EFFECT OF SOLUTION HEAT-TREATED ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF 27Mn-4Si-2Al-Nb-TYPE STEEL

Gabriela FOJT-DYMARA, Marek OPIELA

Institute of Engineering Processes Automation and Integrated Manufacturing Systems, Silesian University of Technology, Gliwice, Poland, EU, gabriela.fojt-dymara@polsl.pl

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Abstract

The tests on high-Mn of 27Mn-4Si-2Al-Nb type steel were carried out. The steel was solution heat-treatment at different temperatures in a range from 900 °C to 1200 °C. The tensile testes had performed at room temperature under a strain rate of $2.5 \cdot 10^{-3}$ s^{-1} on of the flat specimens were 6.35 mm in length and 3 mm in diameter and a gauge length of 25 mm. Effect of different grain size on microstructure and strain hardening behavior of high-Mn steel solution heat-treated was analyzed. The strength properties increase considerably with a decrease of grain size from 360 µm to 20 µm, where in the critical grain growth took place between 1000 °C and 1100 °C. The inverse relationship was confirmed between the grain size and ductility. The uniform elongation was increasing from 35 % to 45 % along with the increasing of grain size in the temperature range from 900 °C to 1100 °C and dramatically decreasing at the temperature 1200 °C to the 23 % by grain size 360 µm. Aluminium has segregated on the austenite grain boundaries in steel was solution heat-treated at 1200 °C and the intermetallic phase of Fe_2Al_5 type was observed. The morphological examination after stretching was carried out in a light microscope, high-resolution scanning electron microscope and EBSD analysis.

Keywords: Solution heat-treatment, high Mn steel

1. INTRODUCTION

High-Mn TWIP steels are by triggering the austenite to twin on deformation. The twin boundaries behaving like grain boundaries, strengthening the steel, resulting, again in both high strength and excellent ductility. TWIP steels have fully austenitic and obtain their good properties better properties than TRIP with a uniform elongation twice that of TRIP steel and a considerably higher ultimate strength and n value [1,2]. Grain size considerably affects the strengthening of high-Mn steel. Yuan et al. [3] researched the high-manganese austenitic steel, produced in the process of cold rolling, subsequently subjected to solution heat treated in a temperature range from 700 °C to 1000 °C. They revealed that along with increasing grain size from 2 µm to 30 µm, $YS_{0.2}$ decreased from approx. 400 MPa to about 230 MPa, UTS decreased from approx. 720 MPa to about 510 MPa, while uniform elongation increased more than thrice, i.e. from approx. 15 % to about 55 %. The increase of elongation in coarse-grained steels should be explained by the nucleation of mechanical twins at grain boundaries and easy increase of their quantity inside the grains. Whereas, a relatively low quantity of grain boundaries in coarse-grained steels is the reason for the reduced yield strength [4,5].

2. EXPERIMENTAL PROCEDURE

The tests were carried out on high-manganese steel 27Mn-4Si-2Al-Nb with the chemical composition given in **Table 1**. In order to obtain structures of different grain sizes, the steel was solution heat treatmen in the temperature range from 900 °C to 1200 °C. The steel was annealed in water from 900 °C, 1000 °C, 1100 °C and 1200 °C, with prior heating for 60 minutes, at each of the given temperatures. The metallographic tests were carried out using ZEISS Axio Observer Z1m light microscope. Metallographic samples were prepared using the classical method, i.e. incubated, ground and polished mechanically. In order to reveal the microstructure, prepared metallographic specimens were etched in 4 % nital. In accordance with the ASTM E112-10 standard [6], the average diameter of austenite grains was measured.

