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Enhancement of mechanical properties of high-Mn steels due to the formation of nano-twins in severe plastic deformation

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Abstract: This work presents an overview of high-Mn advanced high-strength steels (AHSS) and their application in automotive industry. It specifies, in particular, the benefits of Twinning Induced Plasticity (TWIP) mechanism and influence of nano-twins on strain hardening and energy absorption abilities of high-Mn steels during the dynamic deformation process.

Keywords: high-Mn steel, mechanical twinning, severe deformation, mechanical properties.

1. INTRODUCTION

The automotive industry is one of the fastest growing industries among all branches of industry that use engineering materials. The need for the constant development of structural materials causes considerable improvement of advanced high-strength steels (AHSS) in the last quarter century. Development and investigation of new materials are important for two main reasons:

- reduction of vehicle weight, which contributes to a decrease of fuel consumption and reduction of the environmental pollution by harmful gases;
- increase of driver and passenger safety in the case of a car collision.

A key aspect of achieving a high level of safety during a car accident is high resistance to cracking and fatigue, as well as the ability to absorption of energy during a car crash. High-Mn TWIP steels have the highest value of deformation energy absorption (E_{ABS}) among all steels used in automotive industry and present very good relation between high tensile strength and high elongation, which is very important in automotive industry. These properties are related to the ability to the formation of mechanical twins and nano-twins [1,2].

2. THEORETICAL BACKGROUND

High manganese austenitic steels belong to the second generation of advanced high-strength steels (AHSS). These steels have unique properties of strain hardening. Based on the method of plasticity enhancement, TWIP (Twinning Induced Plasticity) and TRIP (Transformation Induced Plasticity) steels can be mentioned, as two main types of high-Mn steels. Dislocation glide is the main result of plastic deformation in most steels, however, in high- Mn steels, the creation of deformation twins and/or microstructural transformation of austenite into martensite are dominant deformation mechanisms.

The main factor, which determines the possibility of TWIP/TRIP mechanisms occurrence is stacking fault energy value (SFE). Stacking faults occur during deformation when layers of atoms shift in the non-lattice vector. When stacking fault energy is low, the stacking fault is wider and the probability of twinning process is higher. Twin nucleation is initiated in high strains during microstructure disorder when layers of atoms are shifting in {111} plane. Twin is formed when three partial dislocations grow into each other on adjoining slip planes [3].

Twinning is usually connected with SFE values of 20 - 60 mJ/m^2. When SFE is lower (<20 mJ/m^2), the transition of austenite into martensite becomes the main deformation mechanism (TRIP effect). When SFE is low, twinning process becomes privileged deformation mechanism and takes place before dislocation glide. Twinning mechanism is more favourable than dislocation glide because twins behave like specific obstacles for dislocation movement, which finally leads to an increase of ductility and induce high work hardening rate [3].

SFE value depends on chemical composition, non-metal precipitation and temperature. It was reported by Timokhina et al. [4] that increase of deformation temperature up to 400°C favours the dislocation glide as a major deformation mechanism. Formation of twins depends also on grain size. The decrease of grain size causes a smaller propensity to twinning [4].

3. RESULTS OF SEVERE PLASTIC DEFORMATION TREATMENT

Severe plastic deformation can cause the formation of mechanical twins in nano-scale. This type of twinning is common in high-Mn steels. Gumus et al. [5] presented results of high-velocity compression tests of three different high-Mn steels: Hadfied steel (12% Mn), TWIP (15% Mn) and XIP (21% Mn). In room temperature and low temperature (-170°C), each steel revealed nano-twins in form of separate twins and twins-inside-twins. However, manganese content influences SFE value. Mn generally decreases SFE and makes the twinning process easier to obtain, although some researchers revealed that very high content of Mn can re-increase the SFE value. Therefore, in elevated temperature (200°C) XIP steel, which presents high SFE value revealed only slip as a deformation mechanism, whereas TWIP (medium SFE) and Hadfied steel (low SFE) deformed with both slip and twin mechanisms also in elevated temperature [5].

The foundation of the positive influence of nano-twins is related to their behaviour during plastic deformation. Nano-twins form a large area of boundaries which effectively restrain dislocation movement and improve mechanical strength. The principle of this process is mentioned in work [6] of Bahjati et al. Mechanical properties of X9MnCr16-4 steel were compared in the raw state, hot rolled state and reversion annealed state. Results of this comparison are presented in table 1.

