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Effects of the rolling temperature on microstructure and mechanical properties of 2Cr13/316L laminated composites prepared by accumulative roll-bonding (ARB)

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ABSTRACT

The microstructure and mechanical properties of 2Cr13/316L composite plates by hot-rolling at different rolling temperatures of 1130 °C, 1180 °C, 1250 °C, 1300 °C are investigated in details. With the increase of the rolling temperature, the tensile strength and bending strength of 2Cr13/316Lwere reduced first and then increased slightly due to the coarsening of grains and the increasing of ferrite content in 2Cr13 layers. The highest tensile elongation is obtained at the composite plate with rolling temperature of 1180 °C. 2Cr13/316L composite plates obtained by hot rolling processes were able to withstand larger bending deformation, and no cracks or interfacial delamination can be found in the bending process because of a strong combined interface.

1. Introduction

With the development of modern industry and the progress of science and technology, traditional and single metal or alloy hardly satisfies the increasing requirements of modern industrial applications and some specific working conditions. Recently, to maximize the comprehensive performance of materials, metallic multilayered composites, consisting of metal or alloys, have received more attentions due to their superior mechanical properties, such as higher bending strength, impact resistance, fracture ductility, fatigue life, corrosion resistance, wear and even deformability [1–4], which will be widely used in the fields of automobile, military industry, petrochemical industry, aviation and spaceflight, armor, daily life and so on [5,6]. At present, many manufacturing techniques, such as explosive welding, roll bonding, explosive welding and rolling, brazing, diffusion bonding, extrusion compounding, casting rolling, inversion casting and so on, have been used to produce composite plates [7]. However, the rolling bonding is widely used to manufacture composite plates due to the most economic and productive. The microstructures and mechanical properties of the composite plates produced by rolling bonding, such as Al/Ti [8], Mg/Al [9], Cu/Zn [10], Al/Ni [11], Ti/SS439 [12], Al/steel [13], SS420/SS304 [14], SCM415/SS304 [15], SS304/WT780C [16], SS420/SS301 [17] and so on, have been extensively studied.

The multilayered steel (MLS) composites consisting of brittle/ductile material have high strength and higher toughness, especially the plasticity and toughness of the brittle layer in MLS have been improved. It provides a new idea for the fabrication of high strength and high toughness materials [18].The multi-layered metal composites can be fabricated by alternating SS420 and SS304, which not only has a high tensile strength exceeding 1.2 GPa but also has a good plasticity with 15% uniform elongation [19]. In 2011, P. Lhuissier et al. [17] fabricated multilayered SUS420/SUS301 steel that can withstand an elongation of more than 25%, while monolithic SUS420 is brittle less than 4% elongation. In 2011, M. Ojima et al. [20] measured the stress partitioning behavior of multilayered WT780C/SS316L steel during tensile deformation by in situ neutron diffraction. Due to the multilayered structure, the applied stress is effectively transferred to martensitic, because no stress concentration sites exist. In 2008, Shoichi Nambu et al. [21] fabricated multilayered steels (MLS) by alternating high-strength, as-quenched martensitic and high-ductility austenitic stainless steel, and the results showed that more than 50% elongation of as-quenched martensite in MLS was achieved under tensile loading, while the fracture elongation of martensitic steel is only 6%. The higher ductility can be achieved by forming a stronger interface in a multi-layered structure consisting of brittle martensitic and soft austenitic stainless steel [14,15]. Besides, the higher ductility is related to fracture toughness and layer thickness of martensite in the case of a strong interface. The bending formability of multi-layered composites was

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Table 1
The chemical composition of constituent materials (wt%).

Elements	C	Si	Mn	P	S	Cr	Ni	Cu	Mo	N
316L/1 mm	0.0229	0.471	1.396	0.035	0.0029	16.59	10.14	0.266	2.11	0.0116
2Cr13/1 mm	0.18	0.63	0.38	0.017	0.001	13.36	0.1			
2Cr13/3 mm	0.20	0.42	0.34	0.021	0.001	13.32	0.2			

Table 2
The Mechanical properties of monolithic constituent materials.

Material	Yield strength σ_y/MPa	Tensile strength σ_b/MPa	Elongation δ/%	Hardness /HV
316L/1 mm	273	658	57	157.9
2Cr13/1 mm	366	569	33	182.3
2Cr13/3 mm	375	542	38	179.9

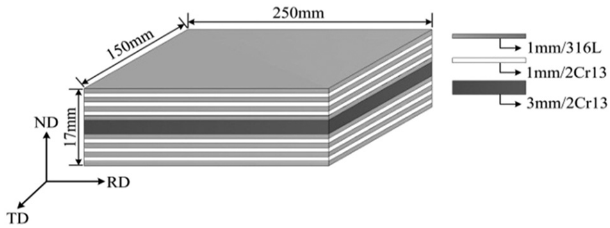

Fig. 1. Symmetrical stacking structure of 2Cr13/316L composite plate before rolling.

evaluated by tensile tests, V-bending tests, and hemming tests. Multi-layered metals were able to bear larger bending with no cracks and delamination in the outer layers [22].

In this paper, 15 layers 2Cr13/316L stainless steel composite plate was produced by hot-rolling technology at different rolling temperature of 1130 °C, 1180 °C, 1250 °C, 1300 °C. Microstructure and mechanical properties of the 2Cr13/316L composite plates were investigated by scanning electron microscopy (SEM), Vickers microhardness, tensile and bending tests. It demonstrates the relationships between the properties and microstructures.

2. Experiments

2.1. Materials

2Cr13/316L composite plates were produced by layering two different types of material. In this study, 1 mm-thick 316L austenitic stainless steel was used with 2Cr13 martensitic stainless steel plates with thicknesses of 1 mm and 3 mm. The chemical compositions and mechanical properties of these components are shown in Tables 1 and 2.

The three plates were machined to 250 mm × 150 mm. Surface cleaning is the key factor that affects sheet metal bonding quality during rolling. Before rolling, the plates were mechanically cleaned and then chemically cleaned with a solution of nitric and hydrochloric acids (HNO_3: HCL: H2O = 1:3:3) in order to completely remove oxide and oil from the plate surface, as well as to increase the surface friction. To prevent oxidation and contamination, the cleaned plates were immediately argon arc welded from all directions using a welding current of 90 A to 100 A. The middle layer of the composite plate was made from 3 mm-thick 2Cr13 martensitic stainless steel. The outer portions of the composite were made from alternately stacked pieces of 1 mm-thick 2Cr13 martensitic and 316L austenitic stainless steels. Four 316L layers and three 2Cr13 layers were alternated on each side. Thus a 15 layer composite with a total thickness of 17 mm was produced, as shown in Fig. 1 (RD represents the rolling direction, ND represents the normal to the rolling direction). The 15 layer stacks were subject to multipath hot-rolling bonding processes at temperatures of 1130 °C, 1180 °C, 1250 °C, and 1300 °C. Finally, the four samples were hot rolled to a thickness of approximately 3 mm, which represents a reduction ratio of approximately 82%.

2.2. Microstructure and Fracture Surface Observations

Microstructures and fracture surfaces were observed and analyzed via scanning electron microscopy (SEM; QUANTA FEG450). Metallographic samples were cut from 2Cr13/316L composite plates made at different rolling temperatures and then ground, polished, and etched in a HNO_3:HCL:H_2O = 1:3:3 solution for 30 s. After the tensile specimens were fractured, the SEM-monitored surface and fracture surface were compared directly.

2.3. Tensile Properties

Tensile experiments were performed to determine the strength, ductility, and fracture modes of the 2Cr13/316L composite plate specimens shown in Fig. 2(a). Tensile tests were performed at room temperature (20 °C) using at an engineering strain rate of $10 \times 10^{-3}\,s^{-1}$.

2.4. Hardness Measurements

In order to determine how 2Cr13/316L composite plate layer hardness changes with the rolling temperature, vickers microhardness was measured using a HVT-1000A automatic hardness instrument (load 50 g, dwell time 15 s).

