International Journal of Modern Manufacturing Technologies
ISSN 2067–3604, Vol. XII, No. 2 / 2020

EFFECT OF SOLUTION HEAT-TREATED CONDITIONS ON STRUCTURE AND MECHANICAL PROPERTIES OF HIGH-MANGANESE STEEL

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Abstract: The high-Mn austenitic steel containing 0.054% C, 24.4% Mn, 3.5% Si, 1.6% Al, 0.0039% N, 0.029% niobium and 0.075% titanium was investigated in the work. The steel was solution heat-treated at different temperatures in a range from 900°C to 1200°C. The microstructure was characterized by light microscopy and scanning electron microscope. The average diameter of austenite grains increased from approx. 14 μm at the solution annealing temperature of 900°C to about 230 μm – for the solution annealing temperature equal 1200°C. The mechanical properties are a compromise between intensity of mechanical twinning and the grain size. It was shown that the solution annealing temperature affects significantly the grain size and strain hardening behavior of the investigated high-Mn steel with Nb and Ti microadditions.

Key words: high-manganese steel, solution heat treatment, structure, grain size, mechanical properties.

1. INTRODUCTION

Rapid development of new steel groups, used in the automotive industry, has been observed since the beginning of the 21st century. Increasingly stringent requirements, related to reducing vehicle weight, increasing passenger safety, reduction of fuel consumption and the amount of exhaust emissions to the environment, have caused an increase of interest in high-manganese austenitic steels. These steels are characterized by a perfect combination of high strength and plasticity. High-manganese austenitic steels, Fe-Mn-Al-Si, usually contain from 15% to 30% Mn, from 0.02% to 0.65% C and diversified concentration of Al and Si. Some steels may also contain Cr or microadditions of Nb, Ti and V, which affect the value of stacking fault energy (SFE) [1-3].

Strain hardening, and hence mechanical properties of high-manganese steels, depend mainly on the structural processes occurring during cold plastic deformation, which are dependent on the SFE of austenite. Partial transformation of austenite into martensite – the TRIP effect (Transformation Induced Plasticity) occurs in the case where the value of SFE of austenite is equal or less than 20 mJ/m^2 [4, 5]. When the SFE value of austenite is in the range of 20÷60 mJ/m^2, then there is an intense mechanical twinning – the TWIP effect (Twinning Induced Plasticity) [6-8]. In addition to SFE, the temperature, strain rate and grain size significantly influence the course of the main strengthening mechanism [9].

Grain size considerably affects the strengthening of steel. Chen, Yuan et al. [10] studied the Fe-25Mn-30Cr-3Al-0.3C type high-manganese austenitic steel, produced in the process of cold rolling, subsequently subjected to annealing in a temperature range from 700°C to 1000°C. They revealed that along with increasing grain size from 2 μm to 30 μm, yield strength (YS) decreased from approx. 400 MPa to about 230 MPa, ultimate tensile strength (UTS) decreased from approx. 720 MPa to about 510 MPa, while uniform elongation (UEl) 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 [7, 11].

It was revealed in [12] that the grain size reduction in high-manganese austenitic steel, containing 31% Mn, 3% Al and 3% Si, caused a significant reduction of the quantity of twins and plasticity decrease. However, in [13, 14] it was shown that the strengthening of steel with high manganese content increases with the increase in the quantity of boundaries of mechanical twins. Formed mechanical twins divide austenite grains, creating strong barriers to moving dislocations, which determines high strengthening of steel.

The purpose of the work is to investigate the impact of solution annealing temperature on grain size and mechanical properties of the newly elaborated Fe-24Mn-3.5Si-1.6Al-0.05C high-manganese austenitic steel with niobium and titanium.

