A. ŚMIGLEWICZ, M.B. JABŁOŃSKA

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THE EFFECT OF STRAIN RATE ON THE IMPACT STRENGTH OF THE HIGH-Mn STEEL

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In the paper, results of impact bending tests of a high-manganese steel of Fe – 30 wt.%, Mn – 9 wt.%, Al – 0,65 wt.%, C grade are presented. The tests were carried out using a flywheel machine, suitable for dynamic stretching and impact bending tests in the range of linear velocity of the forcing element from 5 ÷ 40 m/s. The obtained test results were compared with the results of impact resistance of the studied steel determined using Charpy machine. Structural investigations were carried out using scanning transmission electron microscopy. Surfaces of fractures formed in the break point during bending tests were analyzed, and they indicate a presence of mixed transcrystalline fractures with a predominance of plastic fractures.

Key words: high manganese steels, Charpy impact test, impact bending, high deformation rate

INTRODUCTION

Impact loads of steel, or as a matter of fact, the mode of changes in structure and mechanical properties under the influence of high deformation rates, is the subject of studies in many centers working on strength of structures and material studies worldwide. High and very high deformation rates lead to changes in the structure and mechanical properties of materials and especially steels by increasing, among others, the value of yield point. A plastic deformation of materials caused by dynamic loads differs significantly from deformations under static and quasi-static conditions. A dynamic deformation is, most of all, an effect of wave phenomena occurring in the material being deformed. Among important factors affecting the plastic properties of most metallic materials, deformation rate may be named [1-8].

Deformation rate is the parameter of the plastic working process which may vary in a very wide range, while the other parameters are constant or negligibly low. Studies of materials may be carried out in a very broad range of deformation rates. That is why it is impossible to use a measurement apparatus of a single type. At present, the most frequently used dynamic methods include: tests using a rotary hammer, tests using a split Hopkinson pressure bar, Taylor impact test, plate impact test and expanding ring test [5, 7, 9, 10].

In the literature pertaining to high-manganese steels, there are relatively few reports on tests of steel properties using high deformation rates as well as microstructure analysis. The most publications discuss the analysis of behavior of high-manganese steels subjected to tests with the deformation rates ranging from 10^2 to 10^4 s^{-1}, which allows for carrying out the impact compression, tension and torsion tests [10-15]. Many authors [2, 5, 6, 11, 13] analyzed properties of high-manganese steels after tension tests using high deformation rates, also using the split Hopkinson pressure bar and flywheel machine in the range of dynamic rates $10^2 \div 10^3$ s^{-1}. Every measurement technique provides detailed information only in a specific rate range. Costs, significantly higher than in case of standard tests, are the major problem in dynamic tests.

TEST MATERIALS AND METHODS

A high-manganese steel Fe – 30 wt.%, Mn – 9 wt.%, Al – 0,65 wt.%, C grade was the test material. The steel was prepared in Institute for Ferrous Metallurgy, Gliwice, Poland, in a vacuum induction furnace from Balzers. The casting process was carried out under an argon atmosphere, via a hot tundish, to a water-cooled copper concast mould properly prepared earlier. The concast mould feedstock was rolled into square section with a dimension of 45 mm. The so-prepared material was used for preparation of samples for the impact tests. The test samples with V-notch was made according to PN-EN 10045-1 standard. The impact tests were carried out using a Charpy machine and a flywheel machine of RSO type. The flywheel machine owned by Silesian University of Technology allows for deforming, stretching and bending samples with a linear impact rate in the range of 5 to 40 m/s, corresponding to deformation rates in the range of 10^2 to 10^4 s^{-1}. The impact bending tests using a flywheel machine was carried out with various deformation rates in the range of linear velocity of the working element of 7.5 m/s, 15 m/s, and 30 m/s. During impact bending, the sample is fractured on an anvil using a ram (claw). The interchangeable claw is installed on a flywheel with a very high moment of inertia [3].

A. Śmiglewicz, M.B. Jabłońska, Silesian University of Technology, Faculty of Materials Science and Metallurgy, Katowice, Poland

Fractographic studies of the fractures formed after the Charpy impact test and the impact bending test were carried out by scanning electron microscopy on a Hitachi S-4200 microscope.