2.5. Bending Properties

Bending experiments were performed to investigate the formability of 2Cr13/316L composite plates using the specimens shown in Fig. 2(b). The long directions of these specimens were corresponded to the rolling direction. Three-point bending tests were performed using

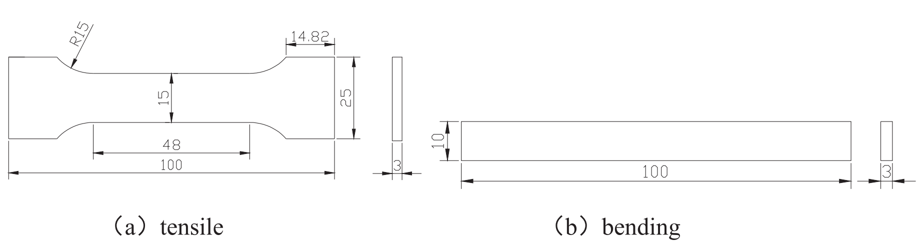

Fig. 2. Dimensions of tensile and bending samples.

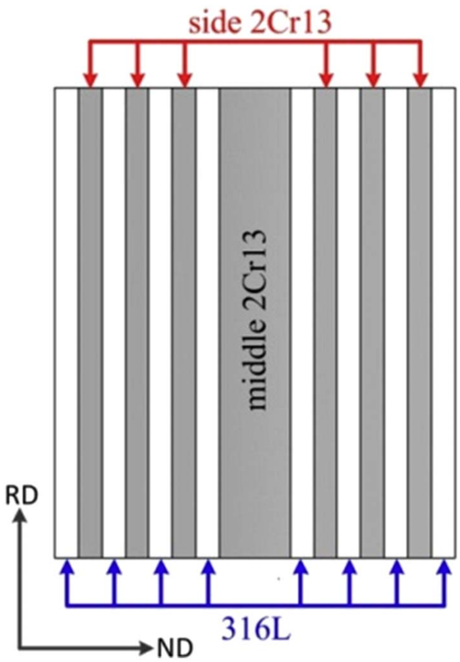

Fig. 3. Schematic of 2Cr13/316L composite plate (RD: rolling direction, ND: Normal to rolling direction).

bending angles of 130 degrees (± 2°) and 180°. To further observe specimen deformation during bending, the sides of the bending specimens were polished and etched before bending so that the microstructure after bending testing could be observed by scanning electron microscopy (SEM; QUANTA FEG450).

3. Results

3.1. Effects of Rolling Temperature on Microstructure

Fig. 3 shows the schematic of 2Cr13/316L composite plate, which is composed of middle 2Cr13 and two sides with 2Cr13 layer and 316L layer.

Figs. 4–8 shows the microstructure morphology of 2Cr13/316L composite plate at rolling temperatures of 1130 °C, 1180 °C, 1250 °C and 1300 °C, respectively.

Fig. 4 presents a macro-profile of composite plate at different rolling temperatures, which consists of 15 layers (ML denotes martensite layer, AL denotes austenitic layer, Interface denotes composite interface), it can be seen that at the rolling temperature of 1130 °C and 1180 °C, the interface between ML and AL keep straight and continuous interface, the thickness of each layer keeps uniform along the rolling direction. When the rolling temperature increases to 1250 °C and 1300 °C, the interface between ML and AL becomes zigzag and a "wave like" structure. The thickness of metal layers at two sides becomes uneven along the rolling direction, and the necking phenomenon appears in the in some places, which is mainly related to different material flow stress, hardness, strength at different rolling temperatures [23,24].

Fig. 5 shows the microstructures of the middle 2Cr13 layer for all plates with various rolling temperatures, it can be seen that at the rolling temperature of 1130 °C, the coarse lath martensite dominates. However, with the increase of the rolling temperature, the microstructures are changed. At 1180 °C, some banded ferrite can be formed except for coarse lath martensite. At 1250 °C, banded ferrite in the middle layer increases and distributes along the rolling direction, which

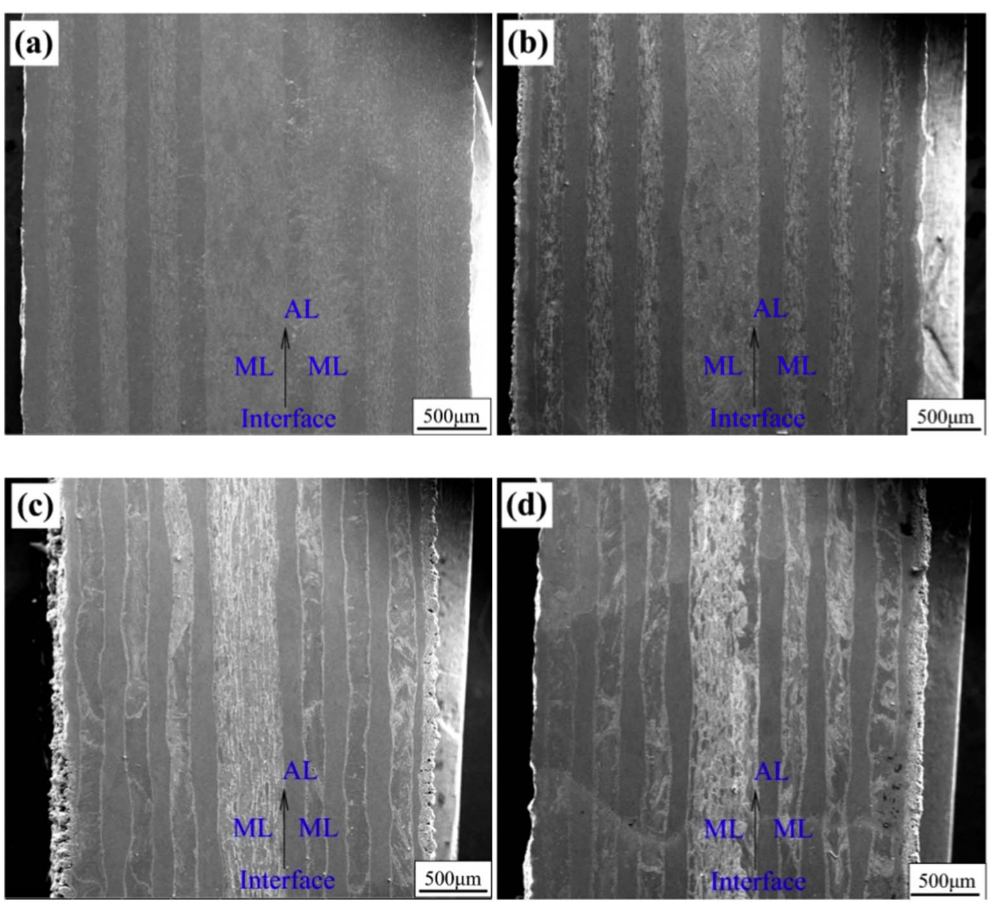

Fig. 4. Macro-profile of composite plate at different rolling temperatures(a)1130 °C, (b)1180°, (c)1250 °C, (d)1300 °C.

