Heat Treatment of Duplex Stainless Steel SAF 2205 Welded Joints

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Abstract: The heat treatment plays an important role in final properties of welded joint. In fact, it may give unwanted structure changes in joint. The duplex stainless steel SAF 2205 welded joint has been heat treated in the temperature range 780-880 ^{o}C for time intervals between 15-45 min. The influence of heat treatment on microstructure of fusion zone (FZ), heat affected zone (HAZ), and base metal (BM) has been investigated. It was found that the chromium nitride precipitated during welding was dissolved and the density of secondary austenite phase was increased in fusion zone and heat affected zone. The sigma phase precipitated at different zones of joint. The grain size and volume fraction of sigma phase (σ) was measured. It was found that its volume is highest at the base metal and lowest at the fusion zone.

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1. Introduction

Duplex stainless steels (DSS) are used in applications that take advantage of their superior corrosion resistance, strength, or both. Because they have higher ferrite content than austenitic stainless steels, they are more ferromagnetic and have higher thermal conductivity and lower thermal expansion [1-5].

The chemical composition of duplex stainless steels has been adjusted such that the base metal microstructure consists of 50% ferrite and 50% austenite.

When duplex stainless steels appeared, they had a reputation of poor weld ability due to their difficulty to maintain the austenitic-ferritic structure ratio during thermal cycles, that resulted in over-ferritized HAZ and weld metal grain growth.

In the fusion zone of welded joint, since ferrite and no austenite forms at the end of solidification, ferrite is stable in the solid state at elevated temperature. When the transformation to austenite begins below the ferrite solvus, austenite first forms along the ferrite grain boundaries. Austenite may form as widmanstatten side plate off the grain boundary austenite, and in ferrite grains. In heat affected zone adjacent to fusion boundary, austenite is transformed to ferrite during welding and grain growth occurs. On cooling austenite reforms again.

Numerous structure changes can occur in the duplex stainless steels heat treatment. Most of these transformations concern the ferrite, due essentially to the fact that the diffusion rate of the alloying elements in this phase are of the order of 100 time faster than their corresponding values in the austenite. This is principally a consequence of the less compact lattice of the b.c.c crystal structure. Moreover, the ferrite is enriched in chromium and molybdenum which are known to promote the formation of intermetallic phases. Furthermore, the solubility in the ferrite of the elements nitrogen, carbon, tungsten and copper fall sharply with decrease in temperature, increasing the probability of precipitation during heat treatment.

It is well known that σ phase is formed in variety of duplex stainless steels [6-9]. This fact has to be taken into account production since σ phase adversely affects both ductility [10] and room temperature ductility [11]. Quantitative chemical analysis shows that chromium, molybdenum and silicon are enriched in sigma phase [12]. The most detrimental development is the precipitation of the σ phase in the HAZ and the weld metal. This occurs when the heat energy input per unit length is high, the cooling rate is low [13], thickness of tubes or plates to be welded is small [14] and multipass welding process is applied.

Sigma phase precipitation is usually accompanied by a depletion of Cr in the adjacent ferrite. This effect is known to have a strong influence on the corrosion behavior [15]. The toughness is also affected by sigma phase precipitation. It decreases rapidly with increasing amounts of sigma phase [16,17] .

2. Experimental procedure

The chemical composition of the duplex stainless steels (SAF 2205) used in this investigation is listed in Table 1.

Table 1. Chemical composition (wt. %)

C	Si	Mn	Cr	Ni	Mo	N
0.025	0.3	1.6	22	5.5	3	0.13

Autogenous bead on plate welding was done using Gas Tungsten Arc Welding (GTAW) process on plat of duplex stainless steel. The welding current and speed were 60A and 0.00039 m/s respectively. The welded plate was cut into samples perpendicular to the welding direction. These samples were subjected to defined different thermal cycles. They were heated to different peak temperatures, hold for different time intervals and then quenched in as shown in Table 2.

Table2. Conditions of thermal cycles

Sample No.	Temperature ^oC	Holding time (min)
1.1	780	15
1.2	780	30
1.3	780	45
2.1	820	15
2.2	820	30
2.3	820	45
3.1	880	15
3.2	880	30
3.3	880	45

The microstructure of samples were examined after etching in color etching (20 ml HCl , 0.6 gr. $K_2S_2O_2$ and 100 ml water). The color etching was used to produce contrast between ferrite and the austenite and to reveal the presence of sigma phase. More detailed studies of microstructure were performed using scanning electron microscope (SEM) provided with energy dispersive X-ray (EDX) unit. The volume fraction of sigma phase was measured by global lab program.