RESULTS AND DISCUSSION

The investigations were carried out for high-manganese steels with an austenitic-ferritic structure. The Charpy impact test was carried out using a hammer with an initial energy of 150 J, which turned out to be too low to break the sample. For next measurements, a hammer with an initial energy of 300 J was used. Doubled energy allowed for breaking next samples. Impact resistance by Charpy method was determined using the formula (1):

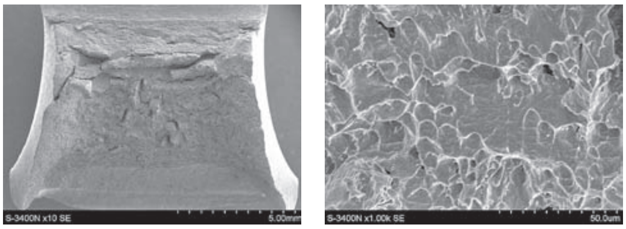
$$KCV = \frac{KV}{S} / J / cm^2 \qquad (1)$$

where: KV – impact work used for breaking the sample / J; S – surface area of the initial cross-section of the sample / cm^2.

After Charpy impact tests, fractographic studies of the obtained fractures were carried out – Figure 1a,b

The dynamic bending test was carried out at the ram linear velocity of 7,5 m/s, 15 m/s, and 30 m/s. Based on the data recorded by the Next View 4,2 software, the following quantities were obtained: duration, force, velocity, which were used for calculations of work and impact resistance. The bending force vs. the test duration for each of the deformation rates studied is plotted in Figure 2.

The result presented in the form of a combined graph of bending force vs. time was used for calculation of work needed to break the sample and impact resistance.



a) b)

Figure 1 Fractures of the tested steel after the Charpy impact test, SEM images; a) mat fracture typical for plastic type; b) surface of transcrystalline ductile fractures

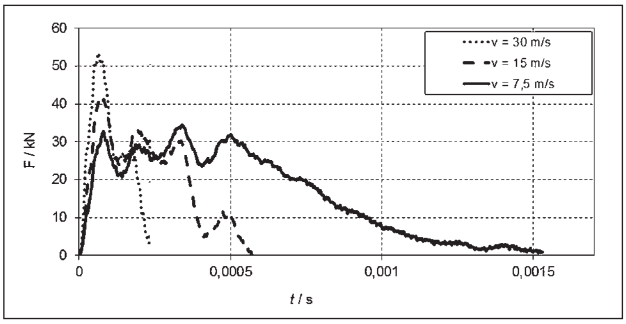


Figure 2 Graph of bending force vs. time for velocities: v = 7,5 m/s; v = 15 m/s; v = 30m/s

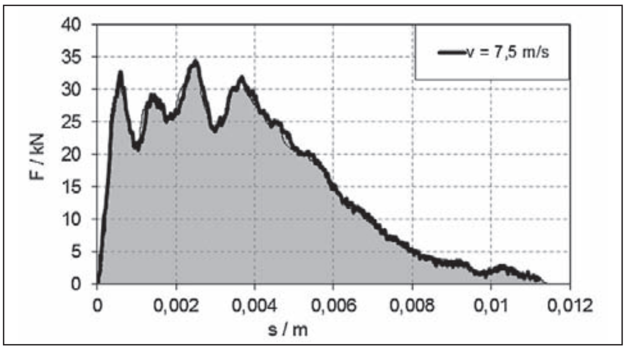


Figure 3 Graph of bending force vs. path for velocity v = 7,5 m/s

Based on the path travelled and the bending force, corresponding graphs for the individual velocities were prepared, with the surface area below the curve constituted the work needed to break the sample. An exemplary graph is shown in Figure 3.

The surface area below the curve was divided into a finite amount of rectangles with the sum of surface areas constituting the whole surface area below the curve, and thus the work L_U needed to break the sample. The impact resistance in the impact bending test was determined based on the dependence (2):

$$U = \frac{L_U}{S} / J / cm^2 \qquad (2)$$

where: L_U – deformation work at the break / J, S – surface area of the initial cross-section of the sample / cm^2.

Comparative results from the test carried out are gathered in Table 1. The graph of bending force vs. time shows a characteristics of the course of the dynamic bending test. It was ascertained that the higher deformation rate, the higher the stress required to break the sample, and thus the higher deformation rate, the shorter the time to break.

Table 1 **Results of impact resistance tests of Fe – 30 wt.%, Mn – 9 wt.%, Al – 0,65 wt.%, C steel after the impact bending test**

	linear velocity								
	v = 7,5 m/s			v = 15 m/s			v = 30 m/s		
F_{max} / kN	35	35	36	41	41	42	53	54	55
L_U / J	163	164	166	173	175	177	192	193	195
S / cm^2	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8
U / J/cm^2	207	208	201	219	220	223	240	242	244

Comparative results from the test carried out are gathered in Table 2.

