ADVANCED THERMO-MECHANICAL TREATMENT OF BIMETALLIC SEMI-PRODUCTS COMPOSED BY S700MC AND 316L STEELS

Anastasiya DOLZHENKO, Zhanna YANUSHKEVICH, Marina ODNOBOKOVA,
Andrey BELYAKOV and Rustam KAIBYSHEV

Belgorod State University, Belgorod, Russian Federation
lugovskaya.anastasiya94@gmail.com

Abstract

The microstructure and mechanical properties of high strength low-carbon steel, an austenitic stainless steel and the bimetallic semi-product produced from these steels were investigated. Two steels, an S700MC-type high strength low-carbon steel and a 316L-type austenitic stainless steel, were used as the layer materials for bimetallic semi-product, which was produced by electro-slag cladding. The both steels were subjected to warm rolling as a method of thermo-mechanical treatment. The effect of processing conditions on the microstructure and mechanical properties of the 316L and S700MC steels and bimetallic semi-product was clarified. The ultrafine-grained microstructures with average transverse grain sizes of 530 nm and 950 nm were developed in the S700MC and 316L steels, respectively, during warm rolling at 923 K. The developed ultrafine-grained microstructures provided similar strength levels with ultimate tensile strengths of 980 MPa and 945 MPa in the S700MC and 316L steels, respectively. The warm rolled bimetallic semi-product was characterized by the improved combination of high strength and high impact toughness in range from 130 J / cm^2 to 540 J / cm^2 depending on the impact test direction.

Keywords: Austenitic stainless steel, high strength low-carbon steel, bimetallic semi-product, thermo-mechanical treatment

1. INTRODUCTION

The layered metallic materials are widely used due to their beneficial property combination providing high strength, corrosion resistance, thermal conductivity, heat resistance, wear resistance, etc. Such materials usually consist of two or more metallic layers. The main advantage of bimetallic materials is a unique combination of properties, which cannot be reached in separate materials. The most promising materials for bimetallic materials are high-strength low-alloy (HSLA) steels for base layer and austenitic stainless steels of 316-type as cladding layer due to their low cost and good combinations of strength, ductility and toughness. However, HSLA steels typically exhibit low Charpy V-notch impact energy of 10 - 40 J at lowered temperatures [1]. And common disadvantage of austenitic stainless steels is their relatively low yield strengths of 200-400 MPa, which limits their usage in critical applications [2]. The most effective approaches to decrease DBTT concurrently with strengthening of structural steels and alloys are the grain refinement, which can be reached with thermomechanical treatment [3-4].

One of the most effective methods to produce bimetallic materials is electro-slag cladding (ESC) [5]. The high strength of joining layers at ESC is reached due to a compound of metals in the liquid state when the cladding material is mixed with the partially fused metal of the base layer. The method of ESC with appropriate technology can ensure the optimal chemical composition, structure and properties of the layers and fusion zone and become the basis for the production of high-strength new corrosion-resistant bimetals. Thus, the aim of the present study is to clarify the effect of thermomechanical treatment on the microstructure and mechanical properties, especially, fracture toughness of bimetallic semi-product. In order to understand the deformation behavior of base layer and clad layer, the microstructure and mechanical properties of the S700MC and 316L steels subjected to different treatments were investigated.