Table 1 Chemical composition of analyzed steel

C	Mn	P	S	Si	Al	Nb	N	O
0.040	27.5	0.002	0.017	4.2	2.0	0.033	0.0028	0.0007

In order to determine the effect of solution heat treatmen temperature on mechanical properties, a static tensile test was carried out in according with ASTME8/E8M-15 standard [7]. The tests were carried out using the Zwick Z100 universal testing machine, equipped with an extensometer for measuring elongation. Flat samples dimension of 6.35 mm x 3 mm and measuring length of 25 mm were strained with a constant strain rate of $2.5{\cdot}10^{-3}\ s^{-1}$, at room temperature. Based on a static tensile test, the yield stress $YS_{0.2}$, ultimate tensile strength UTS, uniform elongation UEl and the reduction in area RA were determined. For each solution heat treatmen temperature, three tensile tests were performed and then the results were averaged. On the basis of the conducted research, the work hardening exponent *n** was determined as a function of increasing plastic deformation:

$$n^* = \frac{d(\ln \sigma)}{d(\ln \varepsilon)} \tag{1}$$

The work hardening exponent *n** was determined in the range from the actual deformation corresponding to the conventional yield stress to the maximum tensile stress value corresponding to the initiation of the neck formation in the sample. The fracture of the samples obtained after a static tensile test were examined in the SUPRA 35 scanning electron microscope from ZIESS, using an accelerating voltage of 15 kV and a magnification in the range from 1000x to 20000x. The chemical composition of the revealed non-metallic inclusions was identified using the EDS energy dispersive X-ray spectrometer produced by EDAX TRIDENT XM4. EBSD research allowed to obtain phase maps, grain distribution maps and IQ quality distribution maps.

3. RESULTS AND DISCUSSION

The structure of high-manganese steel 27Mn-4Si-3Al-Nb obtained by solution heat treatmen in water in the temperature range from 900 °C to 1200 °C is presented in **Figure 1**. This figure shows that the size of austenite grains increases with increasing a solution heat treatmen temperature. The fine-grained structure is visible in steel annealed in water from 900 °C and 1000 °C, and the average grain size is 21 μm and 56 μm respectively. Above 1000°C, a rapid increase in austenite grains was observed. Steel annealed from 1100°C and 1200°C has a coarse structure, and the average diameter of austenite grains is 226 μm and 360 μm respectively. Results confirming the effect of solution heat treatmen temperature on grain size are presented in **Table 2**.

Table 2 Effect of solution heat-treated temperature on the grain size

Solution heat-treatment temperature (°C)	Average diameter (μm)	Average grain area (μm²)	$YS_{0.2}$ (MPa)	UTS (MPa)	UEL (%)	RA (%)
900	20.7	458.9	454±16	784±19	35.1±2.9	41.6±2.0
1000	56.2	2954.5	406±12	705±15	38.3±1.6	43.0±1.2
1100	226.4	47651.8	345±13	658±21	45.0±0.9	48.0±1.0
1200	360.0	128991.0	535±11	635±25	23.6±2.0	37.5±3.5

As grain size increased, an increase in the number of annealing twins was also observed. The rapid growth of austenite grains above 1000 °C is probably caused by the dissolution of Nb carbonitrides and the system approaching the minimum of energy that is accumulated in all grain boundaries. Based on the obtained results, the effect of solution heat treatme temperature and thus the grain size on the mechanical properties of high-manganese steel was observed (**Figure 2**). The obtained results are presented in **Table 2**. In the temperature range from 900 °C to 1100 °C, the value of the yield stress $YS_{0.2}$ decreased from 454 MPa to 345 MPa and the ultimate tensile strength UTS from 784 MPa to 658 MPa. As a result of increasing the solution heat treatmen temperature in the range from 900 °C to 1100 °C, the plastic properties i.e. the value of uniform elongation increased from 35 % to 45 % and the reduction in area from 41 % to 48 %. The sample annealed from 1200 °C showing the largest grain size changed this relationship. It showed the lowest elongation and reduction in area values (23 % and 35 %) at the highest yield stress of $YS_{0.2}$ = 535 MPa. As expected, the diversified size of austenite grain size has an important impact on the strength and plastic properties of 27Mn-4Si-2Al-Nb steel.

