Effect of solution treatment on microstructure and properties of duplex stainless steel

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Abstract. The influence of solution treatment on microstructure and properties of 2205 duplex stainless steel (DSS) was studied. The microstructure, precipitates and corrosion resisting property were observed and analyzed by means of optical microscopy (OM), scanning electron microscopy (SEM) and electrochemical methods. The results showed that a large number of brittle σ-phase precipitates, which deteriorate the plasticity and corrosion resistance of the material, were easy to produce in the duplex stainless steel under the low temperature. The precipitation of σ-phase can be decreased and the plasticity and corrosion resistance can be improved by increasing solution temperature. In addition, the ferrite content increases with the increase of solution temperature, while less affected by cooling rate.

1. Introduction

Duplex stainless steel consists of austenite(γ) and ferrite(δ) phases, which is produced by increasing Cr content or other ferrite formation elements and decreasing Ni content on the basis of austenite stainless steel [1-5]. Compared to traditional austenitic stainless steel and ferritic stainless steel, duplex stainless steel possesses good strength, high toughness, formability, anticorrosion, biocompatibility and weldability. This grade of steel has found extensive application in heat exchangers, water heaters, pressure vessels, storage tanks, rotors, impellers and shafts, digesters and other equipment in pulp and paper production, cargo tanks in chemical tankers, desalination plants, waste gas purifiers and sea water systems etc[6-12].

UNS S2205 is the typical representative of duplex stainless steel, the two phases each account for about 50% in normal state (solution treatment), to ensure its high strength, high corrosion resistance and good welding properties. Some studies have shown that the performance of the DSS is closely connected with the proportion of the two phases and other precipitated phase [13-23]. However, the proportion and other precipitation are depend on the chemical composition, heat treatment temperature and other factors. An improper heat treatment can change the proportion and produce a large amount of brittle phase (such as σ-phase), which is bad for the plasticity, toughness and corrosion resistance of the plate. Especially it is very important and difficult for both materials to achieve good performance with the same heat treatment when DSS is used for clad plates or devices welded with carbon steel.

Therefore, the influence of different solution conditions (especially at 900℃) on the microstructure and precipitates of DSS is studied in present study, in order to provide a reasonable process reference for the subsequent processing of using of DSS in clad plates or other structure.

2. Experimental materials and procedures

2.1 Experimental materials
The material used was a commercial 2205 steel plate (16 mm thickness) produced by rolled at 1160–1180°C and followed by water quenching. The chemical composition of the steel is listed in Table 1.

### Table 1. Composition of the tested steel (wt. %).

| Element | C  | Si  | Mn  | P   | S   | Ni  | Cr  | Mo | N  | Fe |
|---------|----|-----|-----|-----|-----|-----|-----|----|----|----|
| 2205    | 0.02 | 0.50 | 1.30 | 0.02 | 0.008 | 5.2 | 22.5 | 3.1 | 0.16 | Bal. |

Note: Its yield strength is 591MPa, ultimate tensile strength is 715MPa, and total elongation is 25%.

#### 2.2 Experimental procedures

All the solution treatments were carried out in laboratory, and the sample size is 200mm×300mm. The specimens were heated at the rate of 10°C s⁻¹ from room temperature, then kept at the temperatures of 900, 1000, and 1050°C, respectively, for 40 min, and continuously cooled to the ambient temperature by air cooling (AC) or water quench (WQ).

After solution treatments, the tensile test is according to GB/T228.1-2010 and the samples for optical microscope (OM), scanning electron microscopy (SEM & BSE) observation, were etched in copper sulfate and hydrochloric acid aqueous solution (1:5:5). The intergranular corrosion testing carried out by the E method of ASTM A262. In addition, the electrochemical polarization curve of the samples with different solution treatments were determined by the Parstat2273 electrochemical test system, and the pitting broken potential of the samples were characterized also.

#### 3. Results

The mechanical properties of samples with different solution process are shown in Figure 1. The strength of the 2205 duplex stainless steel is increased and elongation decrease after solution treatment at 900 °C, relative to the original state (as rolled). While the solution temperature is higher to 1000 °C, the plasticity is improved, but the strength is little reduced. Further raise the temperature (1050 °C), the plasticity is further improved, and the strength of samples by air cooling are not different from that of water cooling. Intergranular corrosion test results showed that there is a small amount of tiny cracks in the samples after 900 °C quenching. However, the other samples have no cracking and show a good intergranular corrosion resistance.

![Figure 1. Effect of solution temperature on the properties of DSS.](image-url)
ferrite were calculated also. The results were showed in figure 2 and 3. There are a large number of precipitates at the flexural grain boundaries/phase boundaries in the samples after solution treatment at 900 °C (Figure 2a). With the temperature is higher (1000 °C), the precipitates at the grain boundary are decreased, and grain boundary is also more rules (Figure 2b). Further raise solution temperature to 1050 °C, the grain boundary is more clear and there is no more precipitation (Figure 2c and d). The ferrite content of DSS with rolling or solution at 900 °C are both 46% (Figure 3). The ferrite content is increased with the solution temperature increasing. After solution at 1050 °C, the ferrite content is as much as 54%.

