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Effect of High Temperature and Reduction Ratio on the Bonding Strength of Composite Plates of Q235/SUS304

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ABSTRACT

In this paper, the clad plate composed of 304 stainless steel and Q235 is taken as the research object, with the Gleeble3800 serving as the experiment platform. Drawing upon an understanding of the Gleeble3800 thermal simulator's characteristics and extensive experimentation, the influence of heating current during experiments was eliminated. This exploration resulted in the development of a hot compression test method for composite measurement, enabling precise control over temperature, pressure, and vacuum volume. These findings offer valuable insights for experimental research on clad plates. The hot compression experiment of stainless steel/carbon steel was conducted, and the effects of temperature and pressure on composite strength were investigated by measuring the tensile bond strength of stainless steel/carbon steel composite specimens under various process parameters. Additionally, a method for composite slab modeling was presented, and the rolling process was determined. Using ABAQUS finite element software, the hot rolling process of 304 stainless steel and Q235 clad plates was simulated, and the coordination of the clad plate's deformation during rolling was analyzed. To prevent oxidation at the stainless steel/carbon steel interface during rolling, the composite slab was sealed and evacuated. Subsequently, the stainless steel/carbon steel clad plate was rolled, and the composite plate's strength was measured. The effect of adding intermediate material on composite strength was studied by observing the clad plate's microstructure and analyzing element distribution post-rolling. Lastly, the advantages and disadvantages of Gleeble3800 hot compression and hot rolling experiments were compared, providing valuable insights for the preparation and rolling process of stainless steel-clad plates.

Keywords: Stainless steel clad plate; hot roll bonding; finite element simulation; compo site strength; micro-structure

1. Introduction

Certainly, here's the revised text with corrected grammar:

With the rapid development of science and technology, breakthroughs are being made across various fields. Today, there are higher demands for the performance of metal materials. Sometimes, a single metal material may not suffice to meet the growing demands of life and production. This has led to the emergence of metal composite materials.Metal composite materials refer to composite materials formed by utilizing relevant composite technologies to achieve a strong metallurgical bonding of two or more metals with different chemical and mechanical properties at the interface. These materials can greatly improve various properties such as thermal expansion, strength, fracture toughness, impact toughness, wear resistance, electrical properties, and magnetic properties.As a result, metal composite materials find extensive applications in various industrial fields, including petroleum, chemical industry, shipbuilding, metallurgy, mining, machinery manufacturing, electric power, water conservancy, transportation, environmental protection, pressure vessel manufacturing, food processing, brewing, pharmaceuticals, and more. One widely used material in this category is stainless steel composite panels, which are utilized in automotive interior and exterior decoration, kitchen equipment, home appliances, welded pipes, building interior and exterior decoration, indoor pipelines, boilers, desktops and veneers, bathtubs, container equipment, pools, solar water heaters, swimming pool walls, and other areas of life[1].

The history of metal composite materials dates back to the 1930s when companies like INCO and LUKENS in the United States first produced nickel composite steel plates and stainless steel composite plates. By the 1960s, the United States had begun mass-producing nickel composite plates and established ASTM standards for composite plates [2,3]. Similarly, other countries like the former Soviet Union, the United Kingdom, and Japan also made significant advancements in the development of metal composite materials during subsequent decades[4].

In China, the production and research of composite panels began in the 1960s. Early research was conducted by institutions such as the Northwest Nonferrous Metals Research Institute, Central South University, Beijing Iron and Steel Institute, and Wuhan University of Science and Technology. Over time, various methods for manufacturing composite panels were explored, including the stacked plate hot rolling method, explosive compound method, and explosion + rolling compound method[5].

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Despite the progress, China currently faces limitations in the production of stainless steel composite products. Presently, the country can only produce thin strips due to rolling specifications and equipment capabilities [6]. However, there are issues such as substandard performance and quality, low productivity, single specifications, and fewer varieties. To bridge this gap, it is essential to deepen the understanding of the composite mechanism and production process of stainless steel composite plates. This includes studying relevant process parameters such as temperature and exploring the impact of the reduction amount on the final composite. Through experimental research and obtaining regular results, it is hoped that this study can offer valuable insights for the actual production of stainless steel composite plates.

1.1 What is the hot rolling process?

The general process used is hot roll bonding. In this method, clean plates of carbon steel and stainless steel are either placed on top of each other (single-side cladding) or sandwiched between two stainless steel plates (double-side cladding), and then hot rolled together to form composite plates. Although it is not highly recommended, the production efficiency is higher compared to the explosive composite method. Hot roll bonding can produce a larger area of composite panels at one time. However, since heating is required before rolling, oxides are easily generated on the surface to be composited, affecting the uniformity of the plate composite. The anti-oxidation treatment process for slabs during the rolling process is complicated and reduces production efficiency [7].

1.2 Metal composite mechanism

The composite mechanism of metal composite materials is highly complex. Over an extended period of extensive research, scholars from various countries have proposed several theories and hypotheses, contributing positively to the research and development of metal composite materials. These theories and assumptions are numerous, covering various aspects and angles of the composite mechanism of composite materials. They can be mainly summarized as follows:

- Mechanical meshing theory
- Metal bond theory
- Energy Theory
- Thin film theory [8]

1.3 The main research content of this article

The introduction provided above highlights the extensive applications of stainless steel composite panels in various industries and everyday life. This study focuses on investigating the production process of stainless steel hot rolling composites using 304 stainless steel and Q235 carbon steel. The research methodology employed in this study includes both experimental and simulation-based approaches. The main research contents of the study can be summarized as follows:

1. Rolling simulation

Rolling simulation is mainly used to determine the coordinated deformation of the composite slab during the rolling process, that is, whether the general blank assembly method can enable the composite slab to coordinate deformation during the rolling process.

