Ihor DZIOBA, Sebastian LIPIEC
Kielce University of Technology,
Faculty of Mechatronics and Machine Engineering
pkmid@tu.kielce.pl, slipiec@tu.kielce.pl

TESTING THE MECHANICAL PROPERTIES OF S355JR STEEL WITH DIFFERENT TYPES OF MICROSTRUCTURE

Key words

Microstructure, Strength Properties, Fracture Toughness.

Abstract

S355JR steel was objected for testing. Different microstructure types – ferritic-perlitic, ferritic-bainitic and ferritic with coagulated carbon particles were obtained in laboratory conditions. The mechanical properties and the fracture toughness for the steel of various microstructures were determined for a temperature of 20°C. It was shown that the S355JR steel of all tested microstructure types are highly plastic materials and have a high level of the fracture toughness properties.

Introduction

The article presents the results of experimental tests on the S355JR (former symbol – 18G2A) steel. It is a weldable steel, frequently used in welded and heat sealed structures including tanks and pressure pipes [1]. S355JR steel of various types of microstructure were analysed, including those with a ferritic-pearlitic structure (FP) subjected to normalization, and with a ferrite-bainitic structure (FB) after austenitic annealing, and quickly cooled by quenching in oil. These types of the steel were subjected to prolonged annealing that caused coagulation of carbides and the formation of a microstructure of ferrite with large carbide particles (FC1 – material heat soaked after quenching, FC2 – material heat soaked after normalization). An important aspect of the research is the fact that types of the S355JR steel microstructure achieved by heat treatment, FP and FB, occurs in welded joints, in a weld material, and in a heat affected zone material [2–5]. In low carbon steel after long-term operation, a FC type of microstructure was formed [6]. In the performed tests for various microstructure types of S355JR steel, metallographic analysis were carried out, and strength and fracture toughness characteristics were determined. All testing for determining mechanical properties and fracture toughness were performed at the temperature of 20°C.

1. Heat treatment procedures

The S355JR steel was subjected to laboratory heat treatment (Tab. 1). The ferritic-pearlitic microstructure was obtained by normalized treatment (Fig. 1). As a result of austenitic annealing and cooling in oil of the S355JR steel, a ferritic-bainitic structure was obtained (Fig. 2). Obtaining a material of ferrite microstructure with coagulated carbide particles distributed along the grain boundaries and within the ferrite grains (Fig. 3, 4) was possible by prolonged annealing. The used heat treatment regimens of the S355JR steel are presented in Table 1.

Table 1. The heat treatment regimens of the S355JR steel

Structure	1st step			2nd step		
	Annealing			Annealing		
	Time [min]	Temp. [°C]	Cooling medium	Time [min]	Temp. [°C]	Cooling medium
FP	20	950	Air	-	-	-
FB	20	950	Oil	-	-	-
FC1	20	950	Oil	9000	600	Oil
FC2	20	950	Air	9000	600	Oil

a) b)

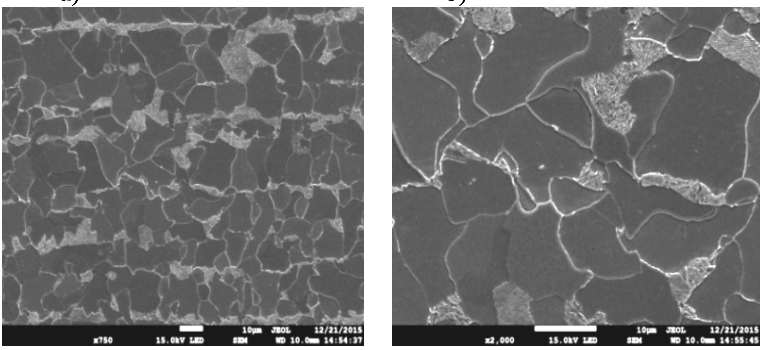

Fig. 1. Ferritic-pearlitic microstructure of the S355JR steel

a) b)