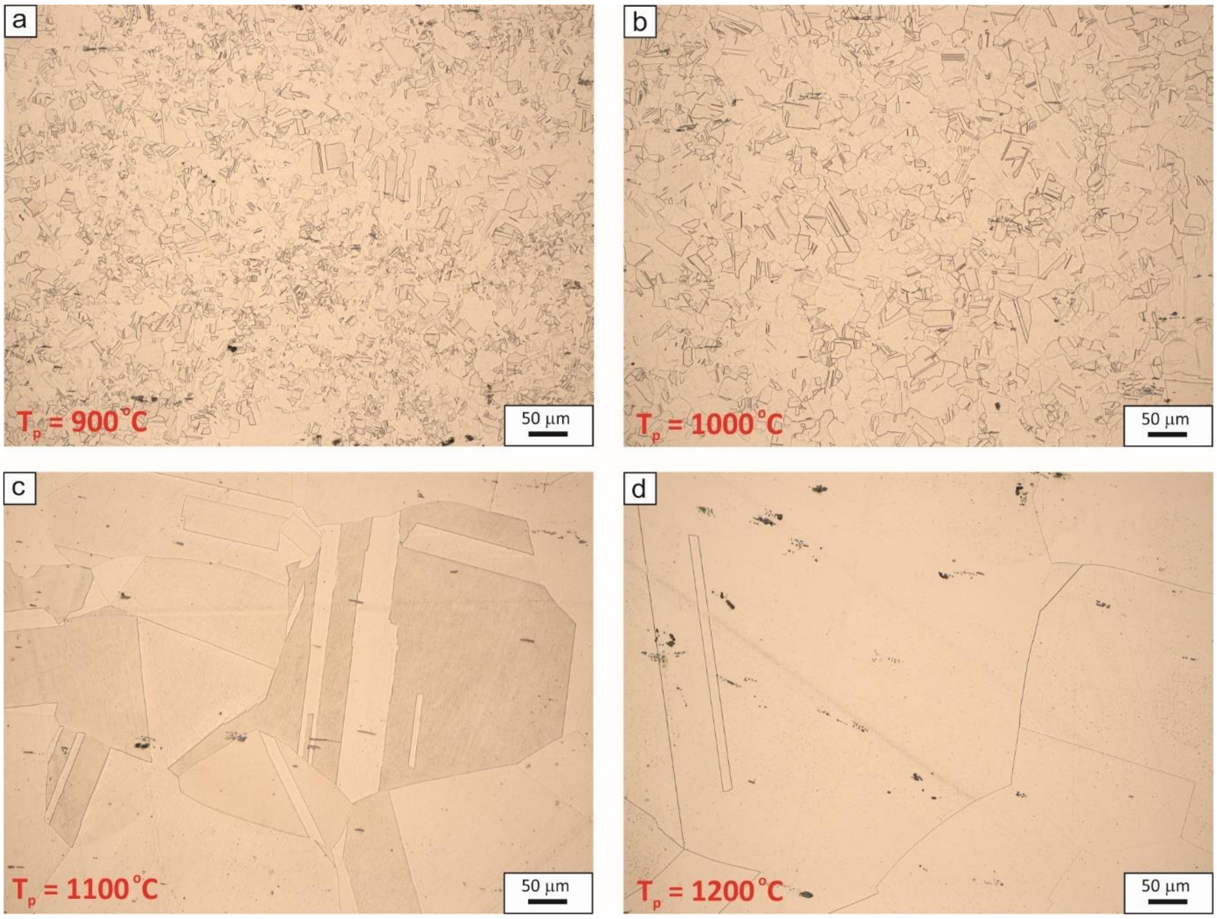

Figure 1 Austenitic structure with many annealing twins after solution he from temperature: 900 °C (a), 1000 °C (b), 1100 °C (c), 1200 °C (d)

Thanks to the static tensile test, the values of the work hardening exponent in the function of true strain were also determined. Steel as a result of deformation strengthened, as presented in **Figure 3**. The steel strengthening process depends on the size of the grain, including the solution heat treatmen temperature, which correlates with the stress-strain curves shown in **Figure 3**. The greatest strengthening is shown by steel solution heat treatmen in water from the temperature of 1100 °C with the greatest elongation and reduction in the area. As the grain size increases, deformation twins are easily formed, which inhibit the dislocation path and eventually strengthen the material. The lowest value of the work hardening exponent is shown by steel solution heat treatmen in water at the temperature of 1200 °C. Regardless of the solution heat treatmen temperature, the fracture of the tested samples is ductile with many craters and voids of various sizes (**Figure 4**).