2. MATERIAL AND EXPERIMENTS

The research was carried out on steel containing 0.054% C, 24.4% Mn, 3.5% Si, 1.6% Al as well as Nb and Ti microadditions at a concentration of 0.029% and 0.075%, respectively. Steels are characterized with high metallurgical purity (0.004% P, 0.016% S, 0.0039% N and 0.0006% O). Modification of non-metallic inclusions was carried out with the use of Ce and La, in a concentration of 0.058% and 0.020%, respectively, which were introduced in the form of mischmetal in an amount of 2.0 g per 1 kg of steel. Steel melting was performed in the TEPLA VSG-100 type laboratory vacuum induction furnace. Initial plastic working of ingots into 30 mm x 150 mm flat bars was carried out with the method of open die forging. Samples for testing were taken from a 6 mm thick metal sheet produced in the process of hot rolling. Specimens with dimensions of 15 mm x 20 mm x 6 mm were subjected to solution annealing in a temperature range 900÷1200°C, with 100°C gradation. Prior to cooling in water, the samples were held at the set temperature for 60 minutes. In order to reveal the microstructure, prepared metallographic specimens were etched in 4% nital. Microstructural observations were carried out using ZEISS Axio Observer light microscope. Average diameter of austenite grains was measured with the use of Axio Vision software in accordance with ASTM E112-10 standard [15].

A static tensile test was performed to investigate the effect of solution annealing temperature on mechanical properties of tested steel. The tests were conducted at room temperature in accordance with ASTME8/E8M-15 standard [16], with the use of ZWICK Z100 universal testing machine. Flat samples with 6.35 mm x 3 mm cross-section and 25 mm gauge length (Figure 1) were subjected to tension at the rate of 0.25 x 10^{-3} s^{-1}.

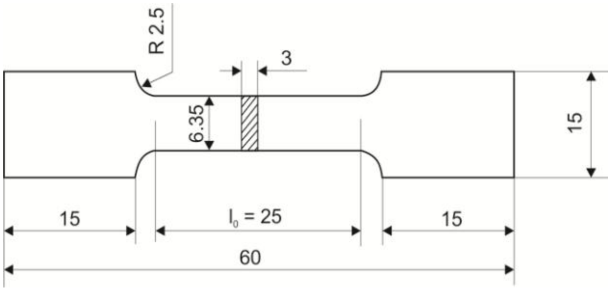

Fig. 1. Shape and dimensions of the specimen used for testing

Performed investigation allowed to determine the yield stress $YS_{0.2}$, ultimate tensile strength UTS, uniform elongation UEl and the reduction in area RA. Obtained results are the average of three tests carried out for each solution annealing temperature.

Examination of fracture surfaces of samples after tensile tests was carried out in ZIESS SUPRA 35 high-resolution scanning electron microscope, applying an accelerating voltage of 15 kV. Observations were performed in the magnifications range of 100÷20000x. Identification of chemical composition of non-metallic inclusions, revealed at the fractures, was carried out using the EDS energy dispersive X-ray spectrometer produced by EDAX TRIDENT XM4.

3. RESULTS AND DISCUSSION

Solution annealing of samples in water in a temperature range from 900÷1200°C allowed to obtain diversified sizes of austenite grains of examined steel. Figure 2 presents the austenitic microstructure of Fe-24Mn-3.5Si-1.6Al-0.05C high-manganese steel obtained after the solution heat treatment under the mentioned conditions. As it results from the figure, fine-grained austenite microstructure is observed for samples annealed in water at the temperature of 900°C and 1000°C (Figure 2(a), (b)). Increasing the solution annealing temperature to 1100°C and 1200°C results in significant growth of austenite grains with annealing twins locating themselves inside the grains (Figure 2(c), (d)). The dependence of austenite grain size as a function of solution annealing temperature is presented in Figure 3. Specimens annealed in water from the temperature of 900°C reveal fine-grained microstructure with an average austenite grain size of approx. 14 μm. Increasing the temperature of solution annealing by 100°C does not lead to significant increase in austenite grain size. Specimens annealed in water from the temperature of 1000°C reveal fine-grained microstructure with an average grain size of approximately 19 μm. Rapid austenite grain growth was observed after exceeding the temperature of 1000°C, as it results from Figure 3. Solution annealing of studied steel samples in water from the temperature of 1100°C results in formation of coarse-grained microstructure with annealing twins, with an average austenite grain diameter of approx. 137 μm. The highest average diameter of austenite grains – equal about 230 μm – was observed for samples which were annealed at the temperature of 1200°C. Rapid austenite grain growth of tested steel, after exceeding solution annealing temperature of 1000°C, is the result of the system approaching the minimum of energy, which is accumulated in all grain boundaries. This effect should also be explained by gradual dissolution of carbonitrides containing Ti and Nb microadditions above this temperature. Similar effects were observed in [3, 17].