2. EXPERIMENTAL

The basic materials for electro-slag cladding were a high-strength low-alloy steel of S700MC (Fe - 0.09C - 0.12Si - 1.19Cr - 1.55Mn - 0.003P - 0.005S - 0.05 Nb - 0.025Al - 0.05Ti - 0.42Mo - 0.09V - 0.003B, all in mass %) and 316L austenitic stainless steel (Fe - 0.04C - 0.4Si - 1.7Mn - 17.3Cr - 10.7Ni - 2.0Mo - 0.04P - 0.05S - 0.09V - 0.04Ti - 0.05Nb - 0.4Cu - 0.19Co, all in mass %). The high-strength low-alloy steel was subjected to homogenization annealing followed by hot forging at a temperature of 1423 K. The chosen processing method included quenching from 1373 K, tempering at 923 K for 1 h and rolling at tempering temperature (tempforming) to a total strain of 1.5. A 316L-type austenitic stainless steel was hot forged at 1373 K followed by air cooling. The starting material was characterized by an average grain size of 21 μm and an average dislocation density of 2.3×10^{12} m^{-2}. The plate rolling of austenitic stainless steel was carried out at 923 K to the total true strain of 1.2. Two steels, S700MC and a 316L, were used as the base and cladding layers for bimetallic semi-product, which was produced by electro-slag cladding.

The structural observations were performed on the RD-ND sections (RD is the rolling direction, ND is the normal direction), using a Quanta 600 FEG scanning electron microscope equipped with an electron back scattering diffraction pattern (EBSP) analyzer incorporating an orientation imaging microscopy (OIM) system. The mean grain size was evaluated on the OIM micrographs as an average distance between high-angle boundaries with misorientation of $\theta \geq 15°$. The samples for structural characterizations were electro-polished using an electrolyte containing 10 % perchloric acid and 90 % acetic acid at a voltage of 20 V at room temperature.

Tensile tests were carried out using an Instron 5882 testing machine. The tensile specimens with gauge dimensions of 12 mm in length, 3 mm in width and 1.5 mm in thickness were prepared with the tensile direction along RD. The specimens were tested at ambient temperature at a crosshead rate of 2 mm / min. Standard Charpy V-notch specimens were tested using an Instron 450 J impact machine (Model SI-1M) with an Instron Dynatup Impulse data acquisition system at temperatures ranging from 77 to 293 K.

3. RESULTS AND DISCUSSION

3.1. Microstructure and mechanical properties of S700MC and 316L steels

Typical microstructures of the present steels subjected to warm rolling are shown in **Figure 1**. The tempforming of a low-alloy S700MC-type steel led to the evolution of ultrafine grained microstructure consisting of grains elongated along RD. The mean transverse grain size is 530 nm (**Figure 1a**). The tempformed steel is characterized by strong ⟨001⟩ || ND and ⟨111⟩ || ND fiber textures (corresponding to red and blue colors, respectively, in **Figure 1a**). It was shown that intensity of the {100} ⟨110⟩ texture increases in low-carbon steels during multi-pass warm plate rolling at temperatures of 813 - 923 K [4, 6]. Indeed, the highest relative intensity of 5 was obtained for ⟨001⟩ || ND texture component. The tempformed microstructure of high strength low-carbon steel is characterized by the formation of dispersed carbides at various boundaries / subboundaries of laths, blocks, packets and prior austenite grains [4].

The microstructure of 316L-type austenitic stainless steel that evolves during rolling is characterized by an elongation of original grains along the rolling axis and corresponding axial alignment of strain-induced grain boundaries (**Figure 1b**). As a result, the developed microstructure consists of elongated grains with the mean transverse grain size of 1.3 μm. The presence of well-developed spatial subboundary net, some portions in which exhibit high-angle misorientations and look like incomplete grain boundaries in the grain interiors, is indicative of continuous DRX as the main mechanism responsible for the microstructure evolution during rolling at 923 K [5, 6]. Also the frequently corrugated grain boundaries suggest a possibility of partial contribution of discontinuous DRX to the development of new fine grains at boundaries of elongated grains. It should also be noted that the warm rolling of austenitic steel does not lead to any specific texture development. The fiber texture of <101> || ND, which is inherent in face centered cubic metals, is alternated with various orientations including <111> || ND and <100> || ND in **Figure 1b.**