Table 1. Comparison of main mechanical properties of high-Mn steel after different thermo-mechanical treatment stages [6]

Steel condition	Yield strength [MPa]	Tensile strength [MPa]	Tensile elongation [%]
Raw	394	564	3
Hot rolling	450	1131	37
Reversion annealed	970	1384	37

Due to thermo-mechanical treatment, it is possible to significantly improve properties of high-Mn steel accordingly to yield and tensile strength and tensile elongation. In-depth microscopic analysis revealed that severe deformation leads to creation of nano-twins inside the microtwins and within the microbands [4,6]

Jabłońska [7] presented results of X30MnAl27-3 TWIP steel dynamic deformation with increasing strain rates from $5 \cdot 10^2$ up to $3{,}5 \cdot 10^3$ s^{-1}. Examination on flywheel machine exposed that with increasing strain value, steel underwent increasing tensile strength (from 1000 to 1200 MPa) and hardening process. Good plasticity of this steel is also indicated by ductile fracture surfaces. Similar results were presented in other work of Jabłońska et al. [8], where high-Mn steel was deformed on a flywheel machine with increasing rate ($10^2 \div 10^4$ s^{-1}). Again the tensile strength was gradually increasing from 640 MPa for static tensile test up to 1080 MPa for highest linear velocity test. Moreover in this work hardness variability was also measured. The hardness of investigated samples increased respectively from 315 HV1 to 360 HV1. Fractographic observations revealed a mechanical twinning in deformed steel [7-8].

In the next investigation, Jabłońska et al. [9] tested X55MnAl25-3 steel mechanical properties and energy absorption index (SEA) after deformation with different strain rates. Results of this investigation are presented in fig. 1.

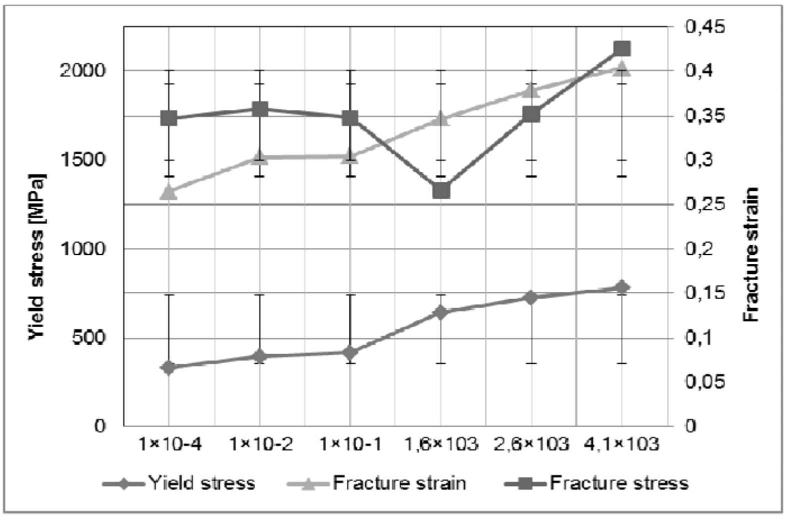

Figure 1. Influence of strain rate on mechanical properties of X55MnAl25-3 steel [9]

Yield stress and fracture strain constantly and significantly increase with increasing strain rate. Fig. 1 shows also, that fracture stress value decreased above $1 \cdot 10^{-1}$ strain rate and then increased to the value of 0,425. Moreover, SEA values calculations gave irregular results for each strain rate. The highest energy absorption value was obtained for $2{,}6\cdot10^{3}$ strain rate [9].

Type of cooling medium has a small influence on final mechanical properties of hot rolled TWIP steel. In work [10] of Jabłońska et al., X45MnAl20-3V austenitic steel was cooled in air and in water after hot rolling from the temperature of 950°C. As can be seen in table 2, the variability of tensile strength, hardness and elongation for each cooling medium is insignificant and can be related to the presence of vanadium in chemical composition. Nevertheless, microstructure investigation revealed the existence of mechanical twins in each sample [10].

Table 2. Comparison of mechanical properties of X45MnAl20-3V austenitic steel cooled from annealing temperature in air and water [10]

Cooling medium	Properties			
	HV 10 (initial state)	$R_{0,2}$ [MPa]	R_m [MPa]	A_5 [%]
Air	283	370	590	80
Water	210	370	525	83

Deformation mechanism seems to have the biggest influence on mechanical properties. Jabłońska [11] presents behaviour of X55MnAl25-5 steel in the tensile test and compression test with different strain rates from 0,0005 s^{-1} to 4650 s^{-1}. In tensile test, tensile strength increased from 915 MPa in 0,0005 s^{-1} rate up to 1617 MPa in 4650 s^{-1} rate (76% growth). Values of yield stress in compression test was respectively 800 MPa and 1200 MPa (50% growth). Fig. 2a and 2b prove that low deformation rate initiates only single twins whereas dislocation glide remains the major deformation mechanism. In high rate deformation, mechanical twinning with the contribution of nano-twins becomes the privileged deformation mechanism (fig. 3a and 3b) [11].