As expected, diversified size of austenite grains has an important impact on mechanical properties of examined steel (Figure 4). The figure shows the curves registered during tensile test for different solution annealing temperatures.

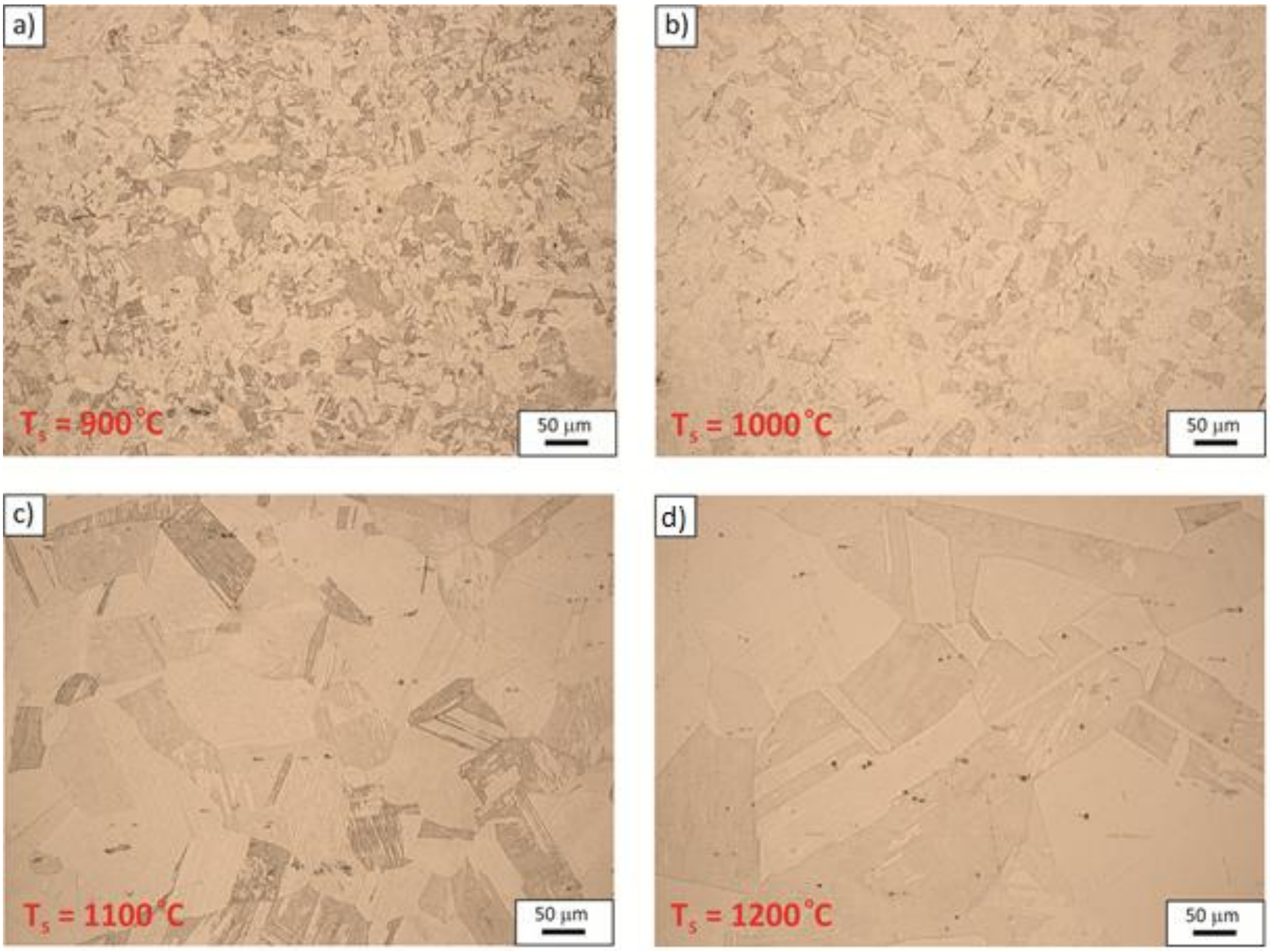

Fig. 2. Austenitic microstructure after solution heat-treated at the temperature of (a) 900 °C, (b) 1000 °C, (c) 1100 °C and (d) 1200 °C

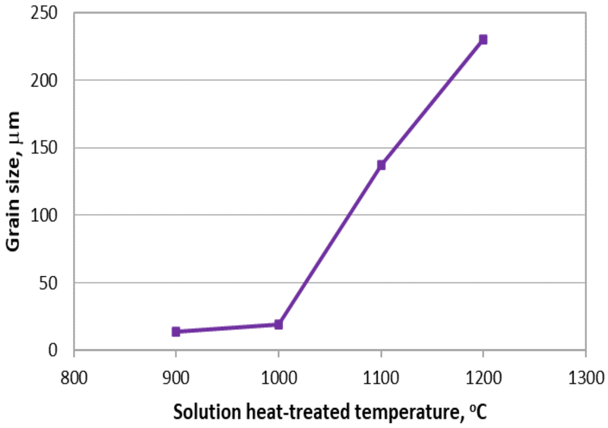

Fig. 3. Dependence of austenite grain size on solution heat-treated temperature

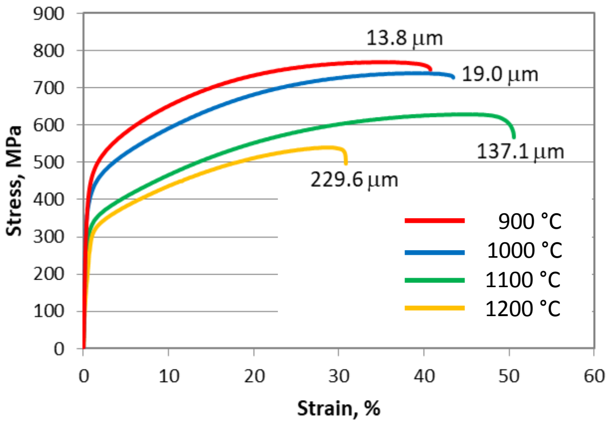

Fig. 4. Dependence of austenite grain size on stress-strain

Detailed results of the research on the impact of solution annealing temperature and grain size on mechanical properties are summarized in Table 1. It follows from the data set together in the table that grain size clearly affects both the strength and plasticity of investigated high-manganese austenitic steel. The highest strength ($YS_{0.2}$ ~ 478 MPa; UTS ~ 770 MPa) was noted for a specimen subjected to solution annealing in water at the temperature of 900°C, characterized with the finest grain. The increase in grain size, caused by increase of solution annealing temperature from 900°C to 1200°C, led to decrease in yield strength from 478 MPa to 310 MPa and tensile strength from 770 MPa to 540 MPa. Decrease of strength is accompanied by significant increase of elongation, but only in the range of solution annealing temperature from 900÷1100°C.