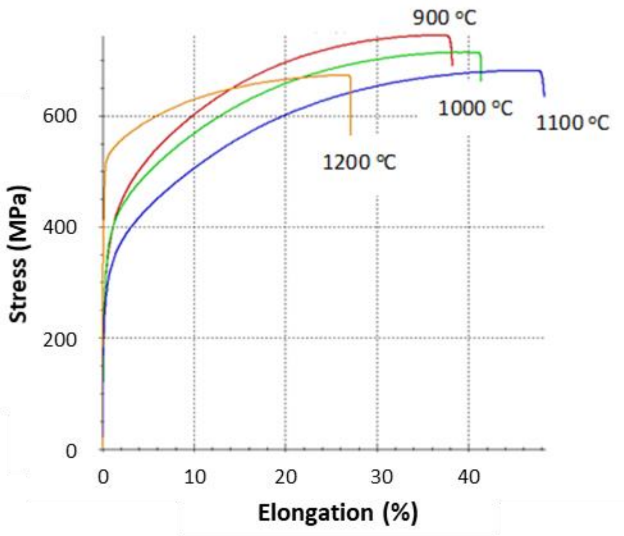

Figure 2 The stress-strain curves in the function of the solution heat treatmen temperature

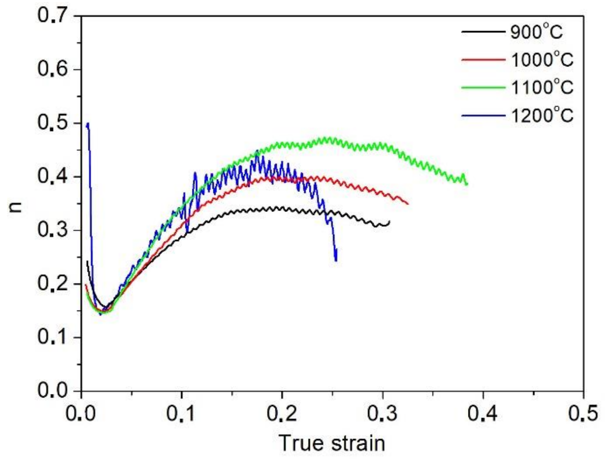

Figure 3 Dependence the work hardening exponent in the function of the deformation