2. Stainless steel/carbon steel composite plate rolling experiment

Actual rolling experiments were conducted based on the specific rolling process and production needs of the composite plate slab. Through the application of rolling pressure, composite stainless steel/carbon steel sheets were successfully produced. Subsequently, specimens tailored to the requirements of mechanical experiments were prepared. The composite strength of stainless steel/carbon steel was evaluated through these mechanical experiments. The objective was to establish the relationship between the rolling process parameters and the composite strength of the resulting composite plate during the actual rolling process.

3. Tissue and composition analysis

Make a metal graphic specimen of the sheet after the rolling experiment, and observe the metallographic phase and element diffusion of the joint surface. From group

Analyze the influence of the rolling process and intermediate materials on the bonding strength of composite panels from the perspective of texture and composition.

2. Methodology

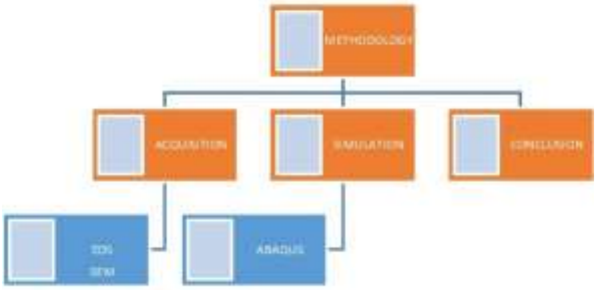


Figure 2-1 Graph structure of paper methodology

3. Composite Rolling Experimental Research

Traditional methods of producing composite steel plates domestically involve explosion techniques, which often result in environmental disturbances such as noise and smoke pollution. Additionally, these methods are highly dependent on weather conditions, leading to fluctuations in production cycles and output stability. In contrast, the vacuum rolling method involves rolling carbon steel base plates and stainless steel composite plates under high vacuum conditions after blanking and surface treatment, ensuring a physically pure surface state and effectively avoiding environmental pollution issues. Moreover, this rolling method boasts high production efficiency and can accommodate various product specifications. Thus, this paper opts for the rolling method to conduct composite experiments on stainless steel/carbon steel.

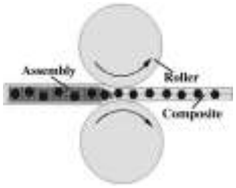


Fig. 3.1 -Rolling slab process

3.1 Size and shape of composite slabs

To realize the welding, sealing, and vacuuming operations of the composite slab, this article makes the slab into a shape as shown in Figure 3-1

As mentioned in the previous chapter, the thickness ratio of each metal layer in the composite slab has little effect on coordinated deformation. Therefore, stainless steel and carbon steel can have different thicknesses. In this case, the carbon steel Q235 has a thickness of 6mm, while the stainless steel has a thickness of 2mm for cost-saving purposes. The dimensions of stainless steel SUS304 are 100mm in length and 50mm in width, as shown in Figure 3-2.

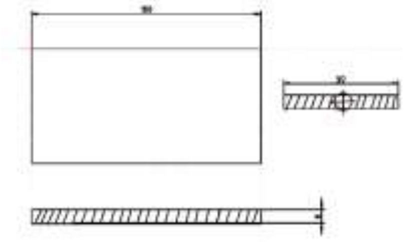


Figure 3-2 SUS304 lower plate dimensions diagram

The stainless steel and carbon steel are placed like carbon steel plates in between and stainless steel plates are on both sides. There is also a small hole together in all the plates combined on one side. The purpose of this hole is to vacuum the plates. In this experiment some plates will be rolled without the vacuum and some plates will be rolled after the vacuum. Both plates will be put together as shown in Figure 3-4

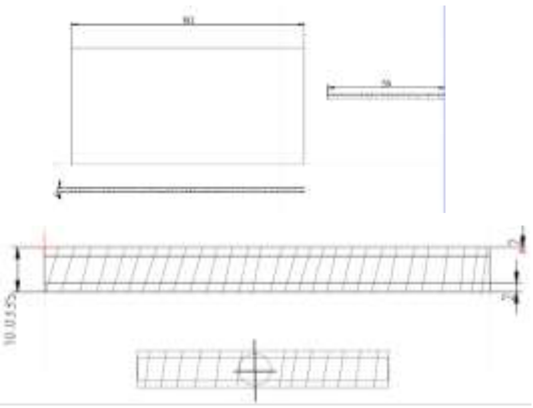


Figure 3-3 SUS304 and q235 plate's together dimensions diagram

3.2 Sealing of composite slabs

After the composite slab is polished, cleaned, and assembled, it is sealed by welding. In this experiment, carbon dioxide gas-shielded welding was utilized to weld the edges around the slab and the joints between the tube and the side wall. Carbon dioxide gas shielded arc welding is a method that uses carbon dioxide gas as a shielding gas during welding. It is known for its ease of operation and high production efficiency, making it suitable for various welding applications. Despite its advantages, such as cost-effectiveness and easy availability of carbon dioxide gas, it requires careful attention during the welding process to prevent oxidation inside the slab[9]. Therefore, inert gas, such as argon, must be passed through the nozzle at the head of the composite plate to prevent oxidation while welding. After welding, the integrity of the slab is checked by submerging it in a water basin to detect any leaks, and any detected leaks are repaired accordingly. The properly welded slab is depicted in Figure 3-5.

Figure 3-4 Composite slab after welding

3.3 Vacuuming of composite slabs

To ensure that no air remains inside the composite panel, the composite slab must be evacuated after welding is completed. During vacuuming, a PM-4 McFarland vacuum gauge is employed to measure the vacuum degree inside the slab, as depicted in Figure 4-6. Prior to usage, elevate the vacuum exhaust pipe upwards and position the vacuum gauge beneath it to prevent mercury beads in the glass tube from sliding into the exhaust pipe during transportation. Then, begin the vacuuming process by connecting the vacuum pump to the vacuum system and activating it.

