Effect of Solution Treatment on Microstructure and Mechanical Properties of 2205 Duplex Stainless Steel

Mohan Mehta, Pravin Jadhav, Afroz Shaikh, Santosh Kumar, and Shreyas Kirwai

***Abstract*—Duplex stainless steels have dual phase microstructure consisting of approximately equal volume fraction of ferrite and austenite. Volume fraction of phases significantly affects mechanical properties of duplex stainless steels. In the present work, effect of solution treatment temperatures (in the range of 900 – 1150 °C) on microstructure (phase % of ferrite and austenite) and mechanical properties like tensile (room temperature (RT)) and Charpy impact (RT and -25 °C) of duplex stainless steel, 2205 were investigated. Analysis indicates that with increase in solution treatment temperature, % ferrite phase increases and % austenite phase decreases. 50 – 50% combination of both phases was obtained around 1020 °C. Tensile test results indicate that yield strength and ultimate tensile strength remains similar for all temperatures. Maximum Charpy strength was obtained at 1050 °C. A sudden drop in charpy strength was observed at 950 °C for both RT and -25 °C tests. Microstructural and SEM analysis reveals the presence of intermetallic phases like sigma (*σ*) and chi (*χ*), precipitated at ferrite/ferrite boundary and ferrite/austenite grain boundary which may cause the decrease in impact properties.**

***Index Terms*—Duplex stainless steel, chi (*χ*) and sigma (*σ*) phase.**

I. Introduction

Duplex stainless steel has a dual-phase microstructure consisting of approximately equal volume fraction of ferrite, α and austenite, γ phases. Due to the balanced dual phase microstructure of ferrite and austenite, these types of steel combine the properties of ferrite stainless steel (like higher strength & stress corrosion cracking resistance) and austenitic stainless steel (like higher ductility, toughness, corrosion resistance). Thus these steels are widely used in the chemical, petrochemical, nuclear, marine and paper industries [1]–[5]. Duplex stainless steels have good resistance to stress-corrosion cracking in environments containing higher concentration of chlorides. However, problems occur in environments where atomic hydrogen forms [6].

Mechanical properties of DSS strongly depend upon the percentage of its constituent phases which can be modified / varied by change in chemical composition and heat treatment [7]-[8]. But the additions of such alloying elements come with unavoidable disadvantages; the most important of them being the microstructural instability of the material. During operation or use the duplex stainless steels are frequently exposed to high temperatures and thus, are exposed to different intermetallic phase precipitation [6], [9]-[11]. The most common intermetallic phases found in duplex stainless steel are sigma (*σ*), chi (*χ*) and laves phases.

The σ-phase is one of the very common intermediate phases, being hard, brittle, non-magnetic and stable. Precipitation of the sigma phase in steel increases the brittleness, hardness and decreases ultimate and yield strengths. The σ-phase precipitates first at the points of contact between grains, then at grain interfaces, and upon exposure for longer time at higher temperatures, on non-coherent grain boundaries and inclusions within grains [12]. The χ-phase may occur in austenitic, ferritic, and duplex stainless steels and its precipitation is also associated with negative effects on mechanical and corrosion properties. While σ-phase is present in the binary Fe–Cr system, χ-phase appears only in the Fe–Cr–Mo ternary and in the Fe–Cr–Ni–Mo and Fe–Cr–Ni–Ti quaternary systems [13], [14]. In duplex stainless steels, χ-phase occurs in lesser amounts than σ-phase; however its presence is also considered to be detrimental to the steel properties.

The aim of the present work is to study the effect of solution treatment temperature on variation of percentage of ferrite & austenite phase in the microstructure and to find out the optimum temperature to obtain ideal microstructure of 50 – 50 % of both phases. Furthermore, to study its effect on mechanical properties like tensile and Charpy impact of 2205 steel. Effect of intermetallic phase (*σ*, *χ*) formation has also been studied during the course of this work.

II. Experimental Work

The investigated material is 2205 duplex stainless steel in solution annealed condition. The chemical composition of the same is shown in Table I. Microstructure of as received material is shown in Fig. 1.