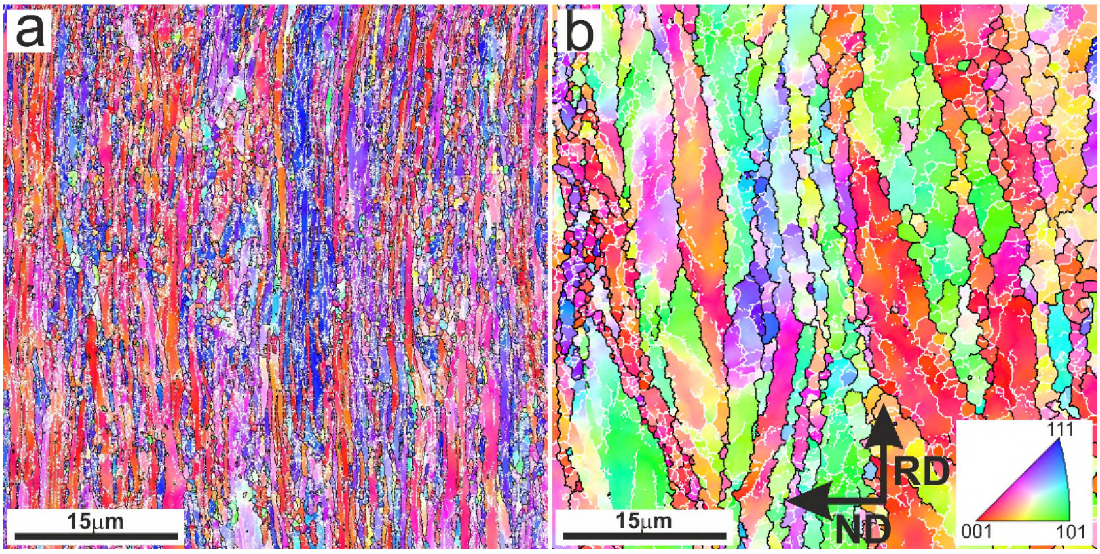

Figure 1 Microstructures developed in an S700MC-type steel through tempforming (a) and warm rolled austenitic stainless steel (b). Colors correspond to the crystallographic direction along the normal direction (ND)

The tensile properties of the tempformed S700MC steel characterized by almost the same ultimate tensile strength and yield strength of 1100 and 1090 MPa, respectively. The tempforming significantly increases the strength due to the formation of ultrafine grain layered structure. An increase in the strength after tempforming is accompanied by a decrease in total elongation to 9 %. Rolling at temperature of 923 K resulted in remarkable strengthening of 316L austenitic stainless steel. The room temperature yield strength increases from 230 MPa to 870 MPa after warm rolling. Correspondingly, the strengthening is accompanied by a degradation of plasticity.

3.2. Impact toughness of S700MC and 316L steels

The Charpy V-notch impact absorbed energy of the tempformed S700MC and warm rolled 316L steels at different test temperatures is presented in **Table 1**. The Charpy test specimens from the tempformed S700MC steel were not completely broken at T ≥ 233 K after impact tests with the impact direction || ND. Therefore, the real values of the V-notch impact energy at these temperatures should be higher than indicated in **Table 1**. These specimens exhibit superior delamination toughness. The high impact energy of 109 J / cm^2 is obtained even at liquid nitrogen temperature.

Table 1 The Charpy V-notch impact absorbed energy (KCV, J / cm^2) of the S700MC and 316L steel at different temperatures

Test temperature, K	**293**	**263**	**233**	**213**	**183**	**77**
S700MC	436	428	463	360	303	99
316L	78	95	87	75	80	97

The microstructure of bimetallic semi-products obtained by electro-slag cladding is shown in **Figure 2**. The joint of bimetallic material is characterized by mixed microstructure with average thickness of the fusion zone of about 60 µm (**Figures 2 a, b**).