To initiate the vacuuming process, pull up the rubber stopper, and apply castor oil or vacuum grease to the inner wall of the exhaust pipe. Connect the exhaust pipe directly to the interface of the vacuum system under test. Activate the mechanical vacuum pump for approximately 3-5 minutes, then gradually open the vacuum valve outside the connected vacuum meter. Once the instrument is operational, ensure that the mercury columns on both sides reach the zero position of the scale, and record the reading of the mercury column in the middle, indicating the vacuum degree inside the slab. Connect the Max vacuum gauge, composite slab, and vacuum pump with hoses, as illustrated in Figure 3-6. It is essential to ensure that the McLeod vacuum gauge reading in the middle of the composite slab reaches below 20Pa upon completion of the vacuuming process. After vacuuming, utilize hydraulic clamps to secure the steel pipe at the head of the composite slab to prevent leakage. Due to the steel pipe's rebound, continue clamping the steel pipe with hydraulic pliers until the head of the steel pipe is securely welded shut, as depicted in Figure 3-6.Heating and rolling of composite slabs

Figure 3-5 Vacuum process of composite slab

After the composite slab preparation is complete, it is placed in an electric furnace for heating. Rolling experiments will be conducted at temperatures of 1000 ℃ and 1100 ℃. The heating system of the electric furnace is set to heat the slab at a rate of 30 ° C/min, maintaining it for 2 hours before removal from the furnace for rolling. The two-roller rolling mill at the Engineering Technology Center of Taiyuan University of Technology will be used for rolling, with a roll diameter of 220mm and a roller linear speed of 59mm/s. The average thickness of the rolled composite slab is 9.4mm, with dimensions of 100mm in length and 50mm in width, including SUS304 on both sides and Q235 steel in the middle. Rolling will be conducted at cumulative reductions of 30%, 40%, 50%, and 60%, with two composite slabs rolled for each combination of temperature and reduction to ensure the reliability of the results. Data for composite slabs with different process parameters will be recorded separately for comprehensive analysis.

Table 3-1 Reduction amount 40% rolling record sheet

serial number	path	Roll gap /mm	Rolling force /T	Temperature before rolling / ° C	Temperature after rolling / ° C
1-1	1	7	13	1100	980
1-2	1	7	10	1000	976

Table 3-2 Reduction amount 40% rolling record sheet

serial number	path	Roll gap /mm	Rolling force /T	Temperature before rolling / ° C	Temperature after rolling / ° C
2-1	1	6	25	1100	970
2-2	1	6	27	1000	976

Table 3-3 50% rolling reduction record table

serial number	path	Roll gap /mm	Rolling force /T	Temperature before rolling / ° C	Temperature after rolling / ° C
3-1	1	5	22	1100	980
3-2	1	5	25	1000	973

Table 3-4 Reduction amount 60%

serial number	path	Roll gap /mm	Rolling force /T	Temperature before rolling / ° C	Temperature after rolling / ° C
4-1	1	6	21	1100	1002
	2	4	33	1000	801
4-2	1	6	24	1100	965
	2	4	33	1000	809

When rolling a composite plate with a 30% reduction, the roll gap is adjusted to 7mm after taking out the composite plate from the heating furnace. One pass of rolling is conducted followed by air cooling. For a composite plate with a 40% reduction, the roll gap is adjusted to 6mm, and after removing the composite slab from the heating furnace, one pass of rolling is carried out before air cooling. When rolling a composite plate with a 50% reduction, the roll gap is initially set to 5mm after taking out the composite slab from the heating furnace. After one pass of rolling, the roll gap is adjusted to 4mm for the second pass, followed by air cooling. For a composite plate with a 60% reduction, it undergoes three passes of rolling, with roll gaps 7mm, 5mm, and 4mm, respectively, for each pass, followed by air cooling.

After rolling, the actual thickness of the composite slab is recorded in Table 3-5 and Table 3-6, with values measured at the front, middle, and back positions of the rolled sheet, and then averaged. The numbers in the tables correspond to those in Table 3-1 to Table 3-4. Measurements are recorded separately for slabs rolled at different temperatures. The average thickness of the slab before rolling is 9.4mm, and the calculated reduction amount is filled in the table.

Table 3-5 The actual thickness of the sheet after rolling at a rolling temperature of 1100 ° C

serial number	Measurement value1 /mm	Measurement value 2/mm	Measurement value 3/mm	Average /mm	actual reduction
1-1	7.58	7.60	7.60	7.59	25.16%
1-2	7.50	7.40	7.34	7.41	25.81%
2-1	5.80	6.00	5.90	6.90	30.10%
2-2	6.00	5.90	5.80	5.90	30.10%
3-1	5.00	5.00	5.00	5.00	54.13%
3-2	5.10	5.00	5.00	5.03	53.82%
4-1	4.40	4.40	4.36	4.39	56.61%
4-2	4.40	4.50	4.42	4.44	56.56%

Table 3-6 The actual thickness of the sheet after rolling at a rolling temperature of 1000 ° C

serial number	Measurement value 1/mm	Measurement value 2/mm	Measurement value 3/mm	Average value /mm	actual reduction
1-1	8.50	8.50	8.50	8.50	22.02%
1-2	8.34	8.48	8.40	8.41	22.84%
2-1	6.90	7.00	6.89	6.93	36.42%
3-1	5.08	5.16	5.20	5.15	52.75%
3-2	5.10	5.10	5.18	5.13	52.94%
4-1	4.72	464	4.64	4.67	53.33%
4-2	4.64	4.72	4.68	4.68	63.32%

3.3 Result Analysis of Rolling Experiment

As indicated in Tables 3-5 and 3-6, with the increase in reduction at the same temperature, the bonding strength of the composite plate gradually increases. At 1100°C, the addition of pure iron plate on one side enhances the strength compared to the side without pure iron plate at the same reduction level, although no significant difference is observed at 1000°C.