Figure 2. The microstructure of the DSS with different solution temperatures (a) 900-WQ, (b) 1000-WQ, (c) 1050-WQ and (d) 1050-AC.

4. Analysis and discussion

4.1 Effect of solution treatment on precipitates

According to the characteristics of the DSS, the brittle precipitate such as σ-phase, χ-phase, π-phase and alpha is easily appeared in 2205 with different process, in which the σ-phase is the most significant to the properties of DSS. The results of scanning electron microscopy of samples after different solution treatment are shown in figure 4. There are a lot of precipitates, which are clear and distinguishable with backscattered electron (BSE) mode in the ferrite along the interface of austenite and ferrite, for a long time under the 900 °C. The morphology is white block or small dot and the
energy spectrum shows that the precipitate is rich of Cr and Mo (it’s σ-phase, table 2). Its volume is around 8 ~ 10%, that is consistent with other literature research results that σ-phase occur at a specific temperature range (commonly in 650 ~ 950 °C), the peak temperature is around 900 °C. And some studies have also found that the rolling deformation can promote the formation of σ-phase, but does not affect the precipitation peak temperature. Thermodynamic calculation results also show that σ-phase precipitate begin at about 950 °C, and the amount increase with the temperature decrease, intense precipitate around 900 °C (Figure 5). The existence of such Cr -and Mo- rich brittle phase, that deteriorating the plasticity of DSS, and leads to the poor chromium near the grain boundary with reducing its corrosion resistance [13-18].

The Cr -and Mo- rich σ-phase is decreased significantly with the solution temperature increasing, which only exist in local area with a small amount at 1000 °C (Figure 4b). Its morphology is clusters form with the surface is not smooth different from the rules smooth block under 900 °C. Energy spectrum show that Mo content is also reduced, suggests that it’s in dissolve state. The σ-phase dissolve more fully when solution temperature further increase to 1050 °C. There is sporadic precipitation by air cooling but nothing in the case of water cooling (Figure 4c and d). According to the change rule of the precipitation, it is not advisable for this type of DSS to be used at lower temperature solution, for the precipitation of σ-phase. In order to avoid the precipitation of σ-phase and have a good comprehensive performance, the solution temperature should not be below 1000 °C.

![Figure 4. The backscatter electron image of precipitates in the DSS with solution temperature at (a)900 °C-WQ, (b) 1000 °C-WQ, (c) 1050 °C-WQ and (d) 1050 °C-AC.](image)

| Phase      | Cr    | Fe    | Ni    | Mo   |
|------------|-------|-------|-------|------|
| Ferrite    | 26.14 | 66.14 | 3.41  | 4.30 |
| Austenite  | 23.59 | 69.17 | 5.03  | 2.20 |
| Sigma(σ-phase) | 29.44 | 56.30 | 3.18  | 10.00 |
4.2 Effect of solution treatment on corrosion resisting property

The electrochemical analysis of the samples by the different solution treatments were carried out. Results of the corrosion resistance of each process are shown in figure 6 and 7. The obtuse potential, over-blunt potential and pitting broken potential of the samples with different solution process were compared. It is visible that pitting broken potential and blunt potential are low while the passivation range is very narrow with the solution temperature is 900 °C (Figure 7). When the solution temperature rise to 1000 and 1050 °C, the pitting broken potential and blunt potential rise obviously, and the passivation range is wider. And the pitting broken potential of sample by water cooling is slightly higher and the passivation zone is wider also. This shows that the solution temperature had significant effect on the corrosion resistance of DSS. There is a risk to reduce the corrosion resistant ability while the solution temperature is too low. In order to get a good corrosion resistance, the solution temperature should not be below 1000 °C. This is consistent with the precipitation rule of the σ-phase in DSS. In addition, moderate fast cooling is beneficial to the corrosion resistance of DSS after solution treatment. It is consistent with the relevant research results also [7, 23].
1.15  0.29  1.17  1.19  1.24
As rolled  900 WQ  1000 WQ  1050 AC  1050 WQ

Figure 7. The pitting broken potential of DSS with different solution process in 6.0%NaCl solution at 70°C.

5. Conclusion
The main conclusions of this research work are the following.
(1) The physical and chemical properties of duplex stainless steel are affected by the solution temperature significantly. It has poor plasticity and corrosion resistance at lower temperature (900~1000 °C) for the large amount of σ-phase.
(2) Precipitation of Cr- and Mo-rich σ-phase, is closely related to the process of solution treatment. It would result in deterioration of plastic and corrosion resistant properties when there are a large amount of precipitation at low temperature (900 °C). With the increase of temperature, the σ-phase is gradually dissolved, and the precipitation volume decreases. After the temperature is up to 1050 °C, the plasticity and corrosion resistant properties of the duplex stainless steel are improved significantly for the dissolution of σ-phase.
(3) The content of ferrite in duplex stainless steel increases with the increase of solution temperature, while the proportion of ferrite and austenite is less affected by the cooling rate.

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