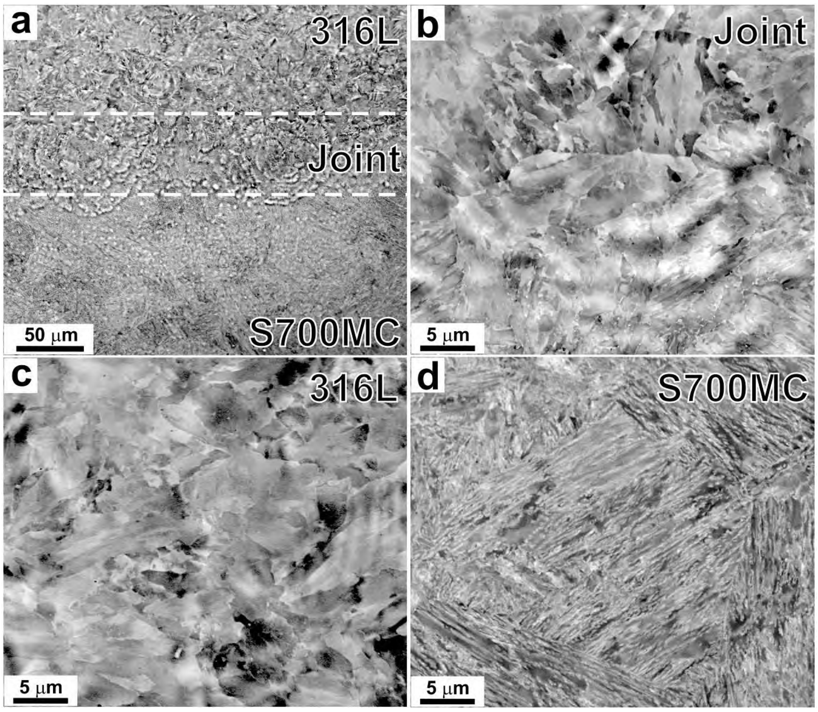

Figure 2 Microstructures of a bimetallic material produced by electro-slag cladding: (a) general view, (b) joint of bimetal, (c) austenitic stainless steel and (d) low-carbon high-strength steel

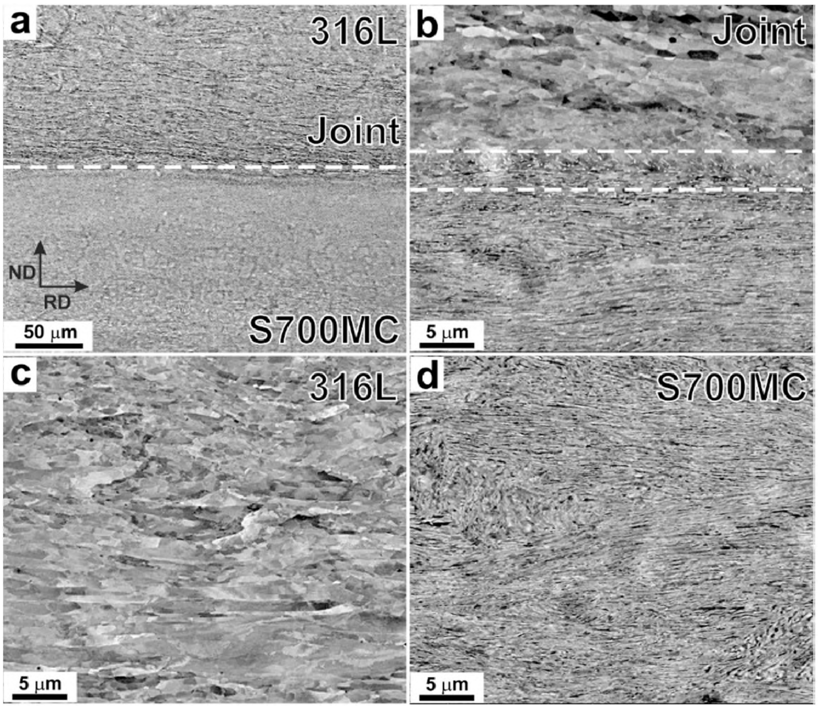

Figure 3 Microstructures of a bimetallic material produced by electro-slag cladding and subsequent thermomecanical treatment: (a) general view, (b) joint of bimetal, (c) austenitic stainless steel and (d) low-carbon high-strength steel

The base layer of the bimetallic sample, i.e., the low-carbon high-strength S700MC steel, is composed of the tempered martensite lath structure, in which prior austenite grains are subdivided into packets and blocks of martensite laths (**Figure 2c**). The cladding layer from 316L austenitic stainless steel consists of equiaxed austenite grains (**Figure 2d**). The micro-hardness of bimetallic semi-product in the fusion zone is about 2300 MPa, while the hardness of the base layer and clad layer are 3400 and 2300 MPa, respectively.