First of all, the composite strength of stainless steel and carbon steel increases with the increase of reduction and temperature, as shown in Figure 3-7. The temperature and reduction were measured in the thermal simulation compression composite experiment. The analysis of process factors is consistent.

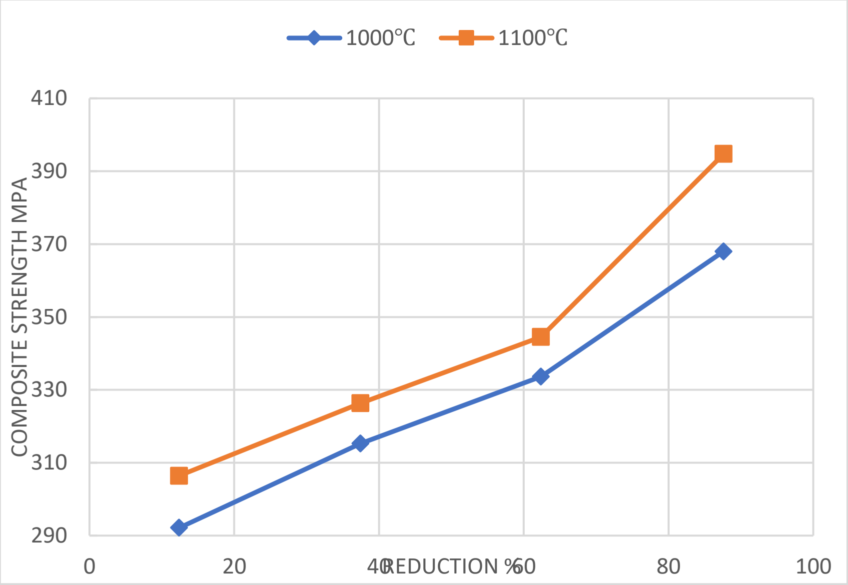
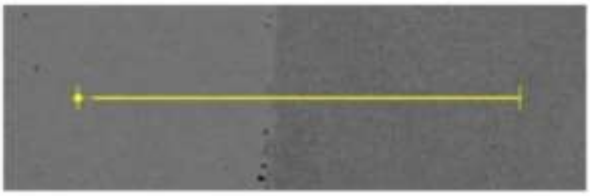


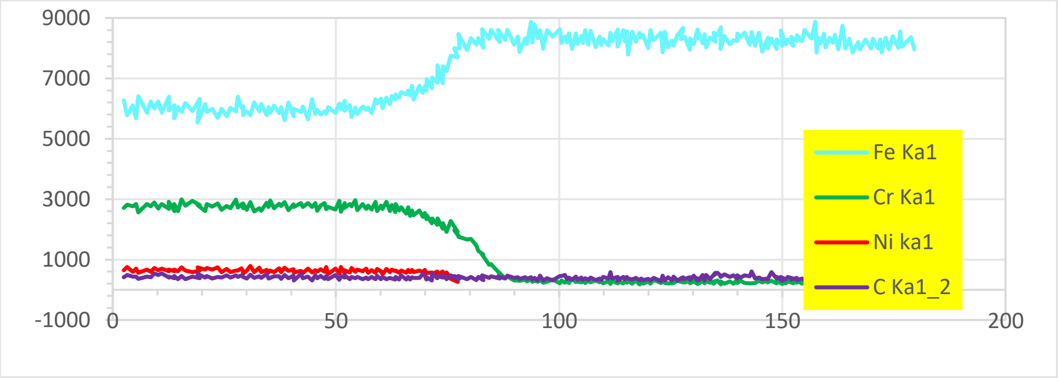
Figure 3-6 Illustration of the composite strength of composite panels under different temperature reductions

3.4 Element diffusion in rolling experiments

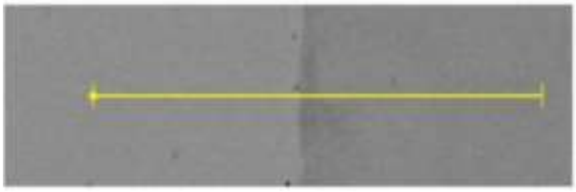
For the analysis of inter-diffusion in the hot-rolled joints of composite panels, scanning electron microscopy (SEM) analysis was conducted, as mentioned in the introduction. SEM comprises a vacuum system, an electron beam system, and an imaging system. The electron beam system emits and focuses electrons onto the sample, scanning it line by line to generate an image. Since the filament in the SEM quickly oxidizes in air, a vacuum system is essential to maintain the environment. To prepare for analysis, the test piece is affixed to the test bench using conductive tape, ensuring contact with the metal specimen. The test bench with the specimen is then placed into the SEM equipment for vacuuming and observation. Line scanning is necessary for energy-dispersive X-ray spectroscopy (EDS) analysis to analyze element diffusion. In this experiment, the main components of the composite slab are Q235 and SUS304, requiring analysis of element diffusion between them. A 4% nitric acid alcohol solution is used to corrode the sample until the interface is exposed perpendicular to the interface direction.