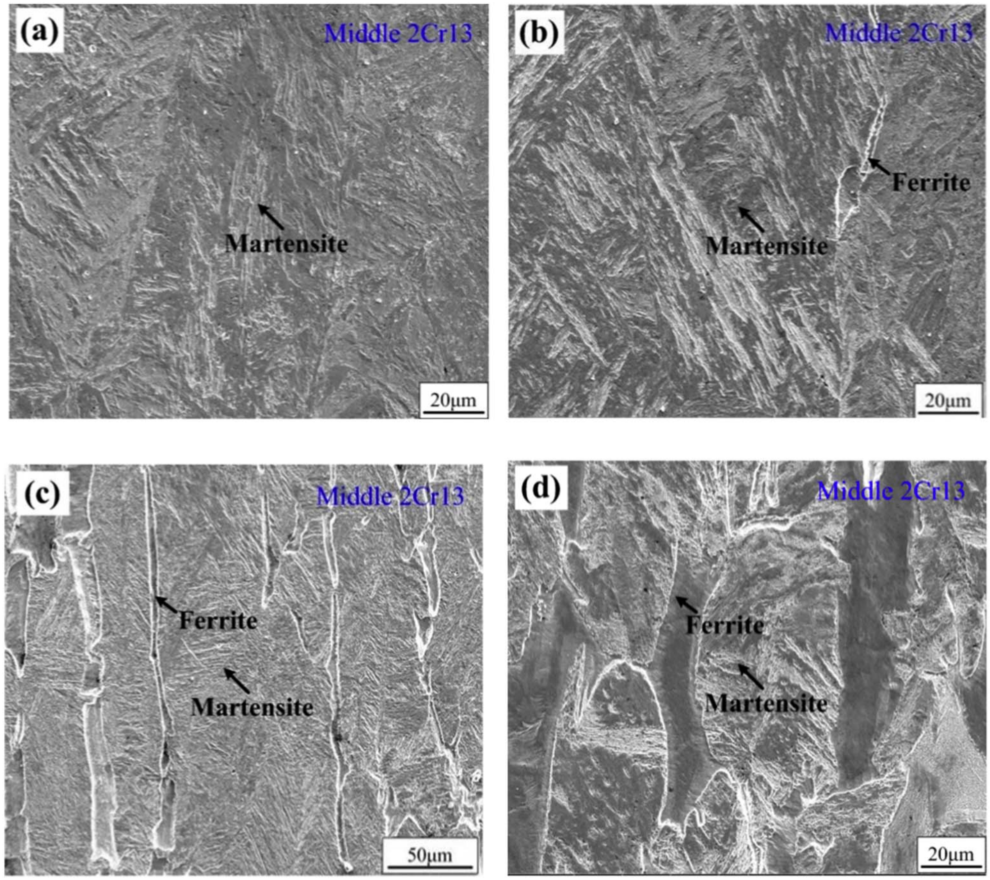

Fig. 5. Microstructure of middle 2Cr13 layer at different rolling temperatures (a)1130 °C, (b)1180 °C, (c)1250 °C, (d)1300 °C.

looks like "gully" shape. At 1300 °C, the ferrite grows and becomes a big block which is wrapped with martensite along the grain boundary. The content of ferrite phase in middle 2Cr13 layer were also summarized in Table 3.

Fig. 6 showed the microstructures of the middle 2Cr13 layer and 316L layer, and 2Cr13 layer on both sides. Only coarse and elongated austenite phase along rolling direction appears in 316L layer. The microstructure of 2Cr13 layer on both sides is composed of martensite and ferrite, and the grains are elongated along the rolling direction. With the increase of the rolling temperature, the content of the ferrite phase increase, which were shown in Table 3. For the specimens with the rolling temperatures of 1250 °C and 1300 °C, the ferrite phase increases and become flake shape along rolling direction. The distribution of martensite phase becomes irregular. In the 2Cr13 layer near the interface, martensite is produced, which is related to the increased diffusion at the interface, especially the diffusion of element Ni. Based on Ref. [25], the diffusion of Ni element increases the hardenability of the martensitic stainless steel. And Mn element may be oxidized and loss, thus Mn elements will be reduced which makes the austenite phase region decrease, the martensite transformation point Ms. shift upon to increase martensitic transformation at undercooling degree, so more martensite can be formed at the interface of 2Cr13 side.

It is very interesting that complete metallurgical bonding can be found at the interface between the austenite layer and martensite layer. Common austenite grains (yellow zone) can be formed at the interface in Fig. 6, which common grain formed along the interface between 316L austenite layer and 2Cr13 layer during rolling processes. It can be referred at the higher rolling temperature, common grain can be formed at austenitizing processes, however the martensite microstructure can be transformed at the ML, and austenite microstructure keeps in the AL due to the difference of the compositions in various layers. The elements at the interface are different from that of the matrix structure, so they have an important influence on the mechanical properties of the interface, but the interface mechanism of the common grain formation remains to be studied further. According to J.G. Tong, et al. [26], the formation of the common grain is concerned with temperature induced recrystallization mechanism. The higher rolling temperature increases atomic energy, atoms at the interface become active, which contribute to the growth of the new grain nucleus and recrystallization at the interface, the different crystal orientation at the two sides of composite is rearranged under the plastic deformation and heat diffusion effect, and finally connected due to the formation of eutectic and solid solution.

The X-ray diffraction (XRD) analysis shown in Fig. 7 was performed to confirm the phases in each layer. The microstructures of the center 2Cr13 layer and the 2Cr13 layers on each side are mainly composed of martensitic phases and small amounts of ferrite (Fe−C). An austenitic phase with enriched Cr-Ni-Fe-C appears primarily in the 316L layer. At the interface, a diffusion layer with a thickness of 8.4 μm can be seen in Fig. 8.

3.2. Effects of the Rolling Temperature on Hardness

According to the above analysis, the center layer consists of 2Cr13 martensite, but a ferrite phase can be formed when the rolling temperature is increased. The 316L layer is composed primarily of coarse austenite grains. The 2Cr13 layers on each side consist of various

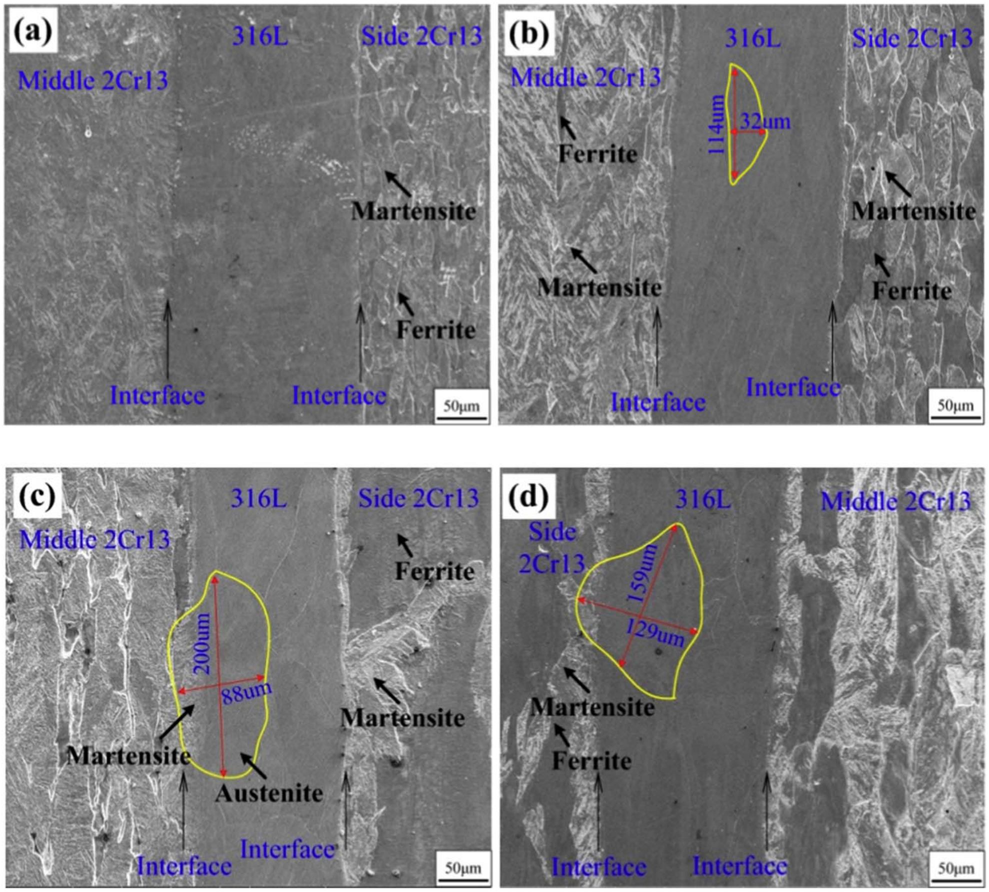

Fig. 6. Microstructure of middle 2Cr13 layer, 316L layer and the side 2Cr13 layer in Fig. 4 at various rolling temperatures. (a)1130 °C, (b)1180 °C, (c)1250 °C, (d)1300 °C.