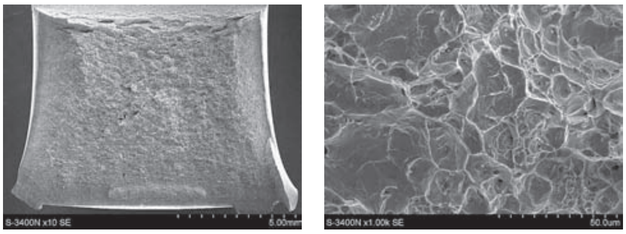
Table 2 **Results of impact resistance tests of the studied Fe – 30 wt.%, Mn – 9 wt.%, Al – 0,65 wt.%, C steel**

Impact resistance / J/cm			
Charpy impact test	Impact bending tests using a flywheel machine		
	7,5 / m/s	15 / m/s	30 / m/s
200	207	222	242

The lowest impact resistance characterizes the material after the Charpy impact test. While comparing the initial Charpy impact test 200 / J/cm^2 to the dynamic bending test at the velocity of 7,5 m/s, the impact resistance of the material increases by 5,3 %. While increasing the deformation rate to 15 m/s and to 30 m/s, the impact resistance increases in relation to the initial test by 11,6 % and 21,6 %, respectively. In the dynamic bending test, the work needed to break the sample at the lowest velocity of 7,5 m/s amounted to 165 / J. When the velocity was increased to 15 m/s and then to 30 m/s, the work needed to break the sample increased by 6 %, and later it increased almost thrice, amounting to 17 %.

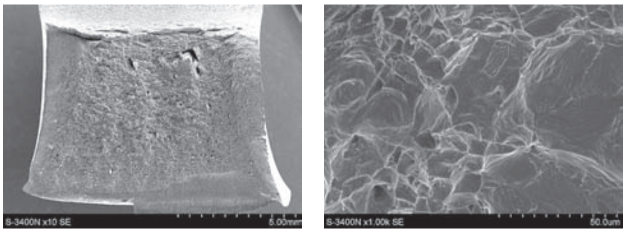
After the Charpy impact test and the impact bending, fractographic studies of the obtained fractures were carried out Figure 1, Figures 4 – 6.

Irrespective of the deformation rate used, the studied steel was characterized by a mixed fracture in the break point. Mostly areas of characteristic plastic fracture occurred, and also areas of were observed. The fracture was characterized by a fibrous structure, presence of interconnected microvoids, as well as mat surface, typical for fractures of plastic type.



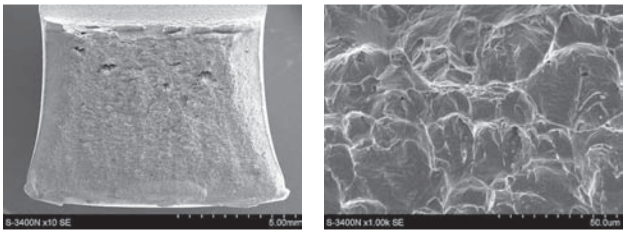
a) b)

Figure 4 Fractures of the tested steel after the impact bending with a velocity of 7.5 m/s, SEM images; a) mat surface with several microcracks; b) surface of transcrystalline ductile fractures with microvoids



a) b)

Figure 5 Fractures of the tested steel after the impact bending with a velocity of 15 m/s, SEM images a) surface with microcracks; b) surface of transcrystalline ductile fractures with presence a cleavage planes



a) b)

Figure 6 Fractures of the tested steel after the impact bending with a velocity of 30 m/s, SEM images; a) well mat surface with several microcracks; b) surface of transcrystalline ductile fractures

CONCLUSIONS

The studied carried out proved an influence of the deformation rates on the ability to transfer dynamic loads of the studied Fe – 30 wt.%, Mn – 9 wt.%, Al – 0,65 wt.%, C steel, confirming an increase in the impact resistance under the influence of increasing deformation rate. For instance, in case of a velocity of 7,5 m/s, the impact resistance amounted to 209,5 / J/cm^2, and for 30 m/s it increased by 15,5 %. The impact resistance determined in the paper expresses the amount of energy per a unit surface area, absorbed by the material at breaking in the result of an high-velocity impact.

The results of studies of the macrostructure of fractures formed in the result of the tests carried out, showed a plastic form of the fractures. Structural analysis revealed void characteristic for plastic transcrystalline breaking on the observed surfaces of the studied steel. Fractographic studies showed a presence of mixed fractures with plastic fractures with crater structure prevailed.

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Note: The responsible translator for English language is Dr. Janusz Mrzigod, Katowice, Poland