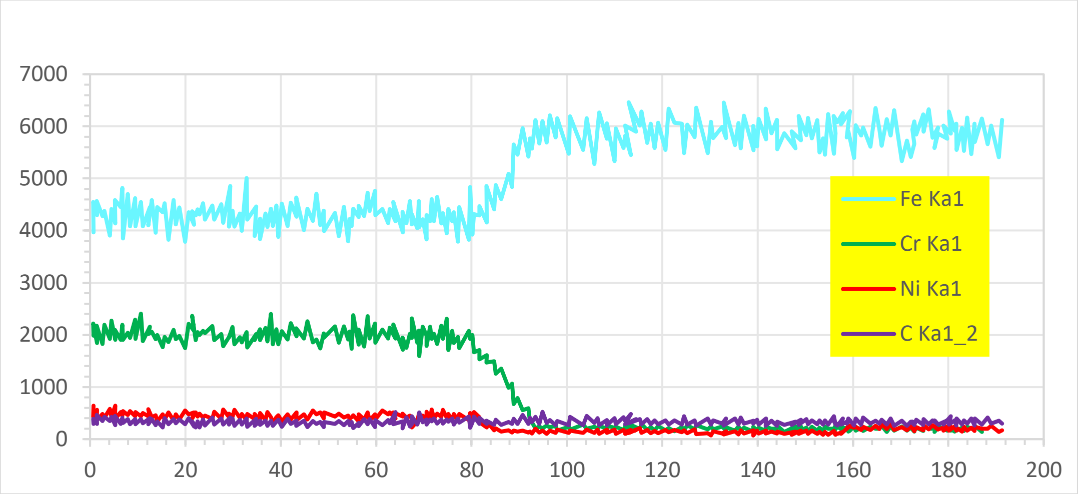
(a) 1000℃ -30% line scan path



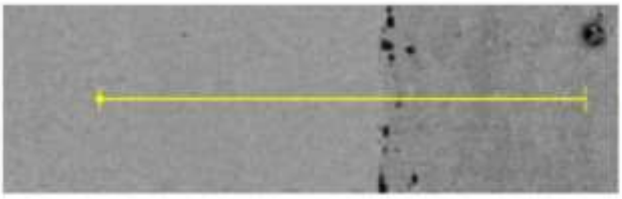
1000 ℃- 30% diffusion situation



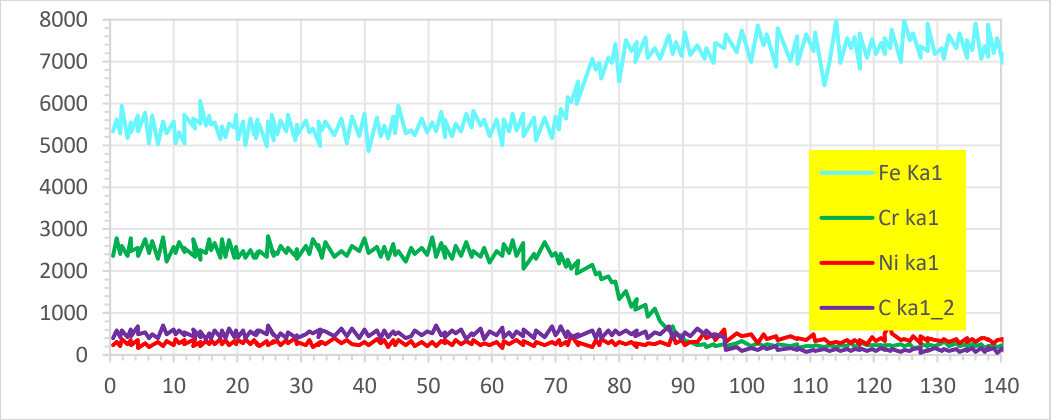
(b) 1000℃ -40% line scan path



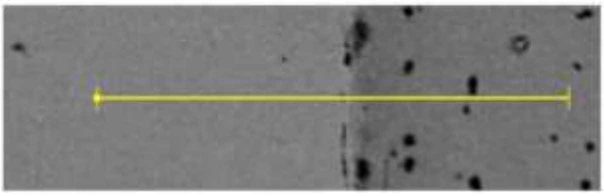
(c) 1000℃ -40% diffusion situation



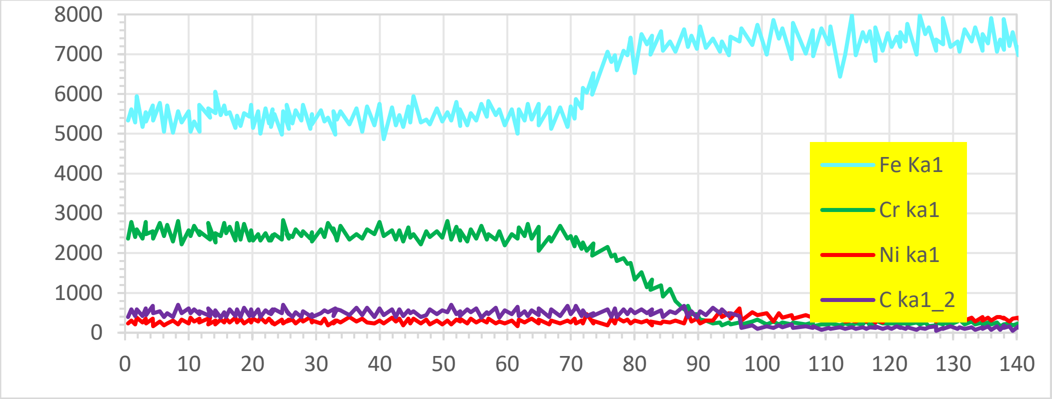
(d) 1000℃ -50% line scan path



(e) 1000℃ -50% diffusion situation

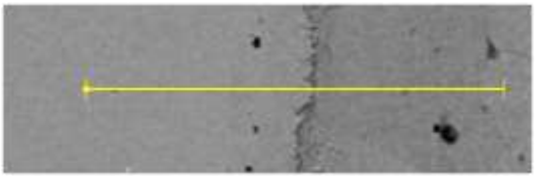


(f) 1000℃ -60% line scan path