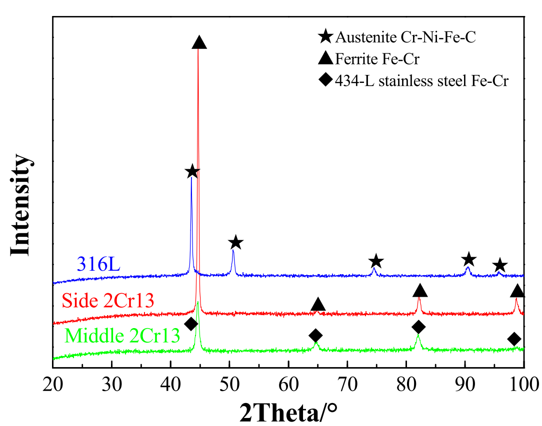

Fig. 7. XRD analysis of MLS at rollingtemperature of 1180 °C.

volume fractions of martensite and ferrite. The hardness distribution of the hot-rolled composite plate can be analyzed based on the hardnesses of the various microstructures in different layers.

Table 4 and Fig. 9 present microhardness distributions of 2Cr13/316L composite plates fabricated at various rolling temperatures. The hardness of the center 2Cr13 layer decreases as the rolling temperature increases further. This effect is related to elemental segregation at high temperatures. In specimens formed at rolling temperatures of 1250 °C and 1300 °C, a large quantity of ferrite phases was formed in the center layer. Part Cr element becomes a solid solution in these ferrite phases, and coarse microstructures form due to the high rolling temperature. The combination of these two factors leads to a decrease of the hardness in the martensitic layer. The hardness of the 316L layer firstly decreases as the rolling temperature increases, then increases slightly as the rolling temperature reaches 1300 °C. This may be related to the effect of the rolling temperature on grain size. In specimens with a rolling temperature of 1130 °C, the average austenite grain size is only 29.3 um. These grains are smaller than those produced at other rolling temperatures, so increased hardness is achieved.

The hardness of 2Cr13 layer on both sides is determined by the hardness of martensite and ferrite, variation of the hardness in the martensite phase at each rolling temperature is very small. For the specimens with the rolling temperatures of 1130 °C and 1180 °C, the hardness of martensite in the 2Cr13 layer on both sides is far lower than that of the center 2Cr13 layer. Because at the lower temperature rolling, the middle rolling layer is mainly composed of coarse martensitic, however, local ferrite can be formed in 2Cr13 layer on both sides, which will induce lower hardness. The hardness of 2Cr13 layer decreases with the increase of the rolling temperature, however at 1300 °C it slightly increases. The microstructure of the 2Cr13 layer on the middle location and two sides are different even at the same rolling temperature. The preliminary analysis relates to the temperature gradient and the thermal deformation behavior of the center and outside regions during the rolling process. The fraction of ferrite content on the middle 2Cr13 layer is less than that on either side of the 2Cr13 layer, which induces the hardness in the 2Cr13 layer on both sides to be far lower than that of the center 2Cr13 layer when the rolling temperature is low. The specific mechanism will be further revealed in the following study.

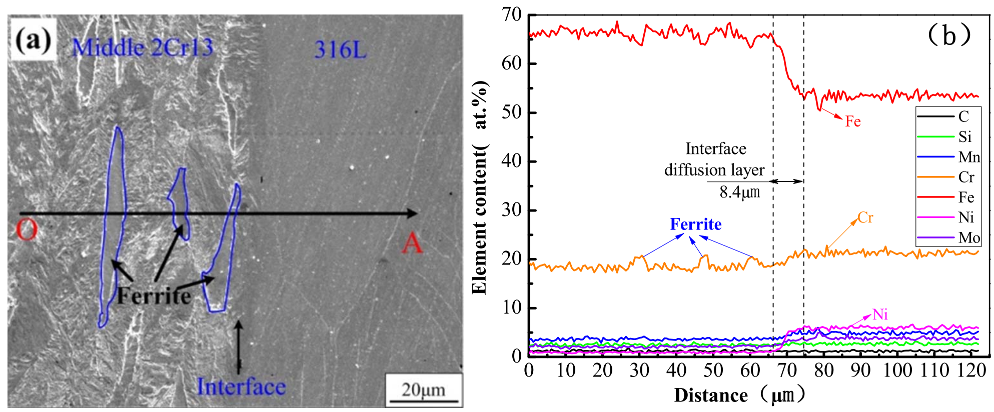

Fig. 8. Line scanning analysis results of MLS at rolling temperature of 1180 °C.

Table 3
Fraction of ferrite content in middle and two sides of 2Cr13 layer and average grain size in 316L layer.

Temperature	1130 °C	1180 °C	1250 °C	1300 °C
Fraction of ferrite content in middle 2Cr13 layer (%)	~	3.7	14.3	30.0
Fraction of ferrite content in two sides of 2Cr13 layer (%)	42.5	52.5	77.4	64.3
Average grain size in 316L layer (μm)	29.3	62.2	121.0	124.9

Table 4
Microhardness distribution of MLS under different rolling temperature.

Hardness distribution		Temperature/°C			
		1130	1180	1250	1300
Hardness(HV) of middle 2Cr13 layer	Martensite	501.4	469.8	402.0	407.0
	Ferrite	~	~	182.7	165.7
Hardness(HV) of 316L layer	Austenite	276.6	245.9	228.8	241.7
Hardness(HV) of both sides 2Cr13 layer	Martensite	390.5	394.5	408.0	389.2
	Ferrite	210.9	188.3	155.6	174.1

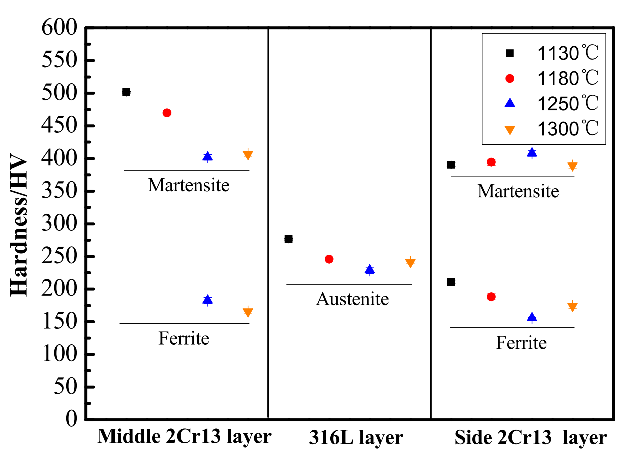

Fig. 9. Microhardness distribution of MLS at different rolling temperatures.

3.3. Effects of the Rolling Temperature on Tensile Strength

Fig. 10 presents the tensile engineering stress-strain curve of composite plates at various rolling temperatures. To reveal the change of the tensile strength and the elongation, the distinct column figure was

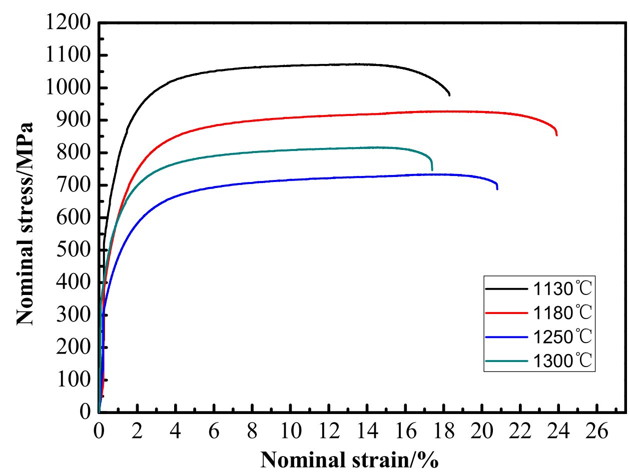

Fig. 10. Engineering stress-engineering strain curves of MLS at different rolling temperatures.