TABLE I: Chemical Composition of 2205 DSS in Wt. %

Material	C	Si	Mn	P	S	Cr	Ni	Mo	N
2205	0.03	1	2	0.03	0.02	21-23	4.5	2.5	0.1

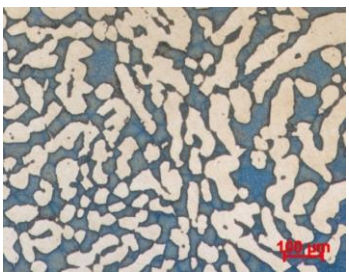

Fig. 1. Microstructure of 2205 steel in as received condition.

The solution treatments were carried out in the temperature

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range of 950 – 1150 °C with a step of 50 °C, with in electrical muffle furnace (Therelax make). All samples were water quenched after solution treated.

Tensile test specimens were prepared in transverse direction from both as-received and solution treatment conditions as per ASTM E8 Standard. Tensile test was carried out on universal testing machine (ZWICK/ROELL). Average values have been used for analysis.

Charpy impact samples were prepared in transverse direction from as-received as well as from solution treatment condition. Impact tests were carried out at room temperature and at -25°C. Test specimens were prepared as per standard ASTM E23. The testing was done on ZWICK/ROELL make machine (450 J capacity). Three tests were carried out for each set. Average values have been used for analysis.

Microstructures of specimens were revealed by using Beraha etchant. CARL ZEISS optical microscope with Image Analyser software Z.2m was used for analysis. Detailed micrography was performed using SEM of CARL-ZEISS MA EVO18 make, equipped with an X-ray energy dispersion system operated at 5-20 kV.

III. Results

A. Tensile Test

Tensile test results of all solution treatment conditions are presented in Fig. 2. Fig. 2(a) shows the variation in the average YS and average UTS of the material with change in solution treatment temperature. Fig. 2(b) shows the effect of the solution treatment temperature on %EL of the material. Test results indicate that there is no significant change in strength properties due to change in solution treatment temperature. % EL increases initially with increase in solution treatment temperature up to highest value at a temperature of 1050 °C and then decreases with further increase in temperature.

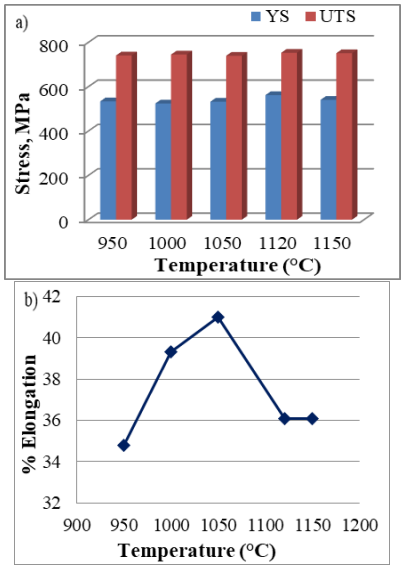

Fig. 2. Average a) YS and UTS b) % El. at different solution treatment temperatures.

B. Charpy Impact Test

The effect of different solution treatments temperatures on average impact energy is shown in Fig. 3. Following can be observed from these results:

1. Charpy impact strength initially increases and then decreases with increase in solution treatment temperature.
2. Impact Strength drops drastically at temperature of 950 °C as compared to intermediate higher temperature i.e. 1000 °C. The said drop is approximately 83% and 94% of the RT and -25 °C test temperature respectively.
3. Furthermore, RT impact strength remains similar beyond 1000 °C but the same are not similar for -25 °C test temperature.
4. Maximum impact strength is observed in a sample solution treated at 1050 °C for both RT and at -25 °C test temperatures.

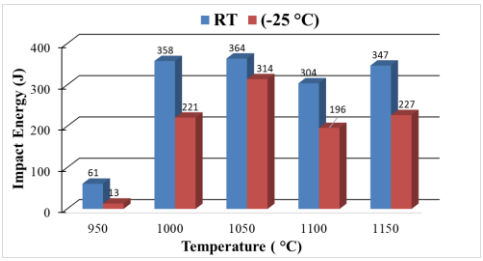

Fig. 3. Charpy impact strength at RT and -25 °C as a function of solution treatment temperature.