3. Results and Discussion

1. Microstructure of welded joint zones.

The microstructure of the autogenous GTAW is shown in Fig. 1. In general, austenite in DSS weld metal is formed from ferrite and Widmanstatten austenite.

In heat affected zone adjacent to fusion boundary, austenite is transformed to ferrite during welding and grain growth occurs. On cooling austenite reforms again.

The possibility of chromium nitride formation during welding of DSS has been indicated in several studies [18-21]. It is more likely to occur in the ferrite phase because the solubility of nitrogen in ferrite drops rapidly with a decrease in temperature. In the present work, although nitride precipitation could not be detected with the light microscope, scanning electron microscopy (SEM) showed that density of nitride precipitation is significantly lower in the vicinity of grain boundary because austenite reformed depletes nitrogen from the grain boundaries and lets these zones free from nitrogen as shown in Fig. 2.

2. Microstructure of heat treatment welded joint

It is observed that, secondary austenite precipitated in ferrite phase with different sizes and density in fusion zone and HAZ as shown in Fig.3. This phase can find in reheated weld beads during multipass welding [5]. There are two distinct forms of secondary austenite. One form simply grows off the existing austenite, as shown in Fig.4 [22]. The other form nucleated within the ferrite phase and is associated with chromium nitrides that have previously precipitated. The cooperative precipitation mechanism for secondary austenite growth at the α-γ proposed by **Lippold *et al.*** [22] as shown in Fig. 5. According to this mechanism, chromium nitride first nucleates at inter-phase interface or in ferrite phase (after welding process), resulting in a local depletion of ferrite-promoting elements Cr and Mo. This local depletion then leads to the nucleation of secondary austenite at the interface and in ferrite and subsequent growth. The original chromium nitride then dissolves since it is isolated from ferrite.

It is also observed that, σ phase precipitated in all zones of joint. It is formed at ferrite/austenite phase boundary and grows in ferrite phase as shown in Figs 6 and 7. It is also formed between secondary austenite of small size in fusion and HAZ where its formation enriches ferrite-promoting elements in ferrite phase as shown in Fig. 8. It is also precipitated in eutectoid structure of σ and austenite as the result of decomposition of ferrite as shown in Figs. 9 and 10.

X-ray spectra were obtained from all phases that could be identified, and the compositions from heat treated sample are summarized in Table 3. The EDX results show that the chromium partitions more to the ferrite, while the nickel partitions more to the austenite. All of the small precipitates analyzed matched the nominal chemistry of sigma (Fig. 11) [23]. There are very slight differences in the γ_1 and γ_2 compositions. The largest differences are that the γ_2 is only 0.9 wt% lower in nickel and 0.8 wt% higher in chromium. The chemistries of the phases match very closely to published data [24].

Table 3. The average chemistries (wt%) of the austenite, delta–ferrite, and sigma phases

Element	Austenite & Ferrite	Austenite ($\gamma 1$)	Secondary austenite (γ_2)	Ferrite (δ)	Sigma (σ)
Si	0.19	0.4	0.2	0.5	0.6
Mo	2.9	2.06	2.1	3.02	4.8
Cr	22.3	21.4	22.3	23.63	26.8
Mn	1.98	3.02	3	2.94	3.1
Ni	5.04	6.84	6.04	4.83	4.2

3. Distribution of σ phase in welded joint

The distribution of σ phase along the thickness of four samples is shown in Fig. 12 a, b, c and d. The distance in curves presents the location of measured sigma phases from the surface of weld. It is observed that there is slight change in the size of σ phase along the thickness of joint. The volume fraction of σ phase increases in the direction of base metal. The average volume fraction in the different zones of samples subjected to heat treatment temperature 820°C in different holding times is explained in Fig. 13. In general, volume fraction of σ phase in base metal has the highest value and that in fusion zone has the lowest. The lattice defects introduced by deformation can act as the nucleation sites for σ phase precipitation [25]. This can explain the enhancement of σ phase precipitation. Welding process tends to increase the volume fraction of ferrite in fusion zone and heat affected zone adjacent to fusion boundary, which will consequently be diluted with respect to ferrite forming elements. This will of course also suppress the sigma phase formation in fusion zone.