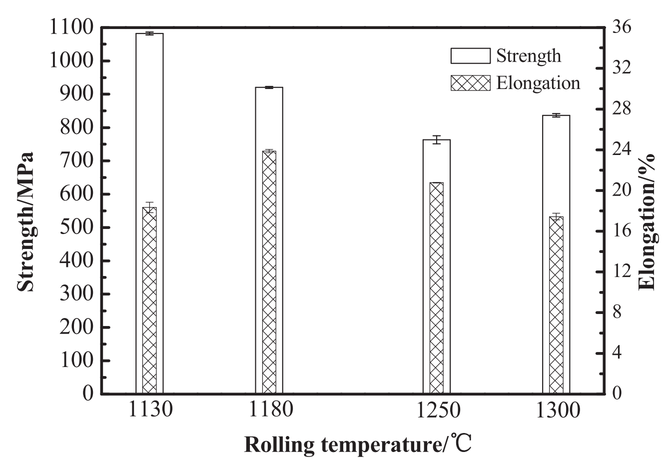

Fig. 11. Strength and elongation of MLS at different rolling temperatures.

drawn in Fig. 11. From Fig. 10 and Fig. 11, it can be seen that the highest yield strength and tensile strength can be obtained at the composite plate with rolling temperature of 1130 °C. The highest tensile elongation is obtained at the composite plate with rolling temperature of 1180 °C.

The tensile strength is firstly decreased, then increased when the rolling temperature is increased. It is mainly related with the formation of the ferrite and coarser grain size in Table 3. The lowest yield strength

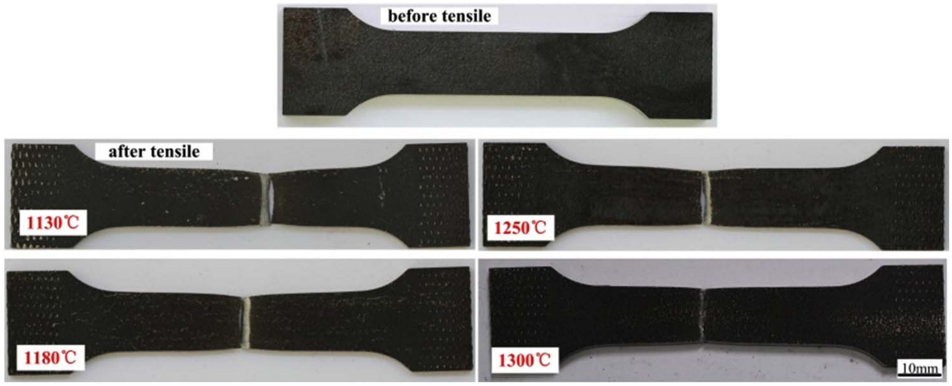

Fig. 12. Macro-tensile fracture featureof MLS at various rolling temperatures.

and tensile strength can be obtained at the composite plate manufactured with rolling temperature of 1250 °C, which should be attributed to banded ferrite phase in Fig. 6. On the whole, the tensile properties of 2Cr13/316L composite plates at different rolling temperatures depend on the amount of the martensite phase and ferrite phase in the center layer and the two sides of the martensite layer, and the size of each layer of the composite plate.

Fig. 12 shows the macro-tensile fracture feature of MLS with various rolling temperatures, it can be seen that necking phenomenon is produced and no any delamination cracking phenomenon can be found. It means that the better connection interface can be formed.

To reveal the relationships between the tensile properties and the rolling temperatures, the corresponded fracture surfaces are respectively observed as shown in Figs. 13–16.

Fig. 13 shows the macro-tensile fracture surfaces. It can be seen that serious interface delamination was produced at the specimens with the rolling temperature of 1130 °C, which seriously affects the lower tensile ductility of 18.3%, which is lower than that of 1180 °C. For the specimen with the rolling temperature of 1180 °C, the hardness of the center layer 2Cr13 decreases to 469.8 HV, the layer cracking and interfacial delamination tendency decreases. With the rolling temperature further increase to 1250 °C and 1300 °C, fracture surface becomes coarser, no interfacial delamination can be produced. It is because that the higher temperature promotes the diffusion of interface elements, and metallurgical bonding interface can be formed.

Fig. 14 presents the magnified fracture morphology of the middle 2Cr13 layer at different rolling temperatures. It can be seen that dimple fracture mode dominates the fracture surface of the specimens with the

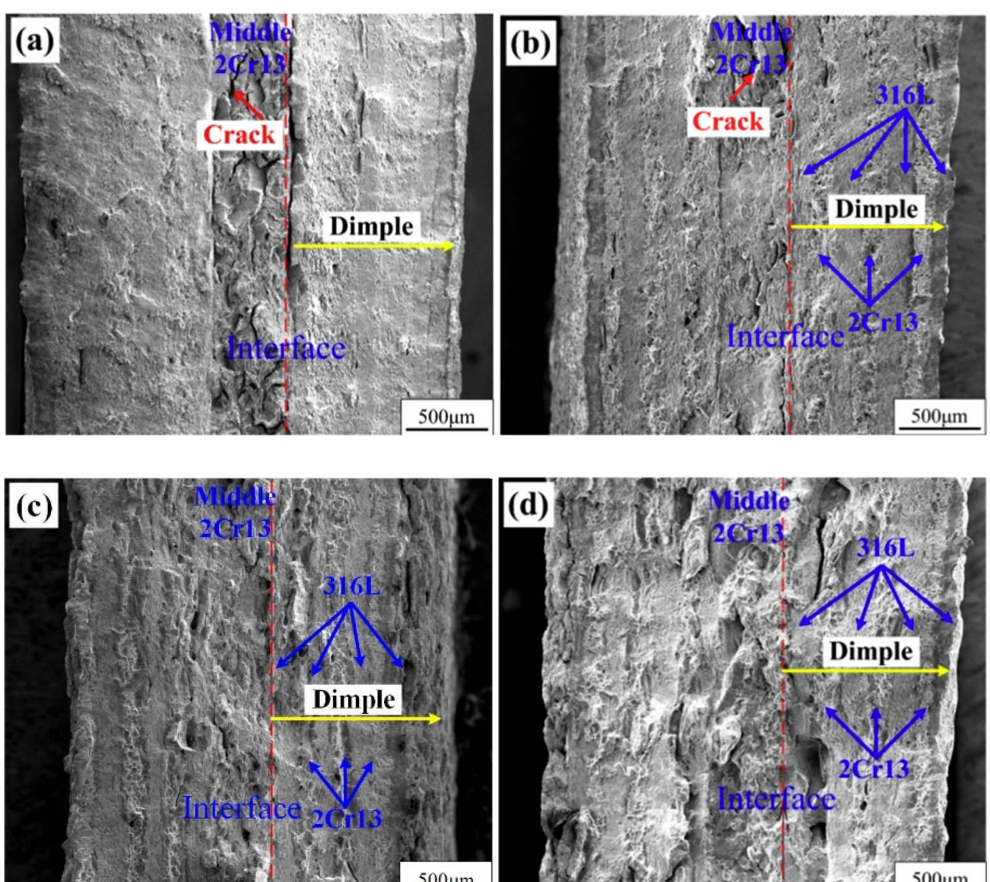

Fig. 13. Macro-tensile fracture surface of MLS at various rolling temperatures. (a)1130 °C, (b)1180 °C, (c)1250 °C, (d)1300 °C.