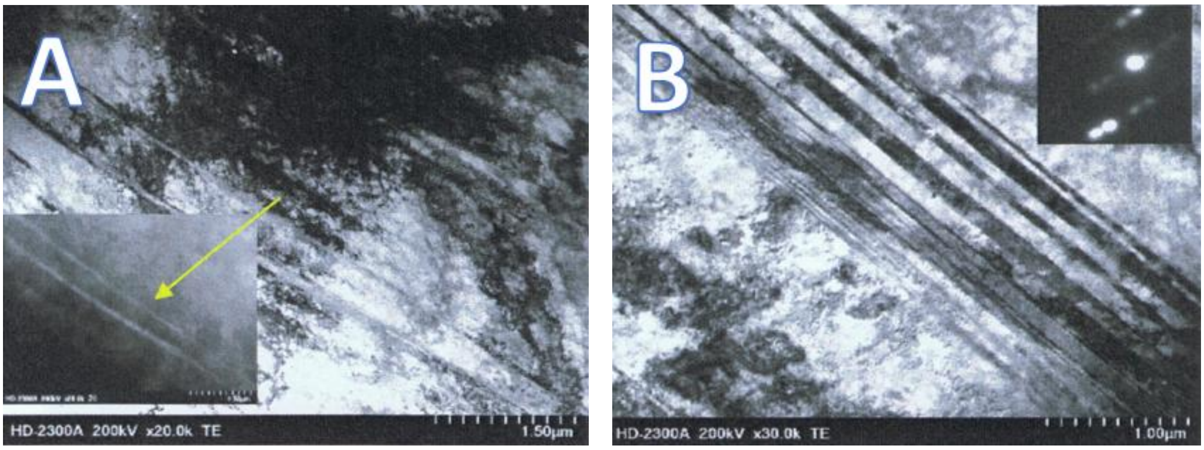

Figure 2. Microstructure of X55MnAl25-5 steel deformed with 0,0005 s^{-1} rate: A- single deformation twins, B- deformation twins in one twinning system against the background of defective matrix [11]

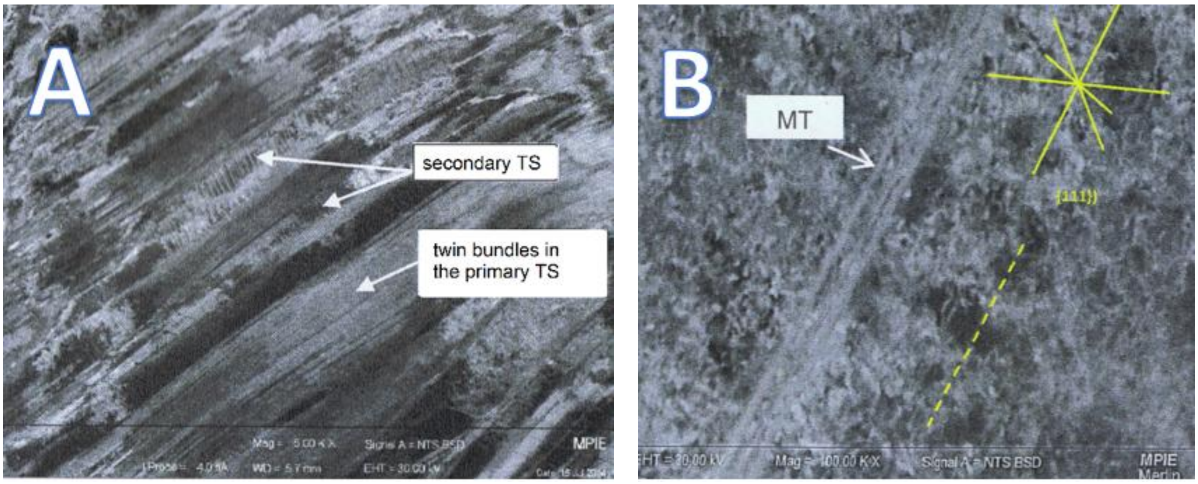

Figure 3. Microstructure of X55MnAl25-5 steel deformed with 4650 s^{-1} rate: A- visible primary and secondary twinning system (TS), B- dislocation cells and a bundle of nano-twins; MT- mechanical twins [11]

3. CONCLUSION

Plastic deformation initiates two main strain hardening processes: dislocation glide and mechanical twinning. While deformation and strain rate increases, the structure of dislocation transforms and twinning process becomes more noticeable. Mechanical twins create advanced dislocation configurations including twin-inside-twin, slip-inside-twin and finally nano-twins within the primary deformation twins. This can be connected with intensive energy accumulation in form of shear bands. These structural changes contribute to the high level of deformation energy absorption (E_{ABS}) and significantly increase mechanical properties. Due to this property in combination with good weldability and the possibility of using hot galvanising as an improvement of corrosion resistance, high-Mn steels can be applied in the automotive industry for structural elements of vehicles [5,11].

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