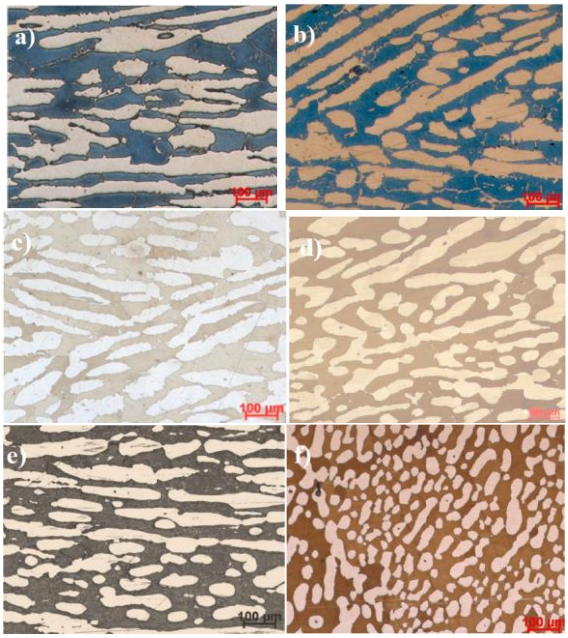

Fig. 4. Microstructure of specimen treated at solution temperature (a) 900 °C (b) 950 °C (c) 1000 °C (d) 1050 °C (e) 1100 °C (f) 1150 °C.

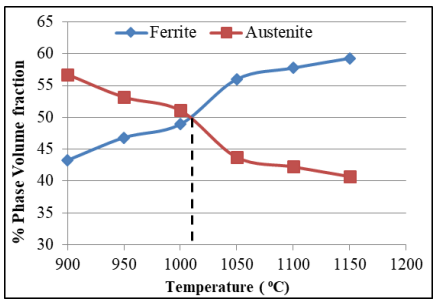

Fig. 5. Variation in volume fraction of ferrite and austenite as a function of solution treatment temperature.

C. Microstructure Analysis

Fig. 4 shows the microstructure of specimen solution

treated at different temperatures. The variation in percentage of ferrite and austenite phases as a function of solution treatment temperature is presented in Fig. 5. It can be observed that with increase in solution treatment temperature, percentage volume fraction of ferrite increases, and that of austenite decreases. 50 % volume fraction of ferrite and austenite could be achieved at a solution treatment temperature of approximately 1020 °C.

D. EDS Analysis

Energy Dispersive Spectroscopy (EDS) analysis was carried out on specimen solution treated at 950 °C and 1000 °C. Intermetallic phases such as σ and χ can be observed in specimen solution treated at 950 °C as shown in Fig. 6, Fig. 7 and Fig. 8. The σ phase precipitation started especially at the ferritic/austenitic interfaces as shown in Fig. 6, but can precipitate also at the ferrite/ferrite grain boundaries. This transformation can be represented by a eutectoid type of reaction, ferrite getting converted into σ-phase and secondary austenite as given in equation (1) [15].

$$\delta = \sigma + \gamma_2 \quad (1)$$

where, δ is Ferrite, σ is Intermetallic phase, γ_2 is secondary austenite phase

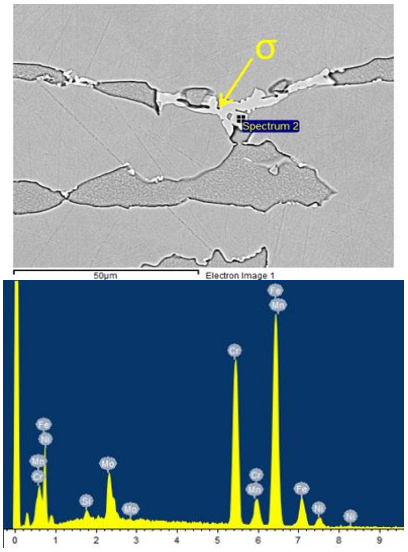

Fig. 6. σ phase precipitation at ferrite-austenite grain boundary.