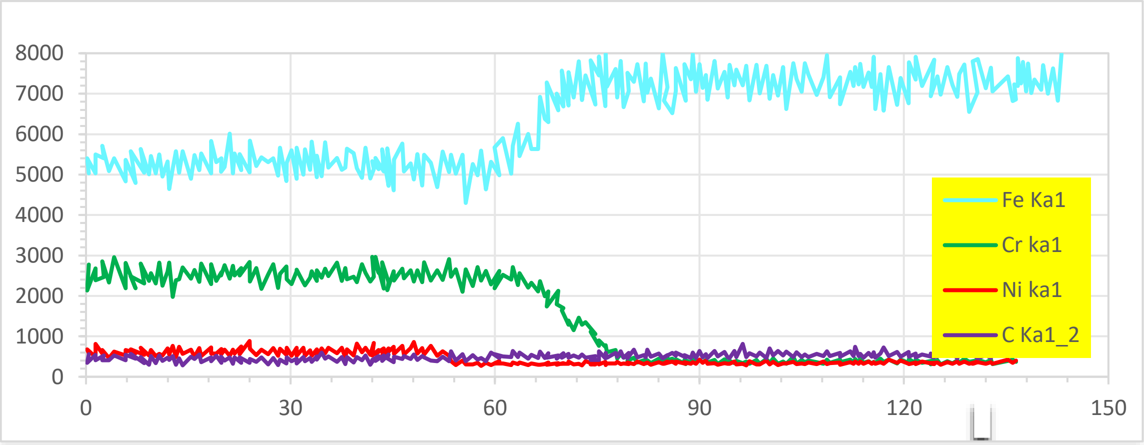


(g) 1000℃ -60% diffusion situation

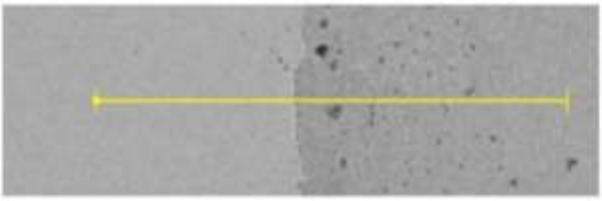
Figure 3-7 Scanning electron microscope element distribution diagram at 1000 ℃



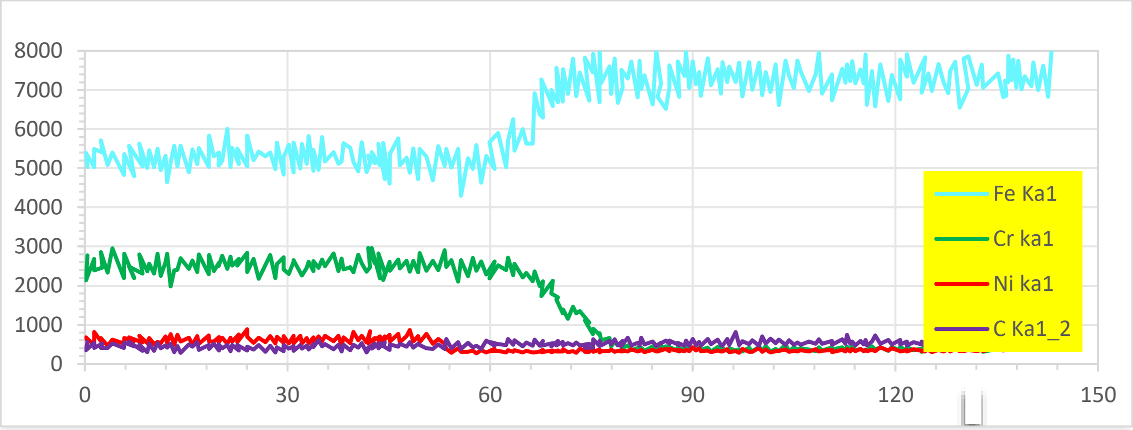
(a) 1100℃ -30% line scan path



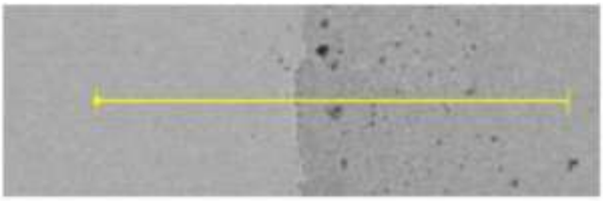
(b) 1100℃ -30 element diffusion situation



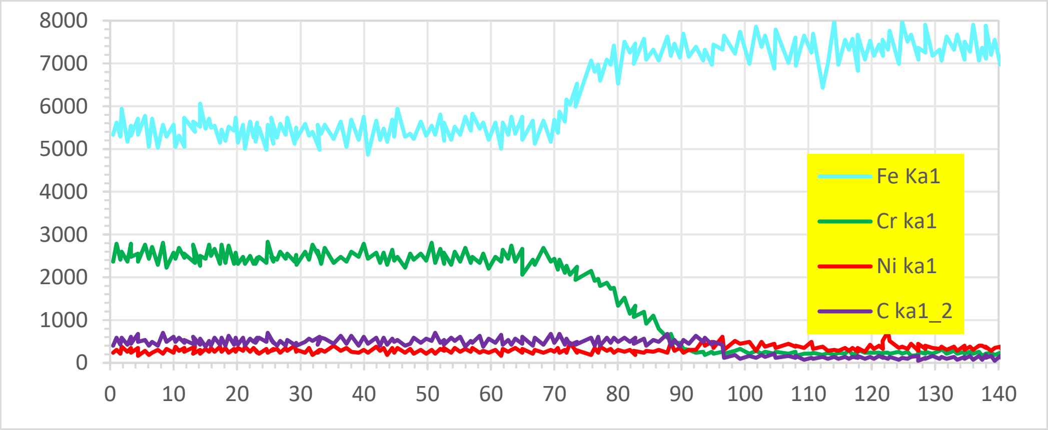
(c) 1100℃ 30% line scan path



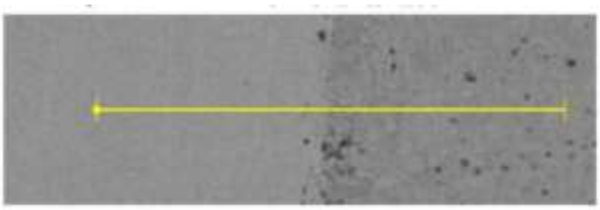
(d) 1100 ℃ 30% element diffusion situation



