Effect of Heat Treatment and Plasma Arc Welding on the Mechanical and Metallurgical Properties of Hastelloy C276

U Mohammed Iqbal ¹ and S Muralidharan ¹
¹Department of Mechanical Engineering, Faculty of Engineering and Technology, SRM Institute of Science and Technology, Kattankulathur, Tamil Nadu - 603203, India.

E-mail: ¹mohammeu@srmist.edu.in

Abstract. Hastelloy is a superalloy which contains nickel, chromium, iron and molybdenum as its major constituents which possess outstanding high temperature strength and oxidation resistance. The objective of this work is to study the heat treatment effect on mechanical and metallurgical properties of Hastelloy C276. A total of four samples are prepared at two different temperatures (700°C and 900°C) and at two different soaking times (4 and 8 hours). Tensile strength, percentage elongation and hardness were measured for the heat-treated samples. Further plasma arc welding was carried out on the heat-treated samples to understand its effect on tensile strength and hardness. The results indicate that there is significant increase in tensile strength and hardness of the hastelloy after heat treatment. Sample processed at 900°C and 8 hours soaking time has the maximum tensile strength and hardness of 378 MPA and 197 HV respectively. There is slight increase in tensile strength of the plasma arc welded samples. The percentage elongation of heat-treated samples is reduced after the welding process. The XRD pattern of the alloy revealed that the alloy is amorphous or microcrystalline in structure. The SEM image reveals the surface topography of the aged samples which confirms the experimental results.

1. Introduction
Hastelloy C276 shows good corrosion resistance and mechanical properties at high temperature in the range of 540-1000°C. This makes it a suitable material in aerospace, power and chemical industries [1]. Gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) are widely used commercial welding processes to weld the C276 alloy. Compared to laser and electron beam welding, the plasma arc welding produce wider weld and heat affected zone. Harmful radiations like ultraviolet and infrared rays were generated during this process that will affect the human health. An increase in the brittleness of the welded parts was observed due to high heat input by these welding processes [2]. It was also reported that in the high thermal processes the micro-segregation of the elements results in the formation of brittle topologically closed packed (TCP) phases [3]. The strength of the weld joint is reduced due to the formation of the TCP phase resulting in weld zone hot cracking. Sihotang et al [4] has analyzed the effect of heat input in welding of hastelloy by GTAW process and it was reported that TCP phase is observed in the weld zone. Ahmed et al [5] have reported the effect of electron beam welding on the hastelloy and concluded that the formation of TCP phase was observed at 900 °C. Manikandan et al [6] analyzed the tensile strength of the C276 alloy before and after the laser beam
welding process and concluded that the tensile strength of the base metal is superior than the welded metal. Yan et al [7] have found that post-weld heat treatment increases the mechanical properties of the welded sample. Moradi et al [8] in their research studies on friction welding of AA6061 have cited that the heat treatment carried out after welding improve the hardness of the weld joint due to precipitation hardening. Sathish Kumar et al [9] successfully welded the C276 alloy without any defect by plasma arc welding.

From the literature studies, it was observed that hastelloy joined by high thermal process such as arc welding reduces the strength of weld due to the hot cracking. Authors overcame these drawbacks by employing plasma arc welding which consumes low heat input in a single pass and reduces the defect. Lot of studies was carried out in analyzing the effect of post weld treatment of hastelloy and according to authors knowledge no work was reported on the effect of pre weld heat treatment of hastelloy. So, the objective of this study is to analyze the pre-weld heat treatment and its effect on the mechanical properties of hastelloy joined by plasma welding process. The heat treatment on the hastelloy was performed at two different temperature viz 700°C and 900°C.

2. Experimental Procedure
Hastelloy C276 was acquired in the form of sheet of thickness 1.12mm. The chemical composition of the Hastelloy C276 in weight percentage is shown in table.1

| Content | Mo | Cr | Fe | W | Co | Mn | Ni |
|---------|----|----|----|---|----|----|----|
| Wt %    | 14-16 | 13.5-14.5 | 3-4 | 3.5-4.5 | 1.5-2 | 1-1.5 | Remainder |

To understand the effect of heat treatment, five different hastelloy samples was prepared at various temperature and soaking time.
1. SAMPLE A (at room temperature)
2. SAMPLE B (at 700°C for 4hrs)
3. SAMPLE C (at 700°C for 8hrs)
4. SAMPLE D (at 900°C for 4hrs)
5. SAMPLE E (at 900°C for 8hrs)

The heat-treated samples are subjected to plasma arc welding. A total of five pairs of Hastelloy sample are welded together. The welded hastelloy sheet is depicted in the figure 1.

Figure 1. Plasma arc welded sheets.
The specimens for conducting the tensile test were prepared as per ASTM E8 as shown in figure 2. ER-3 micro-tensometer (Make:Kudale instruments) was used to determine the tensile strength. The numbers of specimen with welding exactly at the center are 10 while the numbers of specimen which are completely made up of sheet without any welding are 10. Hence total of 20 such tensile specimen are cut by electrical discharge machining process. The exact sample after EDM cut is shown figure 3. Vickers hardness testing machine (Akashi MVK-E3) was used to measure the hardness. 5 kg of load was used for conducting the test and 10 secs was kept as the dwell time during the test.