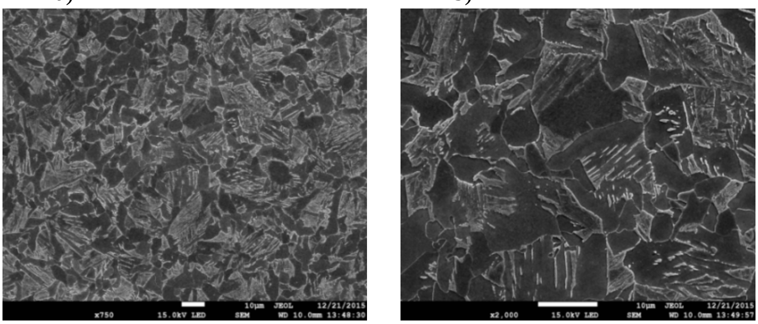

Fig. 2. Ferritic-bainitic microstructure of the S355JR steel

a) b)

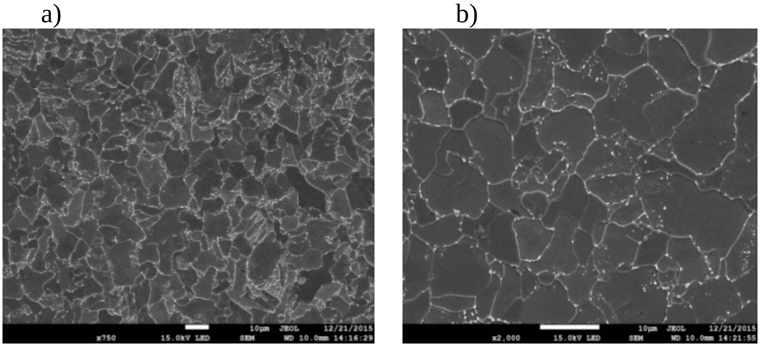

Fig. 3. Ferrite with large carbide particle microstructure of the S355JR steel (annealing after austenitization and quenching)

a) b)

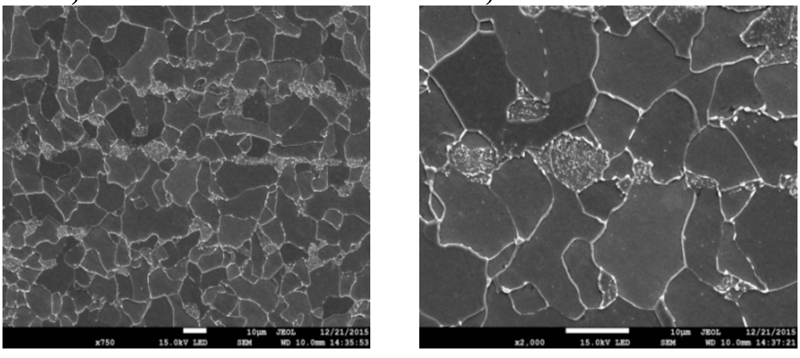

Fig. 4. Ferrite with large carbide particle microstructure of the S355JR steel (annealing after normalization)

2. Experimental studies

2.1. Mechanical properties testing

The strength characteristics of the S355JR steel with different microstructures was determined by conducting uniaxial tensile tests [7] in a UTS/Zwick (100 kN) testing machine. Tests were conducted on standard specimens, round, five-fold, with an initial diameter of 5 mm. The specimens were loaded to destruction. Signals of the force P and extensometer elongation Δu were recorded. Based on the results of the tensile tests, nominal (engineering) and true strength characteristics of the S355JR steel were determined. The true stress values were determined from the relation (1), while the true strain from equation (2):

$$\sigma_t = \sigma(1+\varepsilon) \tag{1}$$

$$\varepsilon_t = \ln(1+\varepsilon) \tag{2}$$

where

σ – nominal stress,
ε – nominal strain.

Engineering (a) and true (b) curves and stress, strain values, Young's modulus and hardness of the S355JR steel with different microstructures are presented in Figure 5 and Table 2. The mechanical properties for all microstructure types are higher than the minimal requirements of the standard for this steel [8]. The determined true material characteristics are necessary for modelling the construction components and for carrying out simulations and analysis by numerical computation.