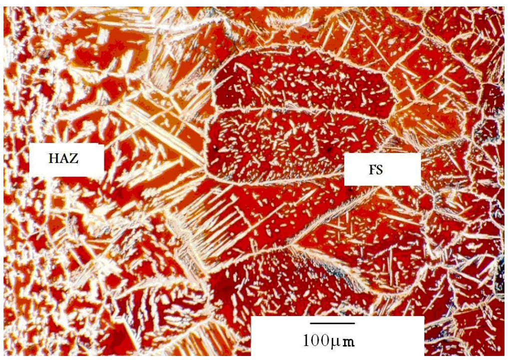


Figure 1. Microstructure of FZ and HAZ without heat treatment.

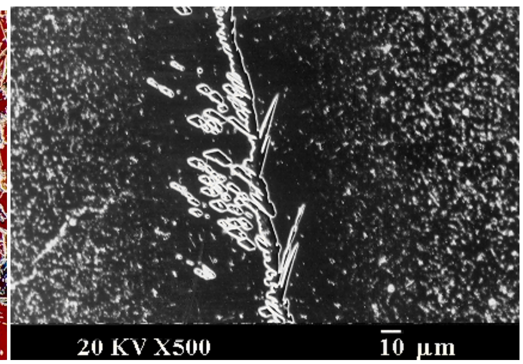


Figure 2. Density of chromium nitride Precipitation in FZ (SEM).

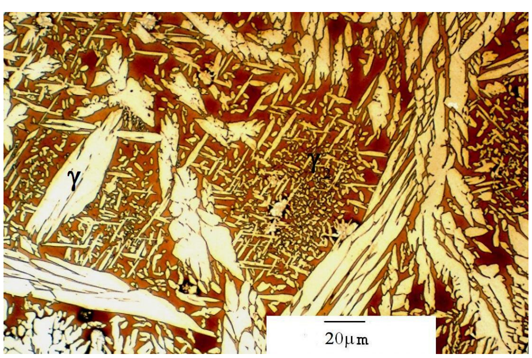


Figure 3. γ_2 precipitation in FZ (sample No. 1.2).

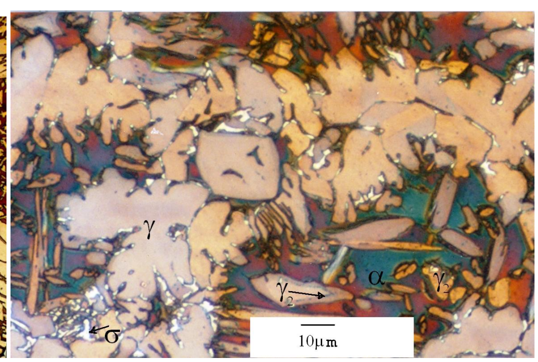


Figure 4. $\gamma_2$precipitation in HAZ (sample No. 1.2).

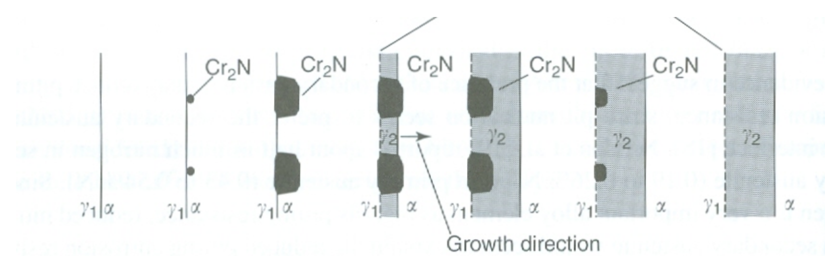


Figure 5. Cooperative growth mechanism for formation of γ_2 (Lippold et al 22)

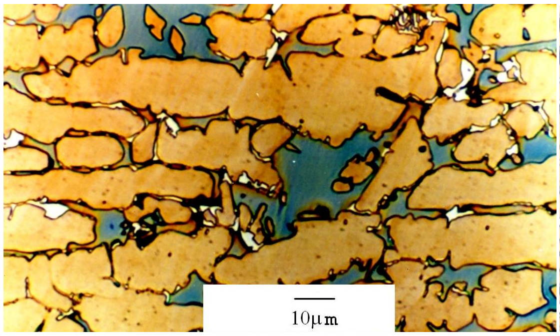


Figure 6. σ Precipitation in MB (sample No.2.3)

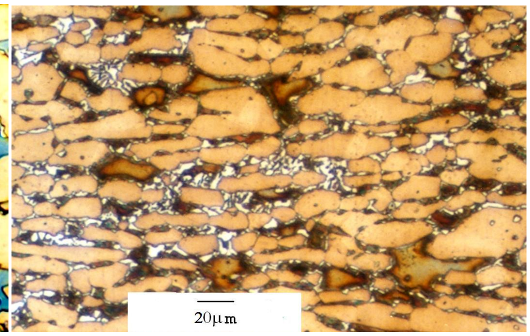


Figure 7. σ Precipitation in MB (sample No.1.3)