The structure characterization of bimetallic material in different zone subjected to thermomechanical treatment is presented in **Figure 3**. The fusion zone of bimetallic semi-product after warm rolling is hardly distinguishable on SEM images and the average thickness is approximately 4 μm (**Figures 3a, b**). The structures of both layers from S700MC and 316L steels after deformation are characterized by elongated grains along the rolling direction. The resulting microstructures of layers after electro-slag cladding and warm rolling correlate with the structures of the S700MC and 316L austenitic stainless steels subjected to temp-forming and warm rolling. The warm rolling of bimetallic semi-product leads to increasing the micro-hardness in cladding layer up to 3300 MPa. While the hardness in the fusion zone remains at the same level (~ 2300 MPa).

3.4. Impact toughness of bimetallic semi-products

The impact toughness of the bimetallic samples obtained by electro-slag cladding was measured in two directions, as shown in **Figure 4a**. The impact toughness of the specimen with V-noth in based layer is more than two times higher than the impact toughness of the specimen with V-noth in cladding layer and corresponds to 267 and 82 J / cm^2, respectively. The load-displacement curve of the former is typical for ausformed low-carbon high-strength S700MC steel tested at room temperature [4]. The total fracture energy is consumed during the initiation of crack with critical dimension and the stage of stable crack propagation.

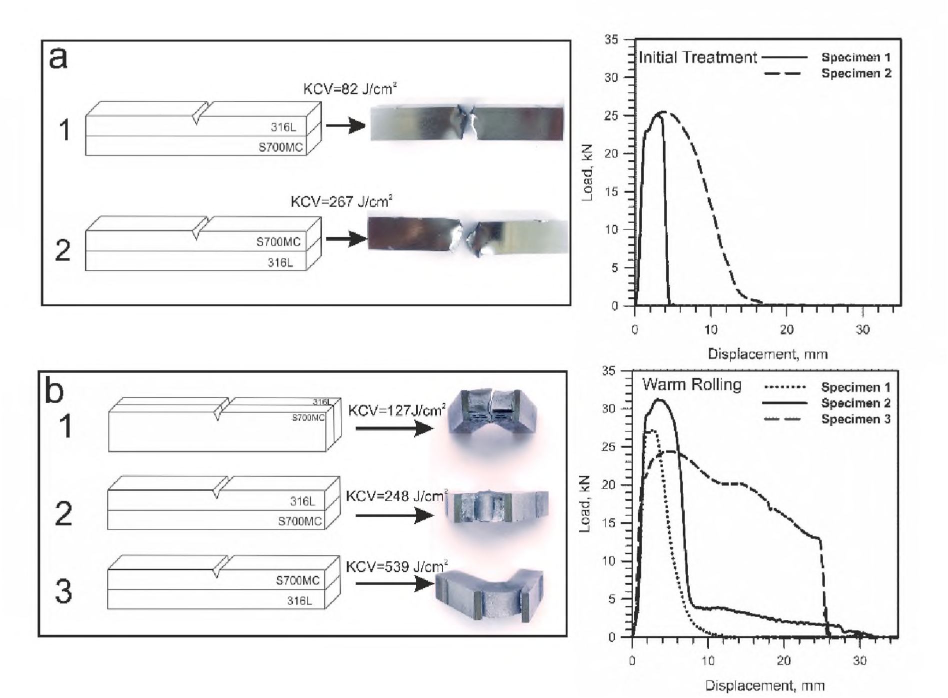

Figure 4 The Charpy V-notched specimens and the load-deflection curves after impact tests of bimetallic material produced by electro-slag cladding (a) and subsequent thermomecanical treatment (b)