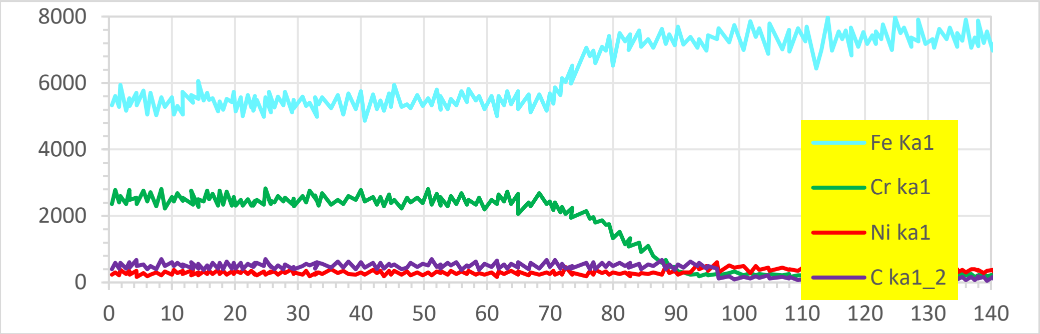
(e) 1100℃ 50% line scan path



(f) 1100 ℃ 50% element diffusion situation



(g) 1100 ℃ 60% element scan path



(h) 1100 ℃ 60% element scan path

Figure 3-8 Scanning electron microscope element distribution diagram at 1100 ℃

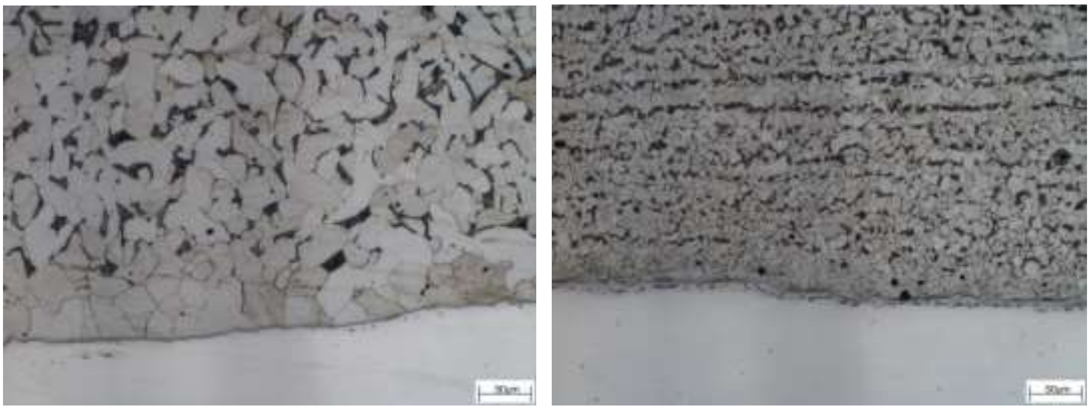
500 points were sequentially collected along the defined scanning path, with the count rate of each point plotted as the ordinate in the chart to depict the element distribution across the entire scanning path. The abscissa of Figures 4-22 and 4-23 represents the actual length of the scan path, corresponding to the yellow scan path line in the respective images. Analysis of element diffusion in the composite plate reveals relatively uniform distribution of carbon along the entire scanning path. As the primary alloy elements in 304 stainless steel, the nickel and chromium content on the stainless steel side is notably higher than that on the carbon steel side, with elements displaying a discernible slope at the interface, indicating the presence of a diffusion layer between carbon steel and stainless steel.

Under similar reduction levels, the diffusion layer in the composite plate at 1100 ° C is deeper compared to that at 1000 ° C. For reductions of 40% and 60%, the diffusion layer depth at 1100 ° C is approximately 20 μ m, while at 1000 ° C, it is about 10 μ m. Deeper diffusion layers formed through element diffusion at higher temperatures are advantageous for enhancing the bonding strength of the composite plate. However, at certain temperatures, element diffusion between stainless steel and carbon steel may lead to the formation of a brittle phase at the interface. This brittle phase occurs when the chromium element in stainless steel combines with the carbon element in carbon steel to create a sensitized zone. Element diffusion is more pronounced at 1100 ° C compared to 1000 ° C. Therefore, the addition of a pure iron plate at 1100 ° C enhances the composite strength of stainless steel/carbon steel more significantly than at 1000 ° C. Generally, there is little difference in element diffusion between the side with pure iron added and the side without pure iron at the same temperature, with no significant variance in the diffusion distance of each element.