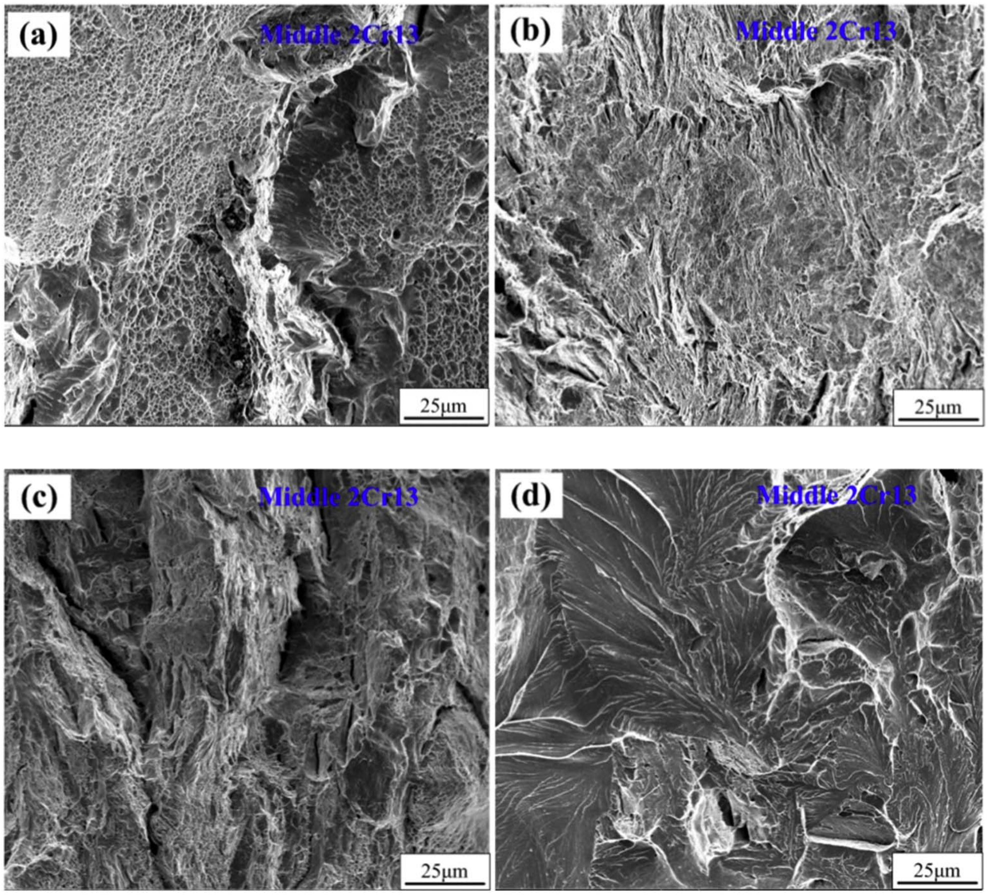

Fig. 14. Magnified tensile fracture surface of middle 2Cr 13 layer in Fig. 13 at various rolling temperatures. (a)1130 °C, (b)1180 °C, (c)1250 °C, (d)1300 °C.

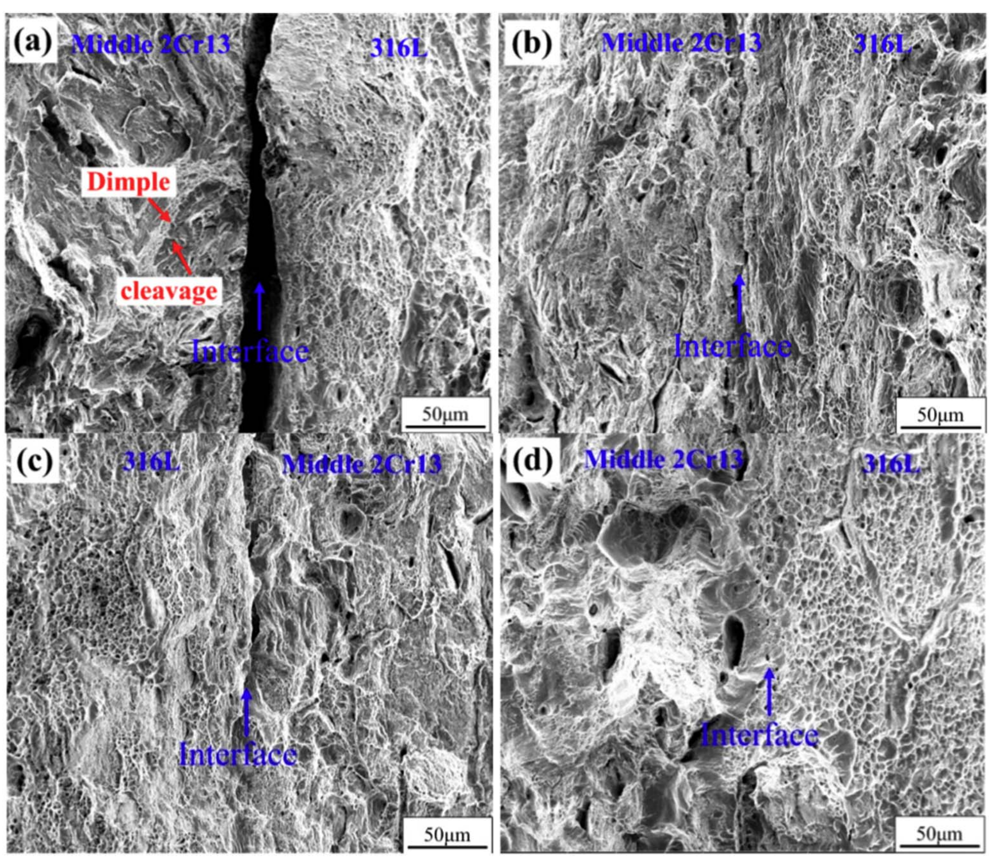

Fig. 15. Magnified tensile fracture surface of the interface layer between the middle 2Cr13 and 316L layers in Fig. 13 at various rolling temperatures. (a)1130 °C, (b)1180 °C, (c)1250 °C, (d)1300 °C.

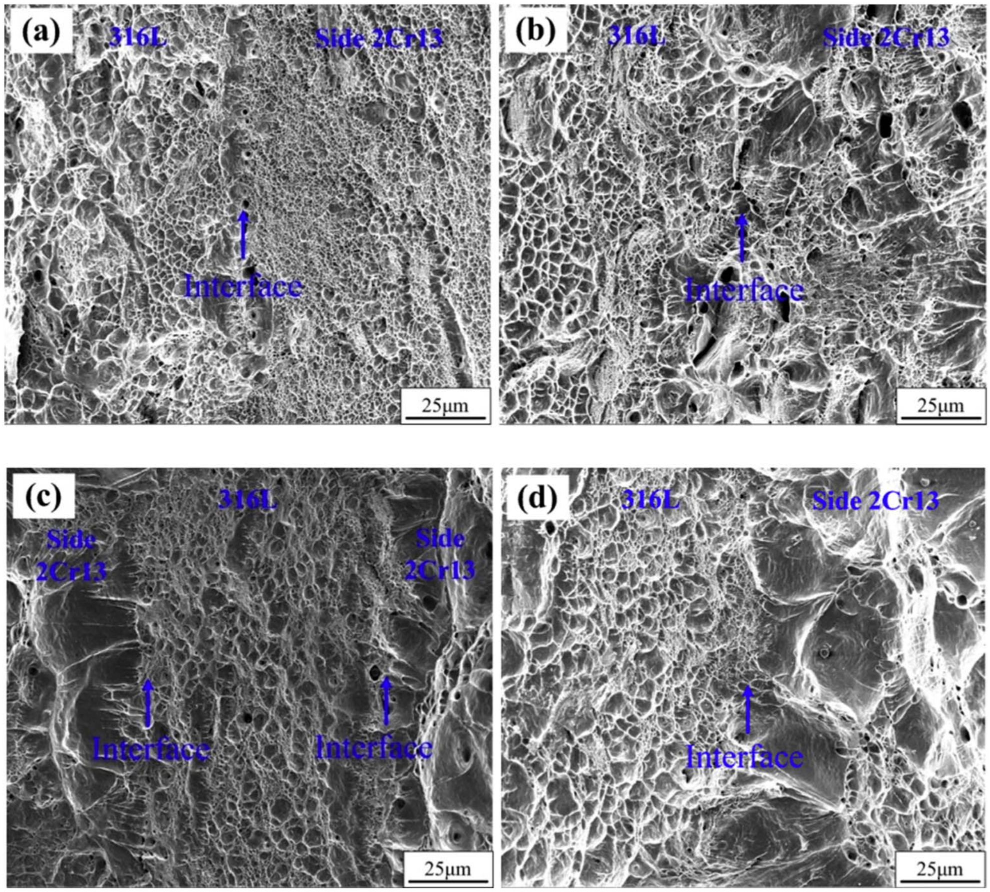

Fig. 16. Magnified tensile fracture surface of the interface layer between the side 2Cr13 and 316L layers in Fig. 13 at various rolling temperatures. (a)1130 °C, (b)1180 °C, (c)1250 °C, (d) 1300 °C.

Table 5
Bend mechanics capability of MLS under different rolling temperature.

