious dependence on the sample direction. As *AI* increases (which is an index of banding), the impact energy decreases in the rolling direction, while it increases in the direction perpendicular to rolling.
2. With the increasing *AI* the differences in the impact energies for the two directions, perpendicular and parallel, increase.
3. At lower temperatures banding has a greater influence on impact properties.

Acknowledgments

The technical and financial support of the Mobarkeh Steel Complex to the present research is gratefully acknowledged.

5 REFERENCES

[1] ASTM International, Metals-Mechanical Testing, Annual Book of ASTM Standards, 2009

[2] J. D. Verhoeven, Journal of Materials Engineering and Performance, 9 (**2000**), 286–296

[3] X. P. Liang, H. Z. Li, L. Huang, T. Hongc, B. Ma, Y. Liu, Transactions Of Nonferrous Metals Society Of China, 22 (**2012**) 6, 1270–1279

[4] S. W. Hwang, J. H. Ji, K. T. Park, Materials Science and Engineering: A, 528 (**2011**), 7267–7275

[5] L. E. Samuels, Light Microscopy of Carbon Steels, ASM International, 1999, 81–124

[6] H. Chandler, Heat Treater's Guide, Practices And Procedures For Irons And Steels, 2nd ed., ASM International, 1995

[7] L. Hellner, T. O. Norrman, Jernkont. Ann., 152 (**1968**), 269–86

[8] W. A. Spitzig, Metallurgical Transactions A, 14 (**1983**), 271

[9] A. S. Bor, Iron Steel Inst. Jpn. Int., 31 (**1991**), 1445–46

[10] E. F. Jatczak, D. J. Girardi, E. S. Rowland, Transactions of American Society of Metals, 48 (**1952**), 279–303

[11] R. A. Grange, Metall Transactions, 2 (**1971**), 417–426

[12] L. Tau, S. Chan, C. Shin, Journal of Marine Science and Technology, 1 (**1993**), 19–22

[13] M. Z. Shah Khan, S. J. Alkemade, G. M. Weston, D. G. Wiese, Int Journal Fatigue, 20 (**1998**), 233–239

[14] P. Shanmugam, S. D. Pathak, Engineering Fracture Mechanics, 53 (**1996**), 991–1005

[15] M. Mazinani, W. J. Poole, Metallurgical and Materials Transactions A, 38 (**2007**), 432

[16] J. J. Mason, R. O. Ritchie, Materials Science and Engineering A, 231 (**1997**) 1–2, 170–182