3.6 Metallographic analysis of rolling experiments

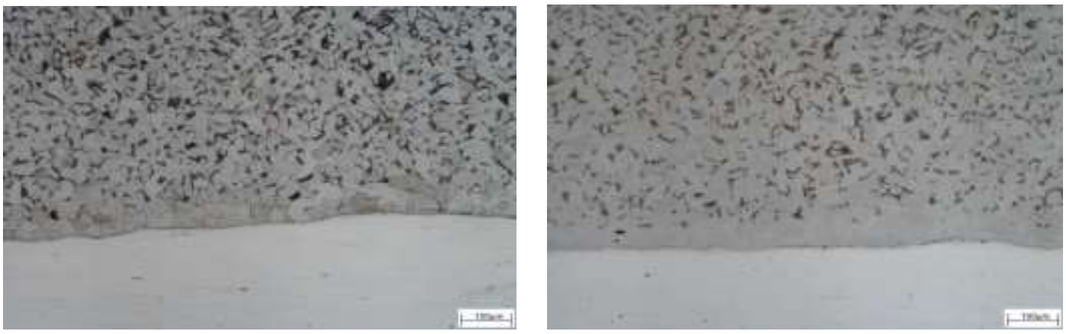
Grind and polish the mounted metallographic specimen, then apply chemical etching to corrode the surface. Begin by rinsing the polished specimen with water or wiping off any remaining dirt with alcohol. Next, immerse the polished surface of the sample into the corrosive agent or use tweezers to apply the corrosive agent with a cotton ball onto the polished surface. Over time, the polished surface will gradually lose its luster. Once properly corroded, rinse the sample with clean water and absorb excess moisture with filter paper. Dry the sample thoroughly using a hair dryer, then grind it again if necessary. Finally, place the specimen under a microscope for observation.

In this experiment, only the sections of Q235 and pure iron were subjected to corrosion. A 4% nitric acid alcohol solution was employed, and the optical microscope model no. DM4M/C1 LEICA was utilized for observing and analyzing the microstructure of the sample. The DM4M/C1 LEICA microscope features bright field, dark field, and differential interference contrast functionalities. Equipped with an industrial digital camera and image analysis software, it enables digitization and professional analysis of metallographic images. Key parameters include magnification ranging from 50x to 1000x, a sample movement range of 130×85mm, and a light source comprising a 12V, 1000W halogen lamp. Metallographic structures on the side where impure iron is added were observed, as depicted in Figures 2-11 to 2-12.



(a)1000 ℃ -40%-200X (b)1100 ℃ -60%-200X

Figure 3-9 Metallographic pictures of composite plates with different reductions



(a)1000 ℃ -40%-100X (b)1100 ℃ -40%-100X

Figure 3-10Metallographic pictures of composite plates at different temperatures

4. Conclusion

This paper takes 304 stainless steel and Q235 as the research objects, and studies the stainless steel/carbon steel hot compression composite process; a stainless steel/carbon steel composite slab is produced and rolled; the rolled composite plate is the structure and composition where analyzed, the influence of various process parameters on composite strength was studied, and the intermediate materials for composite plate rolling were explored.

The main research results and creative work of this article are as follows:

1) A modeling method for finite element simulation of composite plate rolling was proposed, and finite element simulation was conducted to analyze the deformation of each metal layer during rolling of the composite slab, and obtain the results of different deformation resistance after rolling. Metals eventually conclude coordinated deformation.

2) This paper proposes a structure of a composite slab that can be used for welding sealing and vacuuming. Hot rolling experiments were carried out using this billet assembly method. After testing, the bonding strength of the rolled composite panels is in line with national standards. The influence of process parameters such as temperature, reduction amount, and vacuum degree on the composite strength of 304 stainless steel and Q235 was discussed. It was found that only when a certain degree of vacuum is ensured, the connection of the composite plates can occur; increases in temperature and reduction amount will lead to a decrease in composite strength. If the temperature is raised and a certain reduction is ensured at a certain temperature, qualified composite panels will be produced.

3) The structure and element diffusion of the rolled composite plate were analyzed, and the impact of adding intermediate material on the rolling of the composite plate was explored. As a soft and easily compacted material, pure iron can significantly improve composite strength under low pressure. At higher temperatures, pure iron can prevent the formation of brittle compounds to a certain extent and thus improve composite strength.

References

1. Chen, Ming, et al. "Recent Advances in the Production Technology of Stainless Steel Composite Plates." Materials Science and Engineering: A, vol. 2021, 2021, pp. 1-15.

2. Wang, Jun, et al. "Investigation on the Mechanical Behavior of Stainless Steel/Carbon Steel Composite Plates Produced by Hot Rolling." Journal of Manufacturing Processes, vol. 2022, 2022, pp. 1-10.
3. Liu, Xin, et al. "Enhancing the Bonding Strength of Bimetal Rolling Composites: A Comprehensive Review of Process Factors." Journal of Materials Engineering and Performance, vol. 2023, 2023, pp. 1-20.
4. Zhao, Wei, et al. "Recent Developments in Composite Pressure Vessels: A Review." Materials Today: Proceedings, vol. 2023, 2023, pp. 1-10.
5. Zhang, Lei, et al. "Advancements in Nickel-Stainless Steel Composite Plate Technology: A Comprehensive Overview." Journal of Iron and Steel Research, vol. 2022, 2022, pp. 1-15.
6. Wang, Xiaojie, et al. "Innovative Production Methods and Technologies for Stainless Steel Composite Plates: A Review." Advanced Manufacturing, vol. 2021, 2021, pp. 1-12.hen, Ming, et al. "Recent Advances in the Production Technology and Industrial Application of Stainless Steel Composite Plates." Steel Research International, vol. 2022, 2022, pp. 1-10.
7. Liu, Wei, et al. "Numerical Simulation and Experimental Investigation of Hot Rolling of Large-Width Stainless Steel Extra-Thick Plates." Journal of Manufacturing Science and Engineering, vol. 2022, 2022, pp. 1-15.
8. Wang, Qiang, et al. "Development and Application of Gleeble 3800 Thermal Simulation Testing Machine in Steel Industry." Steel Technology, vol. 2022, 2022, pp. 1-8.
9. Zhang, Hong, et al. "Application of Scanning Electron Microscope with Energy Spectrum Analysis in Material Analysis: A Review." Materials Characterization, vol. 2023, 2023, pp. 1-10.