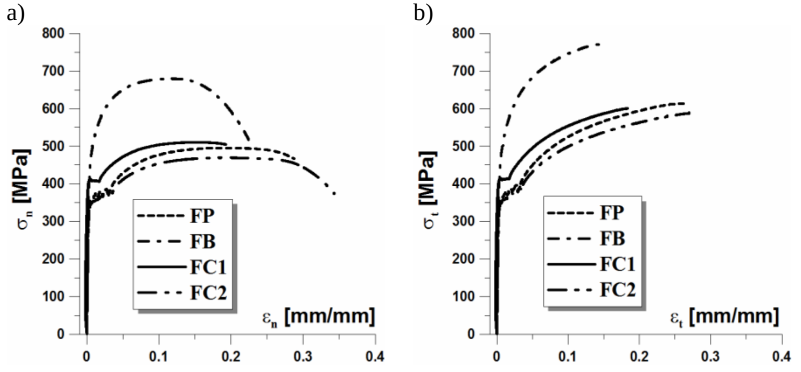

Fig. 5. The stress-strain curves of S355JR steel of different microstructure types: a) the nominal (engineering) records, b) the true records

Table 2. Mechanical properties of S355JR steel of different microstructures

Microstructure	Re [MPa]				R_m		E [GPa]	HV10
	Nominal		True		Nominal	True		
	R_{eL}	R_{eH}	R_{eL}	R_{eH}				
FP	367	386	378	396	495	613	197	144
FB	463		466		679	771	206	194
FC1	406	412	411	414	510	602	200	165
FC2	373	381	384	392	469	588	201	143

2.2. Fracture toughness testing

The results obtained during tensile tests indicate that S355JR steel with different tested microstructures are highly plastic materials; therefore, the critical value of J integral, J_{IC}, was used to determine the fracture toughness Using the procedure of change specimen compliance for subcritical crack extension during the specimens loading made it possible to determine the critical value of J integral, J_{IC} for each single tested specimen [8].

The tests were performed on three-point bend standard specimens SEN(B) with dimensions, $B = 12$, $W = 24$, $S = 96$ (mm). All specimens were adequately prepared for testing by cutting a single-notch and growing of the initial fatigue pre-crack length of $a/W \approx 0.5$. During the fracture toughness tests, signals were recorded in the operate-controlling system of the UTS/Zwick (100kN) testing machine in real time – the load (P), the deflection of the specimen at the point of force application (Δu), and crack mouth opening (δ_M).

Figure 6a presents the records of loading forces in the function of the displacement point of force application for tested specimens of different microstructures. The resistance curves J_R of the test S355JR steel with different microstructures are presented in Figure 6b. The graph of the resistance curves

$J_R$for steel of ferritic-pearlitic structure lies above other curves, and the critical value of J integral shows the highest value, J_{IC} = 377 kN/m, among analysed types of microstructures. The lowest value of the fracture toughness (J_{IC} = 181 kN/m) was obtained by the S355JR steel of a ferritic-bainitic microstructure and its graph of the resistance curves J_R are placed lower than another graphs. The specimens of the S355JR steel of ferrite with a microstructure of coagulated carbide particles for both types of microstructure FC1 and FC2, shows a similar trend of the resistance curves J_R and critical values of the J-integral.

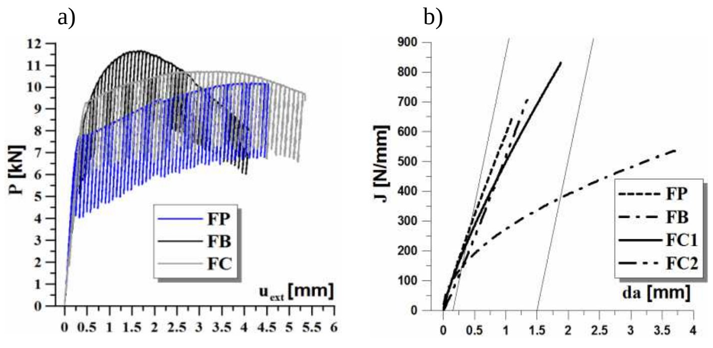

Fig. 6. Graphs for the S355JR steel with different microstructures: a) load – displacement, P-u_{ext}; b) resistance curves, J_R

Summary

The paper presents the determined mechanical properties and fracture toughness of the S355JR steel with various types of microstructure that were obtained as a result of a laboratory heat treatment. The steel after treatment of normalization showed a ferritic-pearlitic microstructure. After austenitic thermal heating and fast cooling (oil was using as the cooling medium), the microstructure of ferritic-bainite was obtained. As result of long-term annealing of steel with ferrite-pearlite and ferrite-bainitic microstructures, degradation of bainite and pearlite and the coagulation and growth of carbides particles were observed.