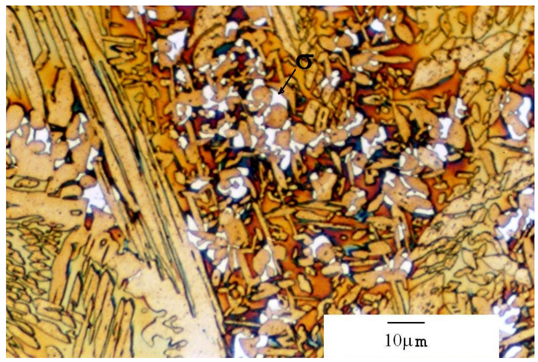


Figure 8. σ Precipitation between γ_2 precipitations (sample No.2.3)

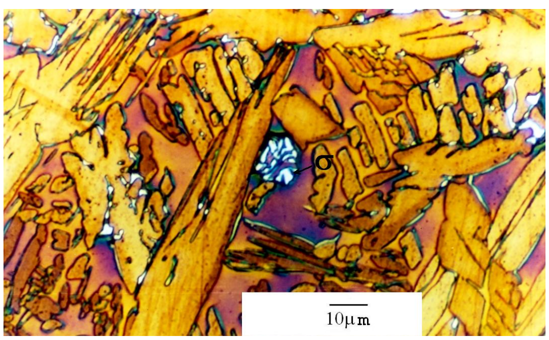


Figure 9. Eutectoid structure of σ/γ_2 (sample No. 3.2)

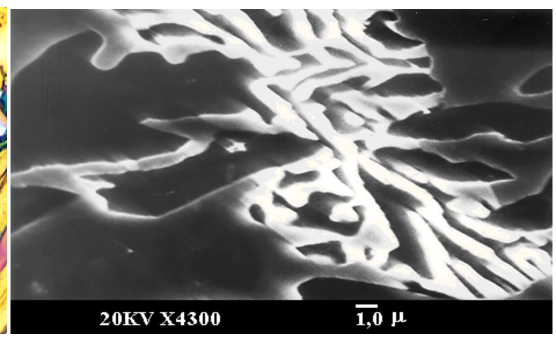


Figure 10. Eutectoid structure of σ/γ_2 (sample No. 2.2) (SEM).

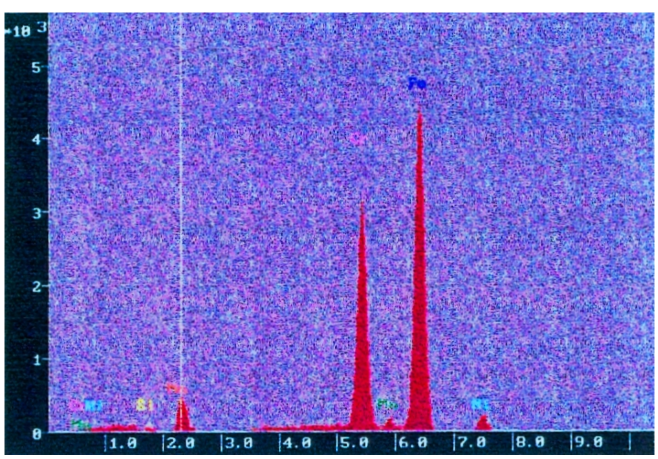
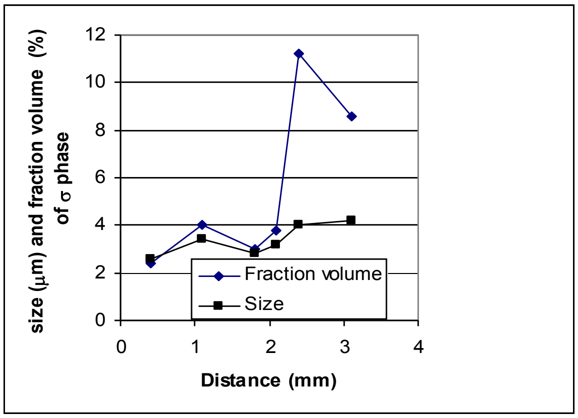
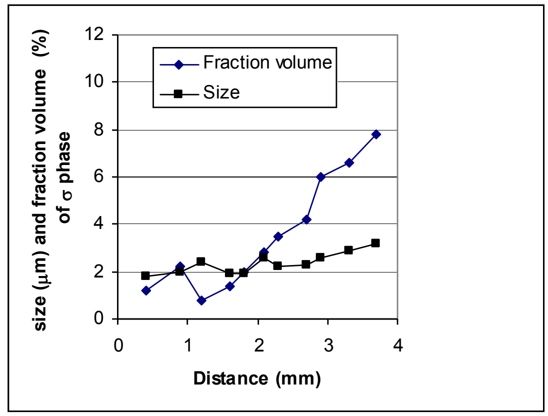


