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THE EFFECT OF STRAIN RATE ON THE MECHANICAL PROPERTIES AND MICROSTRUCTURE OF THE HIGH-Mn STEEL AFTER DYNAMIC DEFORMATION TESTS

WPŁYW PRĘDKOŚCI ODKSZTAŁCENIA NA WŁAŚCIWOŚCI I STRUKTURĘ STALI WYSOKOMANGANOWEJ PO TESTACH DEFORMACJI DYNAMICZNEJ

The paper presents results of dynamic tensile investigations of high-manganese Fe – 20 wt.% Mn – 3 wt.% Al – 3 wt.% Si – 0.2 wt.% steel. The research was carried out on a flywheel machine, which enables to perform dynamic tensile tests and impact bending with a linear velocity of the enforcing element in the range of 5÷40 m/s. It was found that the studied steel was characterized by very good mechanical properties. Strength of the tested materials was determined in the static tensile test and dynamic deformation test, while its hardness was measured with the Vickers hardness test method. The surface of fractures that were created in the areas where the sample was torn were analyzed. These fractures indicate the presence of transcrystalline ductile fractures. Fractographic tests were performed with the use of a scanning electron microscope. The structure was analyzed by light optical microscopy. Substructure studies revealed occurrence of mechanical twinning induced by high strain rates. A detailed analysis of the structure was performed with the use of a transmission scanning electron microscope STEM.

Keywords: high-manganese steel, dynamic deformation test, strain rate, impact strength, mechanical twinning, structure

W pracy przedstawiono wyniki wstępnych badań dynamicznego rozciągania wysokomanganowej stali gatunku X20MnAlSi16-3-3. Badania przeprowadzono na młocie rotacyjnym, który posiada możliwość realizacji prób dynamiczne-go rozciągania i udarowego zginania w zakresie prędkości liniowej elementu wymuszającego od 5÷40 m/s. Badana stal charakteryzuje się bardzo dobrymi właściwościami mechanicznymi. Wyniki badań uzyskano na podstawie statycznej próby rozciągania, próby dynamicznego rozciągania na młocie rotacyjnym oraz pomiaru twardości metodą Vickersa. Przeanalizowa-no powierzchnie przełomów powstałych w miejscu zerwania podczas prób rozciągania, które wskazują na obecność przełomów transkrystalicznych ciągliwych. Badania strukturalne wykonano z wykorzystaniem techniki mikroskopii świetlnej, skaningowej mikroskopii elektronowej i skaningowej transmisyjnej mikroskopii elektronowej. Przeprowadzone badania substruktury ujawniły obecność mechanizmu bliźniakowania mechanicznego, indukowanego w warunkach dużych prędkości odkształcenia.

1. Introduction

In automotive and railway industries, technological solutions are required at present, providing an enhancement in safety and a reduction in energy consumption [1]. Development of new materials and improvement of those currently used in at last 10 years lead to obtaining new generation high-manganese steels such as TRIP, TWIP steels, as well as MBIP steel, with a unique combination of mechanical properties. Today, there are included the group of so-called Ultra High Strength Steels – UHSS [1-3]. Integration of high strength properties and a good formability, ensuring high absorption of energy by structural components, enables application of these new high-manganese steels in construction of means of transport, particularly in elements critical for the safety, and replacement of older generations of DP steels. The newest high-manganese steels, such as TRIP, TWIP, or MBIP, are different than conventional steels by their contents of alloying elements deciding about the microstructure stability and strength properties. In particular, this refers to carbon, which affects hardening of solid solution and is an effective austenite stabiliser; aluminium limiting the deformation-induced $\gamma \rightarrow \varepsilon \rightarrow \alpha$ transformation, stabilising austenite and forming fine precipitations with high dispersion, effectively reducing the size of the austenite grains [4-10]. Additionally, Al increases the value of stacking fault energy (SFE) and corrosion resistance by formation of passive layers; it also decreases the density of steel. Silicon hardens the austenite solid solution, increases tensile strength and crack resistance. Mn-Al steels with SFE value between 20 mJ/m^2 and 60 mJ/m^2 are classified as the so-called TWIP steels with formation of mechanical twins in the austenitic matrix as a privileged mechanism of deformation [1, 2, 8-13]. Their microstructure is characterized by the presence of mechanical

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twins as well as dislocation cells in the austenitic deformed matrix, but with a predominance of the presence of twins. These mechanical twins pose an obstacle to dislocation glide and which significantly favors the strain hardening [8]. In high manganese steels, the strain hardening exponent of this steel increases with an increase in the true strain and strain rate. It was found that for different strain rate, high density deformation twins form during the deformation, and the width of a deformation twin lath decreases as the strain rate increases [13-17]. In the paper, dynamic tensile studies of the high-manganese Fe – 20 wt.% Mn – 3 wt.% Al – 3 wt.% Si – 0.2 wt.% steel were carried out on a flywheel machine, which enables to perform dynamic tensile tests and impact bending. After the studies of mechanical properties, an analysis of the structure and substructure as well as fractures was carried out in order to disclose the cracking character.