Temperature T/°C	Specimen size (length * width * height)/mm	Force F_{bb}/KN	Bending strength σ_{bb}/MPa	Bending deflection under maximum bending strength/mm
1130	100 * 10.11 * 3.46	5.35	3446.8	19.86 –The specimens were not fractured
1180	100 * 10.11 * 3.17	3.60	2763.1	19.16
1250	100 * 10.10 * 3.02	2.55	2162.7	20.77
1300	100 * 10.05 * 3.09	3.20	2601.1	21.72

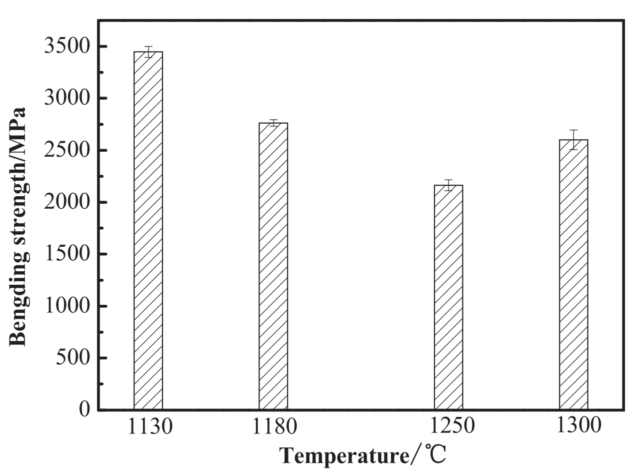

Fig. 17. Relationship between bending strength of MLS and the rolling temperatures.

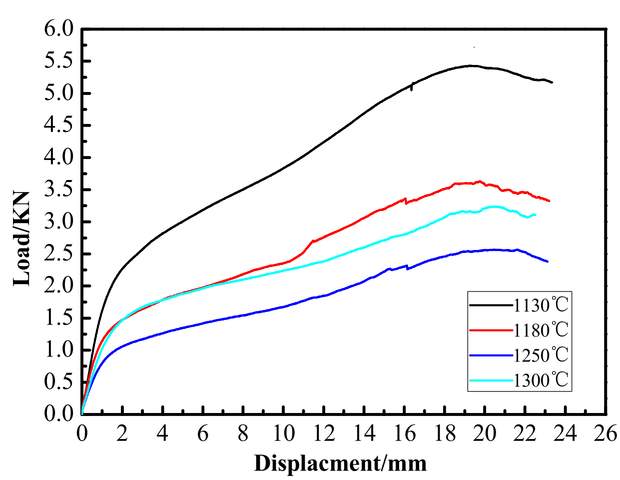

Fig. 18. Bending load-displacement curves of MLS at different rolling temperatures.

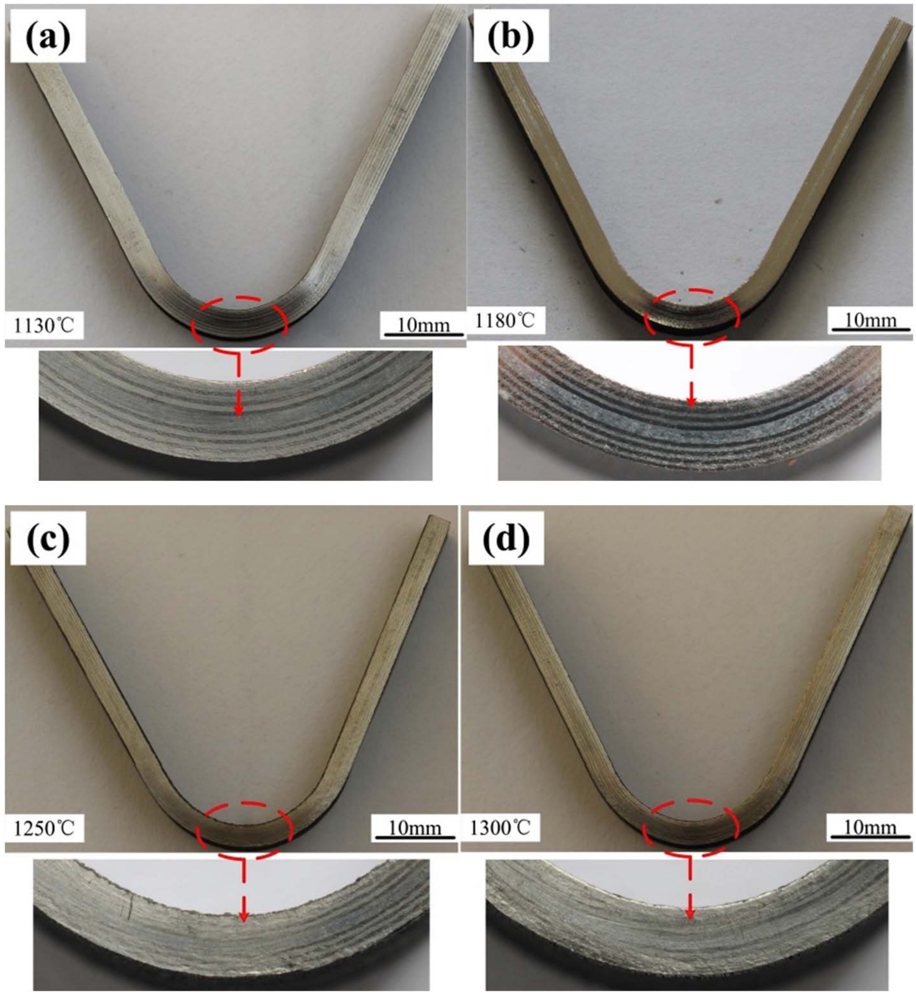

Fig. 19. The macroscopic morphology of MLS obtained at different rolling temperatures bending to 130°.

rolling temperature of 1130, 1180 and 1250 °C. Only when the rolling temperature is increased to 1300 °C, more cleavage fracture surfaces appear except part ductile fracture, so the lower tensile elongation can be reached.

Fig. 15 reveals the tensile fracture surface of the interface layer between the middle 2Cr13 and 316L layers in Fig. 13 for the specimens with different rolling temperatures, it can be seen that with the increase of rolling temperature, the interfacial bonding strength is improved, the layered cracking tendency is relatively low. In particular, for composite plate with the rolling temperature of 1130 °C, the intermediate interface delamination occurred and often accompanied by cleavage fracture at the interface near the middle 2Cr13 layer, but for the composite plate with high rolling temperatures, slip deformation appears in intermediate interface.

Fig. 16 presents the fracture surfaces of the interfaces between the 2Cr13 layer on both sides and 316L layer at different rolling temperatures. It can be seen that the dimple fracture controls the fracture of the interface on both sides of the metal, it means that a good interface can be formed. Because with the increase of the rolling temperature, the ferrite content of 2Cr13 layer on both sides increases, more dimples were formed in tensile processes.

3.4. Effects of the Rolling Temperature on Bending Strength

Table 5 shows the results of three point bending specimens with various rolling temperatures bending to 130 degrees (± 2°).

From Table 5, it can be seen that the higher bending strength of 3446.8 MPa can be obtained in the specimen with the rolling temperature of 1130 °C. The lowest bending strength of 2162.7 MPa can be obtained in the specimen with the rolling temperature of 1250 °C. It is consistent with the measured tensile strength of composite plate. The change of strength for the specimens with the various rolling temperatures is related to the ferrite content of 2Cr13 layers and the grain size of 316L layer. In order to clearly compare the bending strength of the composite plate at different rolling temperatures, the column figure is drawn in Fig. 17.

Fig. 18 shows the load displacement curves of the composite plates with different rolling temperatures during three point bending. It consists of three stages: elastic stage, nonlinear yield stage and failure stage. It can be seen that higher yield limit and bending resistance of composite plate can be obtained for the specimen with the rolling temperature of 1130 °C. The condition of the comparison is that the reduction rate of the composite plate is about 81% at different rolling temperatures, the final thickness is about 3 mm, and the cross-sectional area of the specimen is approximately the same as that of the bending.