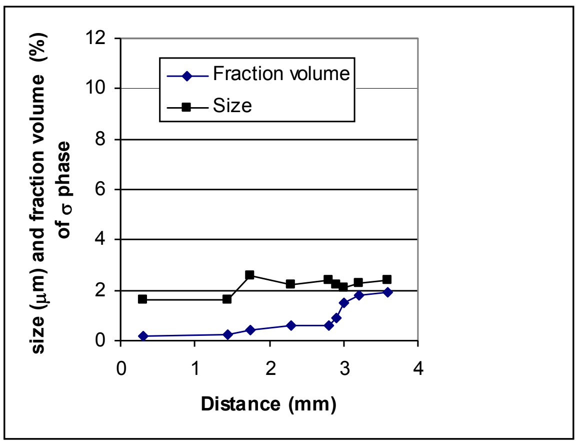
Figure 11. The result of σ phase chemical analysis using EDX.



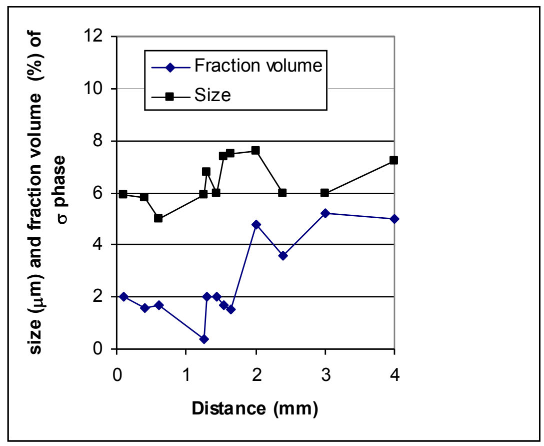
a) Sample No.1.2



b) Sample No.1.3



c) Sample No. 2.1



d) Sample No. 2.3

Figure 12. Size distribution of σ phase along the thickness of four samples

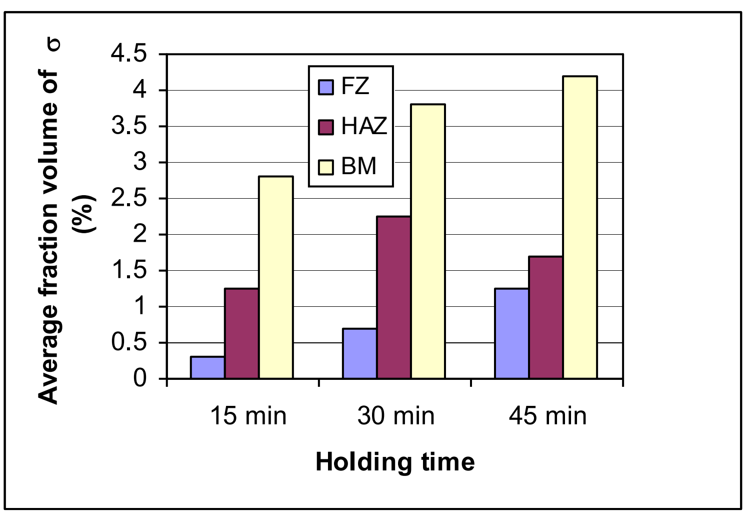


Figure 13. The average volume fraction in the different zones of samples subjected to heat treatment temperature 820^{o}C at different time intervals

Conclusions

The duplex stainless steel SAF 2205 welded joint has been heat treated in the temperature range 780-880 ^{o}C for time intervals between 15-45 min. The influence of heat treatment on microstructure of fusion zone (FZ), heat affected zone (HAZ), and base metal (BM) has been investigated. Based on the obtained results it can be concluded the following:

1- Chromium nitride dissolved and disappeared in fusion zone and HAZ as the result of heat treatment.
2- Secondary austenite phase increased in fusion zone and heat affected zone of welded joint.
3- Volume fraction of phase precipitated in base metal has the highest value while that in fusion zone has the lowest.

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