2. Experimental

A high-manganese steel Fe – 20 wt.% Mn – 3 wt.% Al – 3 wt.% Si – 0.2 wt.% was the material for studies. The steel was smelted in a vacuum induction furnace with a ceramic melting pot, and cast using gravity casting technique. The obtained ingots were forged into round bars with a diameter of 20 mm. The forging was carried out so as to the forging start temperature was in the range of 1150°C ÷1140°C, and the forging finish temperature was not lower than 900°C. After the forging, the bars were subjected to hyperquenching from a temperature of 1170°C. In this material state, the studied steel had a monophase austenitic structure with characteristic annealing twins.

The dynamic tensile tests were carried out on a flywheel machine of RSO type, owned by Institute of Materials Technology of Silesian University of Technology. The device allows for deforming, tensile and bending of samples with an impact linear velocity in the range of 5÷40 m/s, corresponding to deformation rates in the rage of $10^2 \div 10^4$ s^{-1}. During the dynamic tensile tests, the sample is connected to the top holder, and it is deformed by an impact of a ram into the anvil of the bottom holder. The ram linear velocity was determined by a measurement of the rotational speed of the ram's flywheel.

Smooth cylindrical samples with a diameter of 4 mm and a measurement part length of 20 mm were used for the tests, bilateraly threaded in the holder part. During the tests, the course of the tensile force vs. time, and the linear velocity of the ram placed in the flywheel, were recorded. Based on the force characteristics and sample geometry measurements before and after the deformation, the following parameters were determined: limiting deformation ε_g, deformation rate, tensile strength TS, and impact resistance U. Studies of the surfaces of fractures formed as a result of the tensile test, were carried out by scanning microscopy, using a Hitachi S-4200 scanning electron microscope with a resolution of 1.5 nm at 15 kV. The structural studies were carried out by optical light microscopy and in the submicroscopic scale, using transmission scanning electron microscopy. The hardness measurement was carried out by Vickers method under a load of 1 kg.

3. Results

Dynamic deformation tests using flywheel machine were carried out with the ram's linear velocity of 7.5, 15, and 30 m/s. It corresponds to obtained deformation rates in the range of 100÷4000 s^{-1}. The deformation rate vs. linear velocity of the flywheel ram is shown in Fig. 1. Recording time of the signal in the system is 10 s, and volume of a single data file – 20 MB. Time and character of the tensile force course depends on the material type and the deformation rate. The limiting deformation of the studied steel exhibits a slight decreasing tendency in the whole velocity range, ε_g amounts to 1.26, 1.20 and 1.04 for the given ram's linear velocity 7.5, 15, 30 m/s, respectively. The dependence of the steel's tensile strength on the deformation rate is shown in Fig. 2. The studied steel exhibits sensitivity of the stress to the deformation rate. Values of the tensile strength determined after dynamic tests are gathered together with the TS value after the static tensile test. The investigations indicate that an increase in the deformation rate is accompanied by an increase in the tensile strength. In the static tensile test, the average value of TS amounts to 640 MPa, while after the dynamic tensile test, this values increases, reaching averages of 915 MPa and 940 MPa, for the ram's linear velocities of 7.5 m/s and 15 m/s, respectively. At the highest ram's linear velocity used, i.e. 30 m/s, the studied steel exhibits the highest tensile strength,
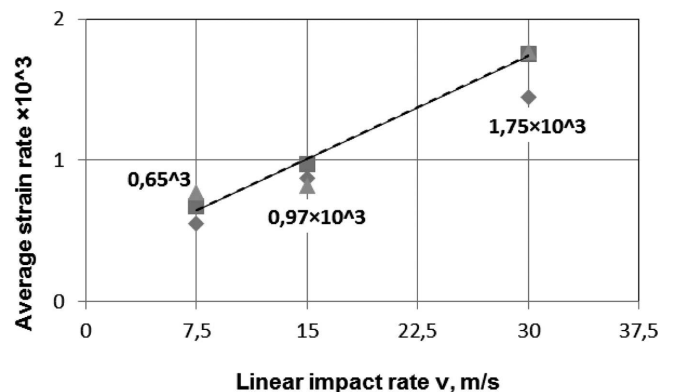