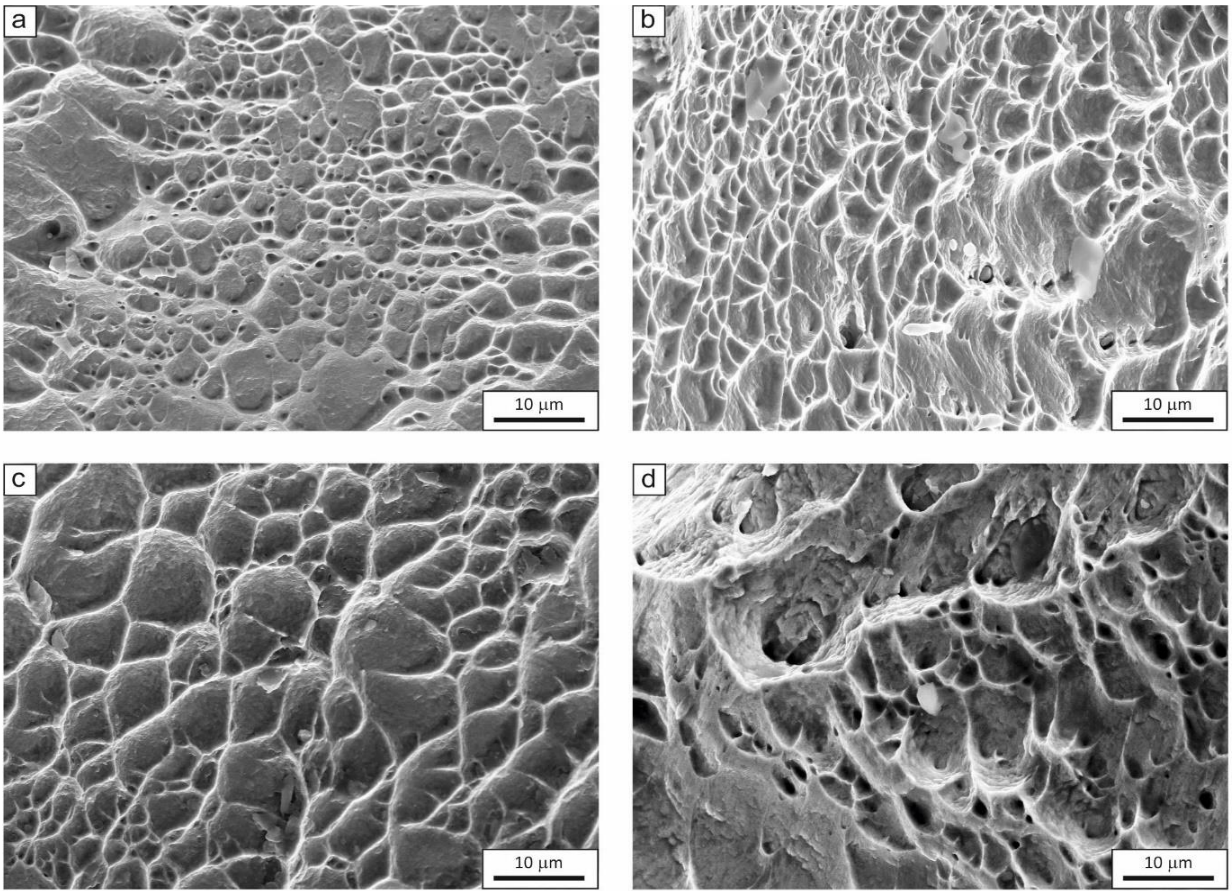

Figure 4 The fracture surface of samples of steel 27Mn-4Si-2Al-Nb after the tensile test; the solution heat treatmen temperature: 900 °C (a), 1000 °C (b), 1100 °C (c), 1200 °C (d)

As the solution heat treatmen temperature increased above 1000 °C, an increase in the size of voids and craters was observed, which correspond to the grain size. On the surfaces of fractures, non-metallic inclusions are located inside the craters. On the basis of qualitative analysis, it was confirmed that these was the most frequently complex non-metallic inclusions of the MnS-AlN (**Figure 5**) or AlN type. Qaban et al. in their work [8] showed that MnS type inclusions are convenient places for the locating of AlN nitrides, which are very detrimental to the ductility of steel. MnS-AlN and AlN particles in TWIP steels were also observed by Hongo et al. [9]. Yang et al. [10] showed that voids formed around non-metallic inclusions are coalescence due to increasing deformation and stress concentration. Such interactions with non-metallic inclusions and voids were observed on the fracture surface on samples annealed with the temperature of 1200 °C (**Figure 4d**). EBSD testing of a sample annealed from the temperature of 1200 °C and then subjected to tensile showed the presence of an intermetallic phase of the Fe2Al5 type (**Figure 6a**), located at the boundaries of the austenite grains and at the point of contact of the grains. Due to the possibility to remove the deformation bands from the surface of the preparation, they were also identified as the Fe_2Al_5 phase (**Figure 6b**), which made it impossible to accurately determine the percentage of this phase. Microhardness studies have shown that this phase is characterized by a higher hardness (432HV0,1) than the matrix (290HV0,1). This type of the phase was not revealed in the structure of steel solution heat treatmen at lower temperatures.