Table 1. Effect of the austenite grain size on mechanical properties of investigated high-Mn steel

Solution heat-treatment temperature, [°C]	Average diameter, [μm]	Yield strength ($YS_{0.2}$), [MPa]	Ultimate tensile strength (UTS), [MPa]	Uniform elongation (UEl), [%]	Reduction in area, (RA), [%]
900	13.8	478.0	770.3	38.3	43.0
1000	19.0	440.3	735.3	42.1	45.2
1100	137.1	336.5	640.2	48.2	51.4
1200	229.6	310.1	540.0	30.0	39.3

Increasing solution annealing temperature to 1200°C leads to decrease of elongation to about 30%. Similar results on the impact of grain size on mechanical properties of high-manganese austenitic steels were achieved in [10, 12, 13]. It is well known – according to the Hall-Petch relationship, that the strength of polycrystalline materials can be increased by refinement of grains. The dependence of stress as a function of grain size can be determined by calculating the inverse of the square root from the grain size [18, 19]. The Hall-Petch linear relationship for studied steel is presented in Figure 5.

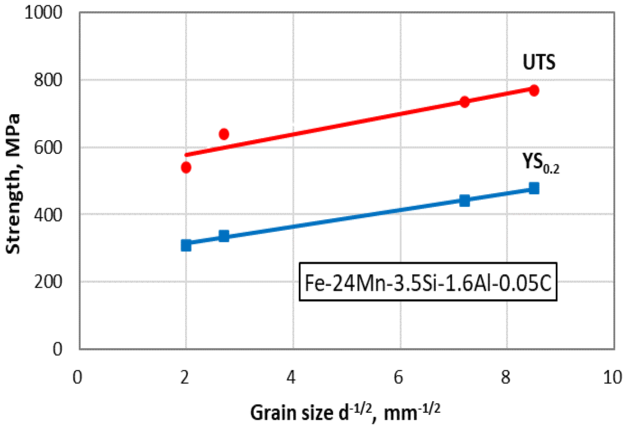

Fig. 5. Dependence of grain sizes in high-Mn austenitic steel on yield strength and ultimate tensile strength

In order to determine the influence of – temperature on the nature of fracture surfaces of samples subjected to tension at the room temperature, the investigated was performed in scanning electron microscope. Topography of fracture surfaces of samples annealed at the temperature of 900°C and 1200°C is shown in Figure 6. Performed investigation revealed that the fractures of samples – regardless of the solution annealing temperature – are ductile with numerous craters and voids of various sizes. Conducted analysis showed that the size of craters increases considerably when the temperature exceeds 1000°C.

Reduced elongation of the sample, annealed at the temperature of 1200°C, should be explained by great size differences of craters that determine different plastic flow conditions in the micro-areas. At this temperature, due to carbon microsegregation caused by increased diffusion rate, macroscopic voids and non-metallic inclusions play an important role in fracture mechanism [20].

Observations carried out in scanning electron microscope allowed to reveal fine non-metallic inclusions (with an average diameter of about 1 μm) of a globular or globular-like form, located primarily in formed craters, with significantly more of them observed at the fractures of samples after solution annealing at higher temperatures. Conducted qualitative analysis of chemical composition of revealed non-metallic inclusions confirmed effectiveness of applied modification of non-metallic inclusions with rare-earth elements, i.e. cerium and lanthanum in the smelting process. In the prevailing number of cases, MnS-type inclusions fully or partially modified with Ce and La were disclosed (Figure 7). Similar results on the effect of rare-earth elements on the modification of non-metallic inclusions were obtained in the works [9, 21, 22].