3. Results and Discussions
The tensile test results indicate that the yield strength of the hastelloy increases after the heat treatment. For each specimen, two samples were prepared and the average of the tensile strength and hardness was tabulated in Table 2. From the Table 2, sample-E processed at 900ºC and 8 hours soaking time exhibit superior mechanical properties. So the optimum yield strength and hardness are 378 Mpa and 197 Hv respectively, which correspond to sample-E. As the tensile strength of the sample E is high, the ductility is reduced. Hence the elongation of sample E with weld is less. This is attributed to the fact that the grains break down from coarse to fine size as the alloy undergoes the heat treatment [7]. The percentage in elongation was reduced after the heat treatment. It is evident from the table 2, sample A has the maximum percentage in elongation of 49%. A Maximum reduction in the percentage of elongation of 5.4% was observed between welded and non-welded sample-E and a least of 3.2% reduction was noted for sample-B. This variation is due to the fact that sample-E processed at 900ºC and 8 hours soaking time exhibit highest increase in the tensile strength between non welded and welded sample.

From the table it is also observed that the hardness increases after the heat treatment. Little or no variation between the hardness of the welded and non-welded sample. This is due to the fact that the welding parameters are kept constant for the entire sample. Hence little variation in hardness was observed in the samples.

| S.No | Type of Sample          | Yield strength(Mpa) | %elongation | Hardness(Hv) |
|------|-------------------------|---------------------|-------------|--------------|
| 1    | SAMPLE A(without weld)  | 343                 | 49          | 162          |
| 2    | SAMPLE A(with weld)     | 346                 | 47          | 164          |
| 3    | SAMPLE B(without weld)  | 351                 | 45.5        | 170          |
| 4    | SAMPLE B(with weld)     | 353                 | 44          | 171          |
| 5    | SAMPLE C(without weld)  | 352                 | 45          | 176          |
| 6    | SAMPLE C(with weld)     | 357                 | 43          | 177          |
| 7    | SAMPLE D(without weld)  | 361                 | 40.5        | 182          |
| 8    | SAMPLE D(with weld)     | 364                 | 39          | 182          |
Figure 4 shows the tensile strength for the various weld and non-welded samples. This is well agreed with the results reported by Sathish Kumar et al [9]. It is clear from the Fig. 4 that the tensile strength is increased after welding in all the samples except for the sample C.

![Figure 4](image.png)

**Figure 4.** The tensile strength of various samples.

### 3.1 Microstructure Analysis

The SEM images of all the five samples were taken to study the effect of heat treatment on the hastelloy. All the SEM was taken at 2000x magnifications. Figure 5 shows the SEM image of sample A (room temperature). It is observed that cluster of voids are present along the grain boundaries. It is also observed that the voids are shallow. Figure 6 depicts the SEM image of sample B which is heat treated at 700ºC and soaked for 4 hours. The image reveals that upon heat treatment equi-spaced grains are evolved and voids are present along the grain boundaries.

![Figure 5](image.png)

**Figure 5.** SEM image of sample A.

![Figure 6](image.png)

**Figure 6.** SEM image of sample B.

The SEM image of sample C is given in figure 7 and it shows fine and coarse grains. Presences of voids are not seen. The grain boundaries become thick which shows presence of carbide and its forms [5]. Figure 8 reveals the SEM image of the sample D, heat treated at 900ºC and soaked for 4 hours. It is shows absence of voids on grain boundaries. Grains are equi-spaced and some are tight packed. This is due to the fact that at high temperature dynamic recrystallization of grain in the sample was initiated [10]. The Figure 9 depicts the SEM image of sample E. It is evident that voids are absent on the grain boundaries and the grain growth can be observed. The increase of temperature leads to the fine grains which improved the mechanical properties of these samples. Sample E is processed at 900ºC and soaked for 8 hours. Due to the high soaking time nucleation of grains are predominant and this results in fine grains in the sample E [11]
It is observed from the Figure 5 to Figure 9 which shows the SEM image of sample that increasing the heat treatment temperature and soaking time reduces the grain size. Due to this, more number of high angle grain boundaries (HAGB) cell block is formed. While applying the load, this HAGB provide high resistance to the slipping of the cell [12]. So the hardness of the sample heat treated at 900ºC temperature is high According to hall patch equation, strength is inversely proportional to the grain size, hence a significant increase in tensile strength is observed [13].

3.2 XRD Analysis
To identify the presence of secondary particles after the weld process the XRD analysis was performed. No significant variation between the XRD pattern of sample B and sample C after the weld was observed. Both the samples are processed at 700ºC and at different soaking time. Similar trend was observed between sample D and sample E after the weld, both are heat treated at 900 ºC. This shows soaking time does not have any effect on the formation of secondary particle in the samples. Figure 10 and Figure 11 show the XRD results of sample C and sample E after the weld respectively. From the Figure 10, it is observed the presence of (M₆C) phase and Cr- rich M₂₃C₆ carbide phase in sample C, whereas in case of sample E only M₂₃C₆ phase was observed as shown in figure 10. Due to a smaller number of secondary phase formation in sample E, the strength of the weld is high [9] and this is clearly reflected in the tensile strength results of sample E. From these results it is understood that pre-weld heat treated haste alloy at 900ºC results in high strength weld joint.
4. Conclusions
In this work the hastelloy was heat treated at five different conditions and plasma arc welding was performed on the heat-treated samples. The tensile strength and hardness of the samples were measured. The SEM and XRD analysis was also carried out and the following conclusions were made.

- The tensile strength and hardness of hastelloy increases with aging, when compared to the room temperature. The maximum increase of 10.2% was achieved for the sample heat treated at 900°C and with soaking time of 8 hours.
After the plasma arc welding, the tensile strength of hastelloy increases, but the percentage of elongation decreases. No variation in hardness was observed after the welding.

- SEM analysis reveals that increasing the temperature, initiates the dynamic recrystallization of grains. The Hastelloy C276 heat treated at 900ºC shows finer grain than the sample processed at 700ºC. Hence sample E exhibit better mechanical properties compared to other samples.
- XRD result indicates that less amount of secondary phase formation in the sample heat treated at 900ºC which improves the strength of weld joint.

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