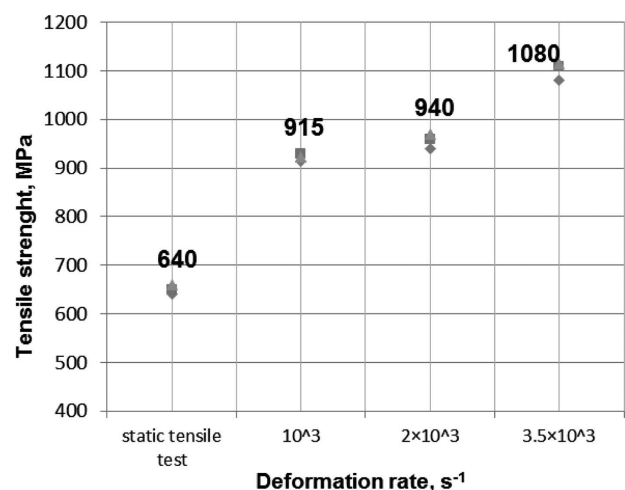Fig. 1. Dependence between the impact linear velocity and the average deformation rate

Fig. 2. The effect of the deformation rate on the ultimate tensile strength of the investigated steel

amounting to 1080 MPa. The studied steel is being strongly hardened, what is confirmed by the results of the hardness test. A hardness measurement series were carried out on a longitudinal microsection of the fracture formed as a result of the test, with a step of 0.2 mm along the axis of the sample. Under static conditions, the average hardness amounts to 315 HV1, and after the tensile test with the ram's linear velocity of 30 m/s it amounts to 360 HV1.

The results of the impact resistance tests indicate that the studied high-manganese steel exhibits an ability to cumulate the deformation energy. In the whole range of the deformation rate used, an increase in the impact resistance of the studied steel is observed, shown in Figure 3.
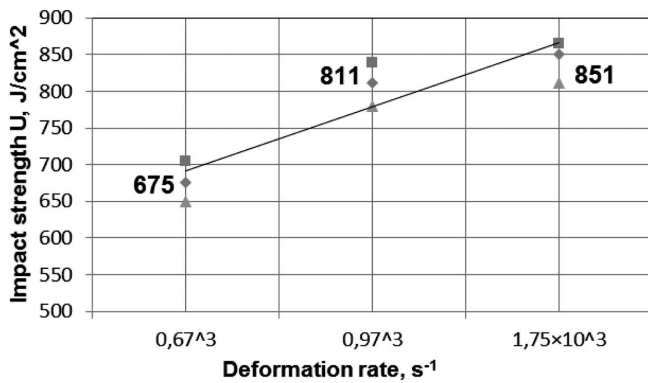
Fig. 3. The effect of the deformation rate on the impact strength of the investigated steel
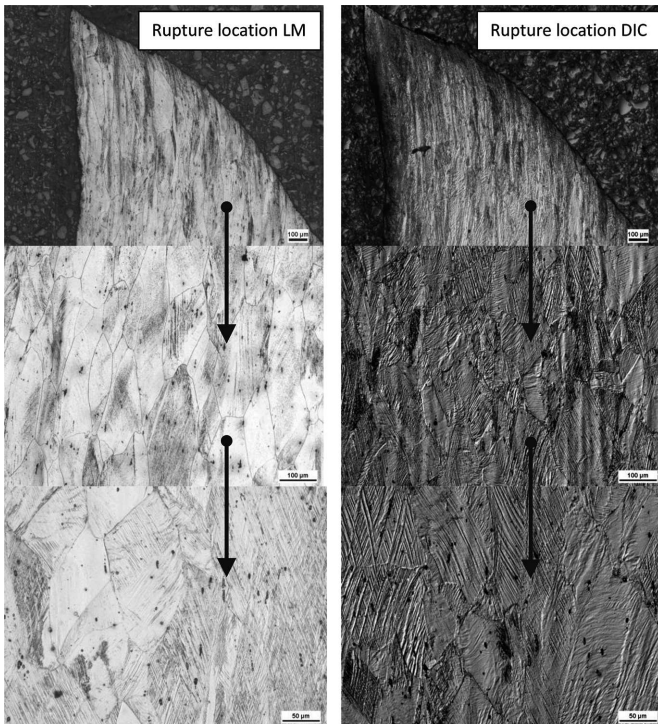
Fig. 4. Microstructure of Fe – 20 wt.% Mn – 3 wt.% Al – 3 wt.% Si – 0.2 wt.% steel after dynamic deformation with a rate of 15 m/s