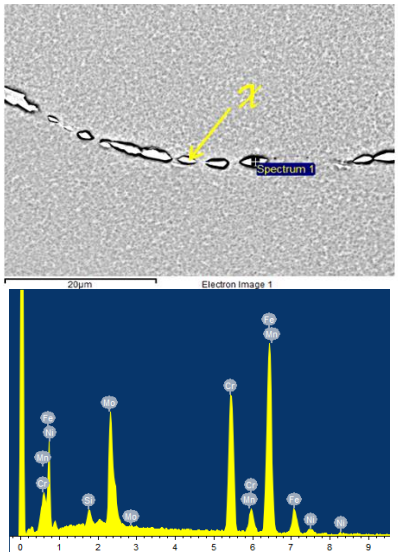

Fig. 7. χ phase precipitation at ferrite-ferrite grain boundary.

The precipitation of χ-phase starts at ferrite/ferrite grain boundaries as can be seen in Fig. 7. The χ- phase precipitates at relatively lower temperatures and in smaller amounts than that of σ phase. The χ-phase is metastable in this steel and is consumed by the σ-phase precipitation.

Presence of σ and χ phase is evident in the specimen solution treated at 950 °C, whereas the same is absent in 1000 °C solution treated specimen as shown in Fig. 8. With the help of EDS, the two intermetallic phases σ and χ can be easily identified in SEM. Molybdenum is richer in χ-phase than σ-phase and hence χ-phase looks brightest [16].

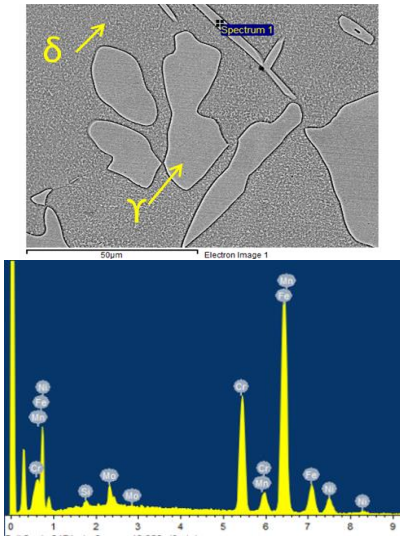

Fig. 8. EDS analysis of sample solution treated at 1000 °C.

The presence of intermetallic phases significantly affects impact properties. The same reduces drastically with increase in percentage of intermetallic phases. The chemical composition of existing phases has been evaluated using EDS and results are presented in Table II.

TABLE II: CONTENTS OF METALLIC ELEMENTS IN AUSTENITE, FERRITE, Σ-PHASE AND X-PHASE

Element	Si	Cr	Mn	Fe	Ni	Mo	Totals
γ (Wt%)	0.55	**21.34**	1.58	65.37	6.88	**4.28**	100
δ (Wt%)	0.63	**23.85**	1.19	64.42	4.76	**5.15**	100
σ (Wt%)	0.75	**28.54**	1.69	56.69	3.36	**8.98**	100
χ (Wt%)	1.16	**24.62**	1.18	49.9	2.07	**21.07**	100

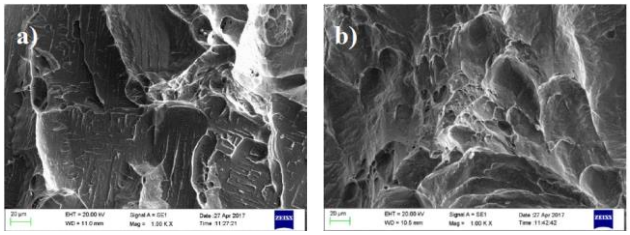

Fig. 9. Fractured surface of RT impact specimen solution treated at a) 950 °C and b) 1050 °C.

When the chemical compositions of the χ and σ are compared (Table II). It was observed that the χ-phase contains more molybdenum and less chromium than the σ phase.