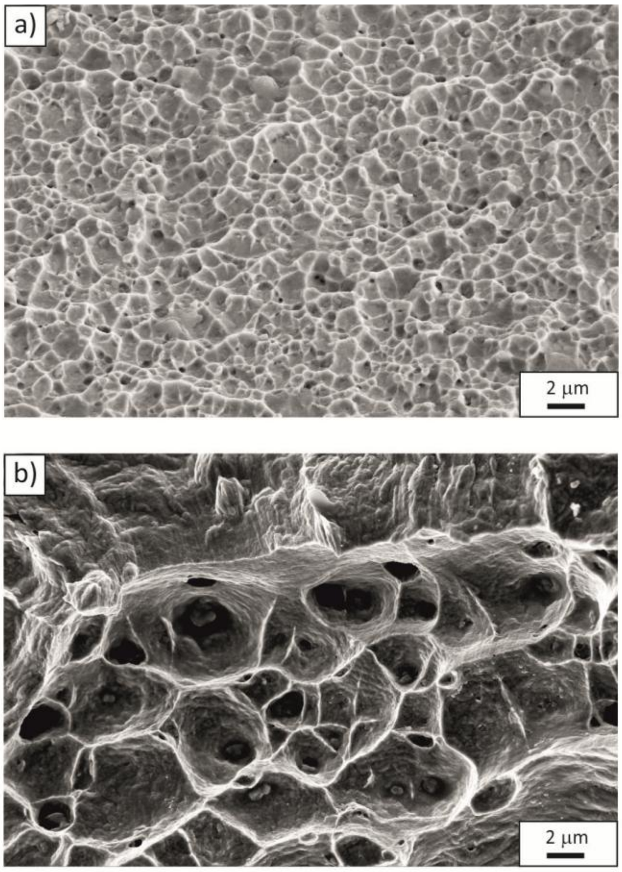

Fig. 6. Ductile fracture samples after tensile test; solution annealing temperature: a) 900 °C, b) 1200 °C