The results of tensile tests indicate that all tested types of microstructures found in the S355JR steel have high plastic properties. The steel of ferritic-bainitic microstructure shows the highest level of strength properties and hardness, but it has the lowest level of plasticity. The S355JR steel with microstructures of ferritic-perlitic and ferritic with coagulated carbides have similar levels of strength and plastic properties.

Because of the high plasticity of the S355JR steel, its fracture toughness was evaluated based on the critical value of the J integral, J_{IC}. For all microstructure types, the ductile mechanism of sub-crack propagation was obtained. Lowest level of the critical value of fracture toughness was found for steel of a ferritic-bainitic microstructure. In contrast, the steel of a ferritic-pearlitic microstructure has the highest critical value of fracture toughness among tested specimens. The critical values of fracture toughness for the S355JR steel of a ferritic microstructure with coagulated carbides are insignificantly lower than the steel with a ferritic-pearlitic microstructure.

Steel S355JR is widely used in various constructions, and often elements made of it are welded. As a result, in the weld material and in the heat affected zone material a material of a bainitic-ferritic microstructure is formed. Long-term use of welded elements, especially at high temperatures, leads to changes in the microstructure and generate a ferritic steel with coagulated carbides. Knowledge about mechanical and fracture properties of S355JR steel with various types of microstructures will help perform more precision analysis of their strength and durability during use.

References

1. Dobrzanski L.A.: Materials science lexicon, basic settlement of polish, foreign and international standard, Metals, Polymers, Ceramics, Composites. Verlag Dshofer. 1999 (in polish).
2. Dzioba I., Skrzypczyk A.: Properties and microstructure of MAG butt-welded joints for 18G2A steel. Welded Rev. 2006, 9–10, pp. 32–35 (in polish).
3. Dzioba I., Neimitz: Application of the standard options of the FITNET Porcedure to the structural integrity assessment of welded specimens containing cracks. International Journal Pressure Vessel and Piping. 2007, 84(8), pp. 475–486.
4. Xueda L., Xiaoping M., Subramanian S.V., Misra R.D.K., Shang Ch.: Structure–Property–Fracture Mechanism Correlation in Heat-Affected Zone of X100 Ferrite−Bainite Pipeline Steel.Metallurgical and Materials Transactions. 2015, Volume 2, Issue 1, pp. 1–11.
5. Boumerzoug Z., Derfouf Ch., Baudin T.: Effect of Welding on Microstructure and Mechanical Properties of an Industrial Low Carbon Steel. Scientific Research Engineering. 2010, 2, pp. 502–506.
6. Dzioba I.: The influence of long-term exploitation on the mechanical properties of the weld joins for power plants pipelines. 2008, 15, pp. 39–42 (in polish).
7. PN-EN ISO 6892-1:2010.: Metallic Materials. Tensile Testing.Part 1.Method of Test at Room Temperature. 2010 (in polish).

8. PN-EN 10025-2:2007.:Hot Rolled Products Of Structural Steels. Part 2. Technical Delivery Conditions For Non-alloy Structural Steels. 2007 (in polish).
9. ASTM E1820-09.: Standard Test Method for Measurement of Fracture Toughness. Annual Book of ASTM Standards.2011, vol. 03.01, pp. 1070–1118.

Financial support from the Polish Ministry of Science and Higher Education under contracts No 2014/15/B/ST8/00205 and 01.0.08.00/2.01.01.01.0008.

Badanie właściwości mechanicznych stali S355JR o różnych typach budowy mikrostrukury

Słowa kluczowe

Mikrostruktura, właściwości wytrzymałościowe, odporność na pękanie.

Streszczenie

Badaniom została poddana stal S355JR. W materiale na skutek przeprowadzenia laboratoryjnej obróbki cieplnej uzyskano mikrostruktury: ferrytyczno-perlityczną, ferrytyczno-bainityczną oraz ferrytu ze skoagulowanymi cząstkami węglików. Charakterystyki wytrzymałościowe oraz odporności na pękanie zostały wyznaczone w temperaturze 20°C. Wykazano, iż stal S355JR o różnej budowie mikrostruktury jest materiałem o wysokiej plastyczności oraz wysokim poziomie charakterystyk odporności na pękanie.