E. Fractography

Fractography of impact tested Charpy specimens, solution

treated at a) 950 °C and b) 1050 °C, is shown in Fig. 9, while for the specimen tested at room temperature and -25 °C, is shown in Fig. 10. Cleavage type of fracture is observed in case of failed Charpy specimens with solution temperature of 950 °C, whereas for 1050 °C, the quasi-cleavage type of fracture (small dimple pattern mixed with cleavage) is observed for both RT and -25 °C testing.

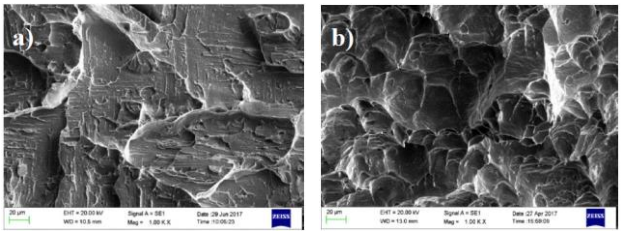

Fig. 10. Fractured surface of -25 °C impact specimen solution treated at a) 950 °C and b) 1050 °C.

IV. Discussion

Duplex stainless steel consists of approximately equal volume fraction of ferrite and austenite phases. Mechanical properties are strongly dependent upon its constituent phases. The volume fraction of these phases can be varied as a function of solution treatment temperature. As temperature increases, % volume fraction of ferrite phase increases and that for austenite phase decreases. The said increase is due to typical diffusion controlled phase transformation of $\gamma \rightarrow \alpha$. A similar type of observation was reported in the research work of Guo *et al*. [16]. The rate of ferrite percentage increase is higher for temperature increase from 1000 °C to 1050 °C as compared to other temperatures. This may be due to dissolution of intermetallic phases like σ and χ phase at temperatures above 1000 °C.

From the tensile test it is observed that there is no variation in yield strength and ultimate tensile strength with change in solution treatment temperature. But some variation in % Elongation is observed. Highest value of % elongation is obtained at 1050 °C temperature. The said values decrease with both decrease and increase in temperature from 1050 °C. The decrease in % El with decrease in temperature may be attributed to the precipitation of intermetallic phases. The decrease in % elongation with increase in temperature may be attributed to martensitic transformation. A similar type of observations was reported in the research works by Ghosh *et al*. and Guo *et al*. [16], [17].

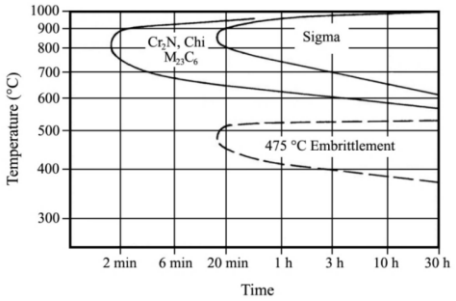

Fig. 11. TTT diagram showing the precipitation of different intermetallic phases that can occur in duplex stainless steels at temperature below 1000 °C.

From Charpy impact test it is observed that the impact strength significantly drops at solution temperature of 950 °C as compared to other temperatures. This decrease in impact strength is due to precipitation of intermetallic phases like σ and χ phase at temperatures below 1000 °C. The precipitation phenomena of these intermetallic phases can be seen from TTT diagram as shown in Fig. 11. Sigma phase being harder and brittle significantly reduces impact strength. Similar type of observations was reported in the research work by Topolska *et al.* [9], [10].

V. Conclusions

In the present study, solution treatments were carried out on the 2205 duplex stainless steel between 900 °C to 1150 °C with steps intervenes of 50 °C, followed by water quenching. The following could be drawn from these trials.

1. With increase in solution treatment temperature, ferrite percentage increases and austenite percentage decreases.
2. Ideal microstructure of 50 – 50 % of austenite and ferrite phase is observed at solution treatment temperature of 1020 °C.
3. There is no significant variation in yield and tensile strengths with increase in solution treatment temperature.
4. Lowest impact strength is observed at 950 °C solution treatment temperature for both RT and -25 °C test temperature. This may be due to presence of σ and χ-phases.
5. Maximum impact strength is observed at 1050 °C solution treatment temperature for both RT and -25 °C test temperatures.

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