After the dynamic tensile test, structural analysis and fractographic observations of the studied steel were carried out in order to determine susceptibility of the steel to mechanical twinning during a deformation and ability for ductile cracking, shown in Figures 4 and 5. In the studied steel subjected to a dynamic deformation, effects of strong hardening are observed. The grains elongate in the direction of the tensile force. In austenite, formation of characteristic deformation twins occurs; the twins are visible in the form of parallel and intersecting bands. The annealing twins disappeared and deformation twins were produced intensively. The more deformation twins can be found near to the fractured surfaces and away from the fractured surfaces deformation twins exist. These twins have regular as well as irregular shapes. The substructure studies showed a presence of mechanical twins being formed in the steel irrespective of the deformation rate used. Example of parallel mechanical twins on the background of deformed austenitic matrix in the studied steel, deformed with a rate of 30 m/s, are shown in Fig. 6. Fractographic studies of the fractures indicate presence of ductile fracture which is characterized by a dimple structure (Fig. 7a, b). To a first approximation the depth of these dimples can be considered as a measure of the ductility. At some regions we observed the lamellar tearing (Fig. 7b).
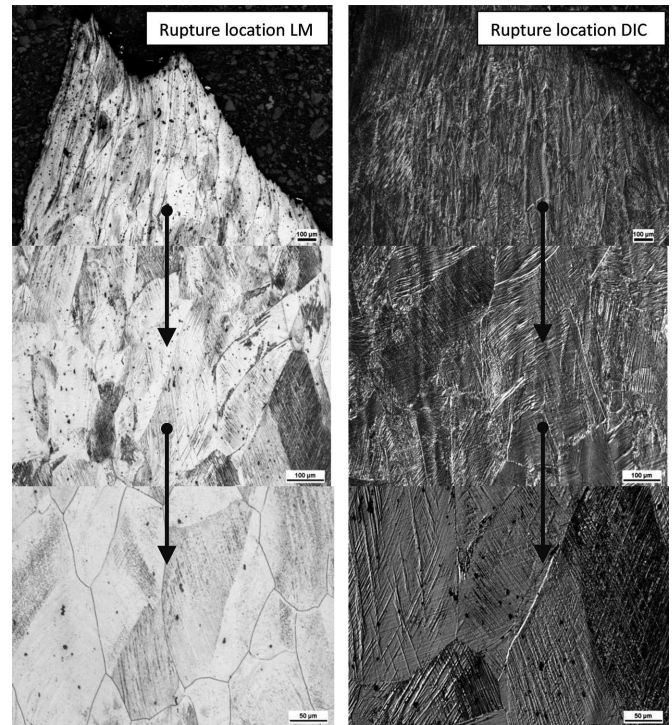
Fig. 5. Microstructure of Fe – 20 wt.% Mn – 3 wt.% Al – 3 wt.% Si – 0.2 wt.% steel after dynamic deformation with a rate of 30 m/s
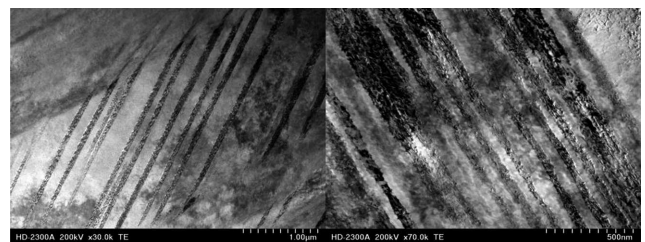
Fig. 6. STEM image on area containing mechanical twins in a sample after dynamic deformation with a rate of 30 m/s
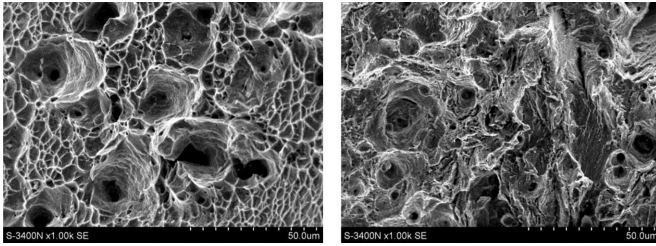
580

Fig. 7. Fractographic analysis of Fe – 20 wt.% Mn – 3 wt.% Al – 3 wt.% Si – 0.2 wt.% steel after dynamic deformation with a rate of: a) 15 m/s, b) 30 m/s. Ductile fracture characterized by a dimple structure with a craters

4. Conclusions

The dynamic tensile studies carried out proved that the high-manganese steel Fe – 20 wt.% Mn – 3 wt.% Al – 3 wt.% Si – 0.2 wt.% C exhibits sensitivity of the stress to the deformation rate. In the whole range of the deformation rate used, an increase in impact resistance of the studied steel is observed, indicating that the steel hardens in the result of a dynamic deformation. Structural analysis indicates that formation of characteristic deformation twins occurs in the austenite. The twins are visible as parallel and intersecting bands. The annealing twins disappeared and deformation twins were produced intensively. The substructure studies confirmed a presence of twinning effects in the deformed austenite, induced by the plastic deformation. Mechanical twins are visible in the form of parallel twin lines. Fractographic studies indicate presence of ductile fracture which is characterized by a dimple structure. To a first approximation the depth of these dimples can be considered as a measure of the ductility. Further studies of the dynamic deformation will be focused on improvement of computational procedures of determination of basic mechanical parameters, and methods for structural evaluation with particular regard to quantitative analysis of the substructure.

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