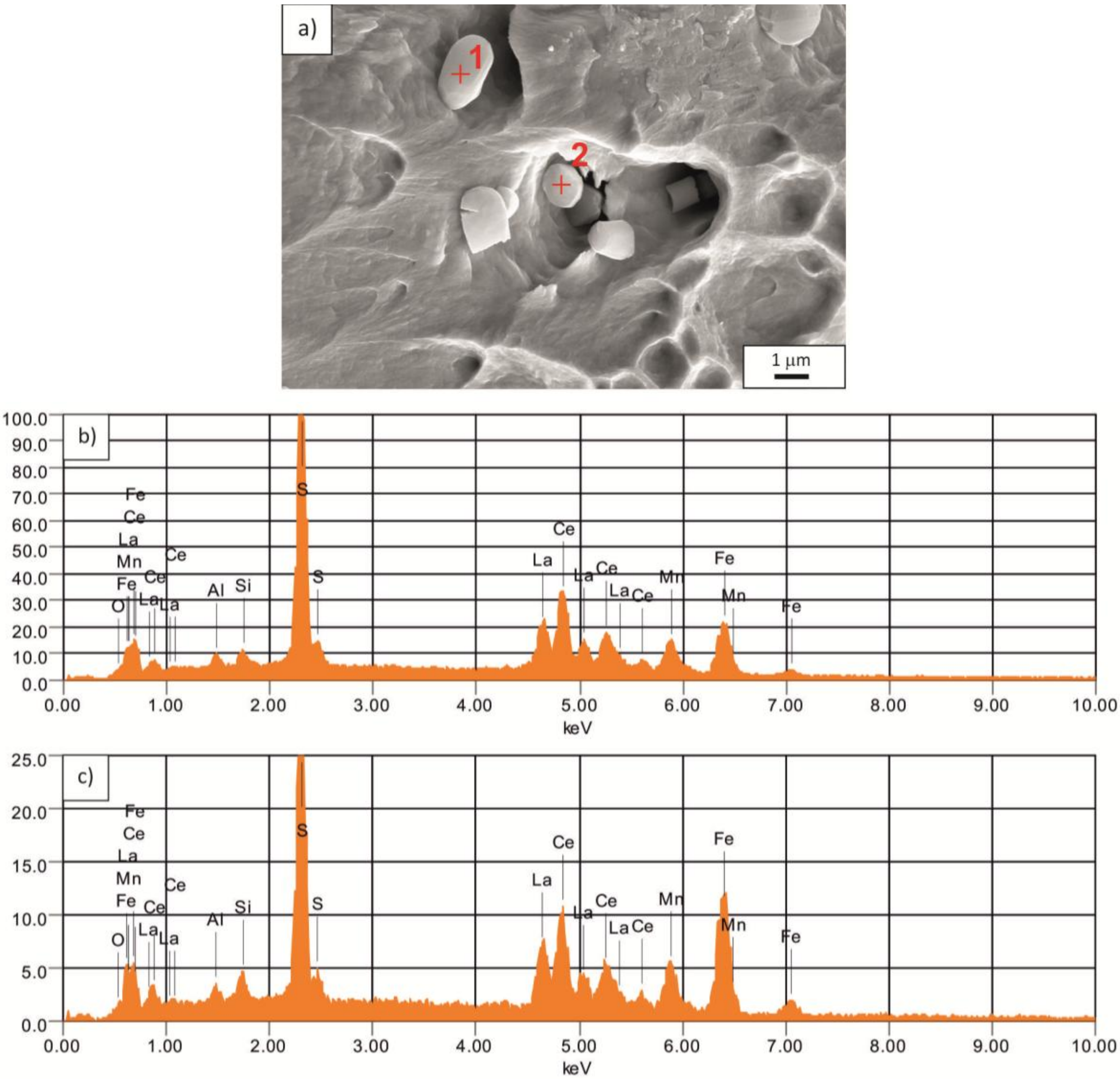

Fig. 7. MnS-type inclusions partially modified with Ce and La: a – view of the inclusions, b – the EDS spectrum of the inclusion 1, c – the EDS spectrum of the inclusion 2; solution annealing temperature of 1100 °C

4. CONCLUSIONS

The work described investigation results of the impact of solution annealing temperature on microstructure and mechanical properties of Fe-24Mn-3.5Si-1.6Al-0.05C high-manganese austenitic steel with Nb and Ti microadditions. Solution annealing in water in the temperature range from 900°C to 1200°C allowed to produce different grain sizes, which determine mechanical properties of examined steel. Along with the decrease of austenite grain size, strength properties increase and plastic properties decrease. Such obvious dependence was revealed in the range of solution annealing temperature from 1100°C to 900°C. In this solution annealing temperature range, $YS_{0.2}$ increased from 337 MPa to 478 MPa, UTS increased from 640 MPa to 770 MPa, while UEl decreased from 48% to 38%. Deviation from this trend applies to the sample annealed in water from the temperature of 1200°C, also showing a slightly different course of the stress-strain curve. This should be explained by large size of austenite grains (of about 230 µm) and heterogeneous voids observed on the fracture surface (Figure 6(b)). Increasing solution annealing temperature from 900°C to 1200°C resulted in growth of austenite grains, with their rapid development observed after exceeding the temperature of 1000°C. This is related to dissolution of Ti and Nb carbonitrides in the solution, which is also consistent with the research results presented in [3, 17].

Investigation of fracture surfaces in scanning electron microscope showed that regardless of the solution annealing temperature applied, samples have a typical ductile fracture, and the size of the dimples corresponds to the size of grains. On the surface of fractures, in prevailing number of cases, globular non metallic MnS-type inclusions were identified, present due to high concentration of Mn in the steel. Revealed non-metallic inclusions were properly modified with rare earth elements (Ce, La) in the process of smelting. Their globular or close to globular form causes that the inclusions of this type will be difficult to deform during plastic working process, and therefore they will not affect the disadvantageous increase of plastic properties anisotropy of finished steel products obtained from this steel.

As shown in [20, 23], areas in the immediate vicinity of non-metallic inclusions are privileged for formation of voids. These fine voids, formed around non-metallic inclusions, undergo coalescence because of increasing strain and concentration of stress. Therefore, premature cracking and low plasticity of the sample annealed from the temperature of 1200°C should be explained by complex correlation between non-metallic inclusions, abnormal grain growth as well as coalescence and growth of voids.

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Received: August 29, 2020 / Accepted: December 15, 2020 / Paper available online: December 20, 2020 © International Journal of Modern Manufacturing Technologies