Fig. 19 presents the macroscopic morphology of the composite plate obtained at different rolling temperatures bending to 130°. The magnified figure of maximum bending moment (marked by red region) in Fig. 19 is shown in followed bottom Figure. It can be seen that the no naked eye cracks can be found in a lateral surface of the specimen, and no interface cracking and delamination fracture occurred in the layer, only plastic deformation can occurred. It means that the interlayer bonding with high quality can be found. To carefully study the deformation behavior of composite plate during bending processes, micro-

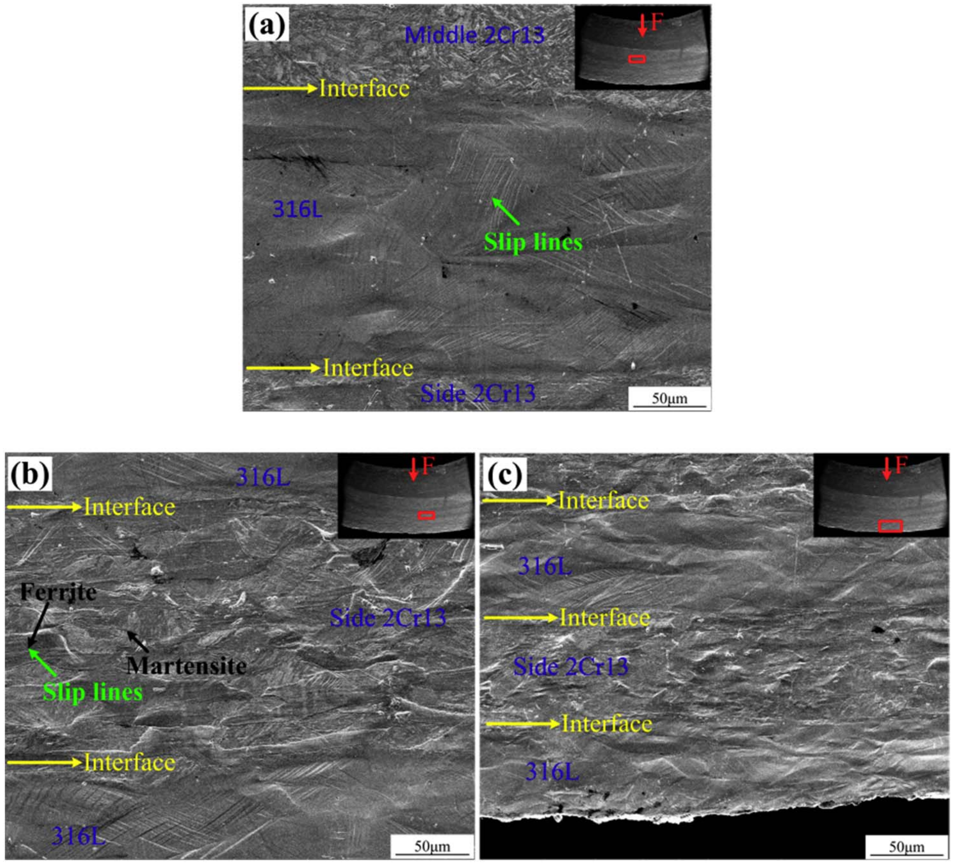

Fig. 20. Micro-scale magnified features ofthe various locations in Fig. 19(b).

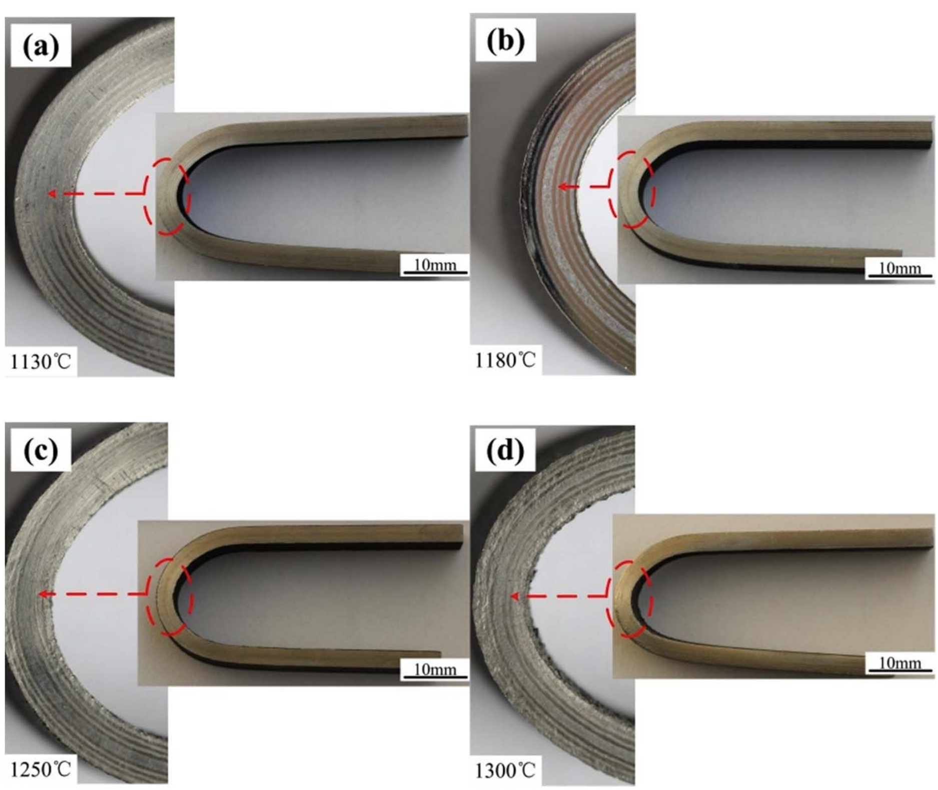

Fig. 21. The macroscopic morphology of MLS obtained at different rolling temperatures bending to 180°.

scale magnified features in Fig. 19(b) can be shown in Fig. 20.

The corresponded location in MLS is shown by red block in subfigure. In 316L layer, huge slip deformation with amounts of slip lines can be produced. Due to various disorientation in various austenitic grains, various slip systems appear in austenitic grain, thus austenitic grain boundaries become uplift or subsidence, the grain boundary is clearly visible. The microstructure of the 2Cr13 layer on both sides is ferrite and martensite, deformation is easily produced in ferrite phase due to physical soft plastic, thus more slipping line can be found in the ferrite phase, and no any intergranular cracking can be seen. However, no local cracking, no delamination and no local fracture phenomenon can be found in the center 2Cr13 layer including full martensite. It means that plasticity deformation of martensite has been improved in the composite plate, and complete metallurgical bonding with high quality can be formed.

Fig. 21 shows the macro-feature of the specimen in Fig. 19 further bending to 180°. It can be seen that when the bending specimens were further bended to 180°, no visible macro-cracks, no interlayer crack and no interlayer fracture can be still found. It means that a good bonding interlayer with increased plastic deformation can be obtained.

4. Conclusions

In this paper,15 layers 2Cr13/316L stainless steel composite plate was produced by hot-rolling technology. The microstructures, tensile and bending properties of the composite plate were studied systematically at different rolling temperatures.Obtained results are summarized as follows.

1. The center 2Cr13 layer with thick lath martensite after the different rolling temperatures has been transformed to banded or massive ferrite which are distributed along the rolling direction. The microstructure of 2Cr13 layer on both sides is composed of martensite and ferrite, and the grains are elongated along the rolling direction. With the increase of rolling temperature, the content of the ferrite phase increases. Only coarse and elongated austenite phase along rolling direction appears in 316L layer.
2. The properties of the composite plates with different rolling temperatures are different, which are depended on the grain size and the content of ferrite phase in the 2Cr13 layers. With the increase of rolling temperature, the tensile strength and bending strength of 2Cr13/316L was reduced first and then increased slightly due to the coarsening of grains and the increase of ferrite content in 2Cr13 layers.
3. 2Cr13/316L composite plate obtained at the rolling temperature of 1130 °C or 1180 °C, and the reduction ratio of 81% can reach higher tensile strength of 1082.3 MPa and 920.6 MPa, the larger tensile elongation of 18.3% and 23.9%, and the flexural strength of 3446.8 MPa and 2763.1 MPa respectively.
4. When 2Cr13/316L composite plates with different rolling temperature are bent to 130°and 180°, higher bending abilities with no fracture and cracking along the layer can be obtained.
5. With the increase of rolling temperature, the interfacial bonding strength is improved, the layered cracking tendency is relatively low.

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Conflicts of Interest

No conflict of interest exits in the submission of this manuscript.

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