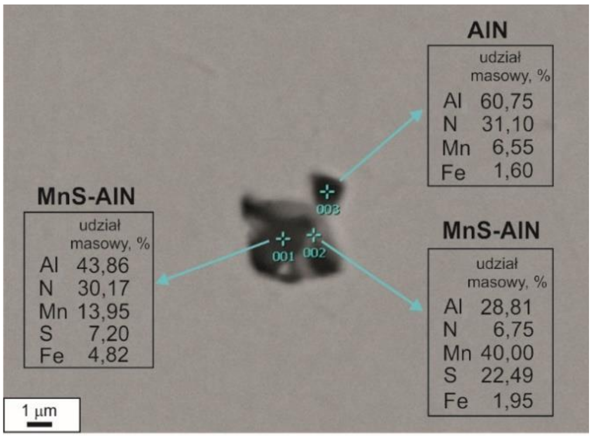

Figure 5 View of complex non-metallic inclusions of MnS-AlN and AlN types; the solution heat treatmen temperature 1200 °C

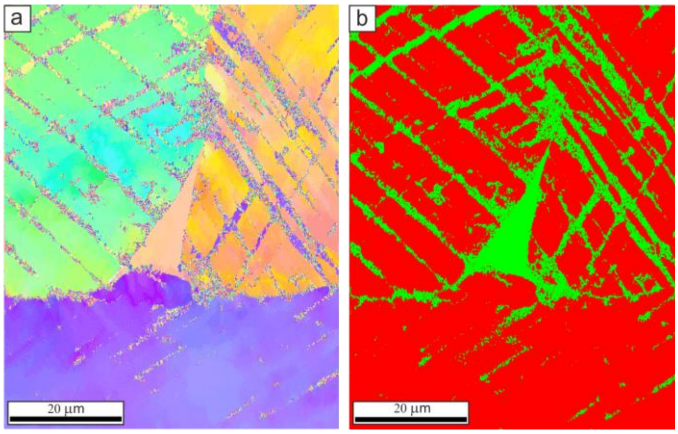

Figure 6 Results of EBSD analysis after solution heat treated from 1200 °C and subsequent tension: a – grain distribution map with different crystalline orientation, b – phase map with the Fe_2Al_5 phase marked in green and slip bands

4. CONCLUSION

The article presents the results of research on the influence of solution heat treated on the structure and mechanical properties of 27Mn-4Si-2Al-Nb steel. The solution heat treated in water in the temperature range from 900 °C to 1200 °C allowed to create a structure with different grain sizes, affecting the mechanical properties of the tested steel. As the grain size of austenite increases in the temperature range from 900 °C to 1100 °C, the strength properties decrease and the plastic properties increase. In this range, the solution heat treatment temperature of YS0.2 decreased from 454 MPa to 345 MPa, UTS from 784 MPa to 658 MPa, and the value of elongation increased from 35 % to 45 % and reduction in area from 41 % to 48 %. The deviation from this trend applies to a sample solution heat treat in water at the temperature of 1200 °C, also showing a different course of the stress-strain curve. This is due to the very large size of austenite grains about 360 μm and the Fe_2Al_5 phase revealed at the grain boundaries. The growth of austenite grains, especially visible after exceeding the temperature of 1000° C, is associated with the dissolution of Nb carbonitrides in solution, which is consistent with the results of research presented in papers [11,12]. Studies of the fracture surface in the scanning electron microscope revealed a ductile fracture with many craters and voids of different sizes, corresponding to the sizes of austenite grains. On the fracture surface, non-metallic inclusions were identified, in the majority of cases they were MnS-AlN and AlN inclusions, which adversely affect the ductility of the studied high-manganese steel. As shown in paper [10,13], the areas closest to non-metallic inclusions are privileged places for the flowing of voids and micropores. These voids coalescence as a result of increasing deformation and stress concentration, leading to cracking. This is confirmed by very low values of plastic properties obtained after solution heat treatment at the temperature of 1200 °C (RA - 37 %, and UEL - 23 %).

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