After warm rolling the impact toughness of the bimetallic specimens significantly increases in respective directions (**Figure 4 b**). The impact test of the specimen 1 is characterized by a brittle fracture of S700MC steel and viscous fracture of austenitic steel and KCV reached to 127 J / cm^2 (**Figure 4 b**). The Charpy specimen 3 with V-notch in base layer exhibit delaminations, i.e., the cracks branch along the impact test specimens, and zigzag-shaped cracks appear. In this case, the bimetal demonstrates the maximum of impact toughness is about 539 J / cm^2. The Charpy specimens with V-notch in base layer and cladding layer do not separate into two pieces after impact test at 293 K (**Figure 4b**).

4. CONCLUSION

The S700MC-type steel subjected to tempforming at 923 K is characterized by the formation of ultrafine grain structure with an average transverse grain size of 530 nm and strong ⟨111⟩ || ND and ⟨001⟩ || ND fiber textures. Warm rolling of the 316L austenitic stainless steel at 923 K resulted in development of highly elongated grains, which interleaved with ultra-fine grains. The thermomechanical treatments of both investigated steels were accompanied by significant strengthening. The ultimate tensile strength of S700MC and 316L steels after deformation reached 1100 and 900 MPa, respectively. The tempformed S700MC steel is characterized by extremely high impact toughness in a wide range of test temperatures. This high fracture toughness is attributed to the delamination, when the fracture occurs by cleavage along the rolling plane with large energy absorption. The electro-slag cladding led to the development of good joint. The average thickness of the fusion zone in bimetallic semi-product after thermomechanical treatment decreased from 60 to 4 μm. The structures of basic layer and cladding layer correspond to the structures, which were formed in S700MC and 316L steels after separate treatments. The maximum value of impact toughness is achieved in specimens with V-notch in the base layer and exceeds 539 J / cm^2. In this case, the bimetallic material is characterized by the delamination of S700MC, which prevents the fracture of cladding layer from austenitic stainless steel.

ACKNOWLEDGEMENTS

The study was financially supported by the Russian Science Foundation, Project No. 17-72-10221. Authors are grateful to the staff of the Joint Research Center, "Technology and Materials", of the Belgorod State National Research University.

REFERENCES

[1] TOMITA, Y. Development of fracture toughness of ultrahigh strength, medium carbon low alloy steels for aerospace applications. *International Materials Reviews,* 2000, vol. 45, pp. 27-37.

[2] MARTIENSSEN, W., WARLIMONT, H. *Springer Handbook of Condensed Matter and Materials Data.* Berlin, Heidelberg: Springer, 2005. 1121 p.

[3] TAKAKI, S., KAWASAKI, K., KIMURA, Y. Mechanical properties of ultra fine grained steels. *Journal of Materials Processing Technology,* 2001, vol. 117, pp. 359-363.

[4] DOLZHENKO, A., YANUSHKEVICH, Z., NIKULIN, S. A., BELYAKOV, A., KAIBYSHEV, R. Impact toughness of an S700MC-type steel: Tempforming vs ausforming. *Materials Science and Engineering A,* 2018, vol. 723, pp. 259-268.

[5] PAK, Susan, RIGDAL, Solveig, KARLSSON, Leif and GUSTAVSSON, Ann-Charlotte. Electroslag and submerged arc stainless steel cladding. *Anti-Corrosion Methods and Materials.* 2001. vol. 45, pp. 42 - 45.

[6] KIMURA, Yuuji, INOUE, Tadanobu, YIN, Fuxing and TSUZAKI, Kaneaki. Inverse temperature dependence of toughness in an ultrafine grain-structure steel. *Science.* 2008. vol. 320, pp. 1057-1060.