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Effect of Heat Treatment Temperature on Mechanical Properties of the AISI 304 Stainless Steel

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Abstract: Austenitic Stainless steels are sensitized when exposed to elevated temperature range of 470-750°C causes carbide precipitations at grain boundaries. Carbide precipitation can have deleterious effects on the resistance to intergranular corrosion and reduces the tensile properties of stainless steels, specifically strength and toughness. This paper evaluates an optimum heat treatment strategy for solution annealing of AISI 304 stainless steel after sensitization. Standard tensile and Hardness test specimens were fabricated using precision Lathe Machine. These samples were subjected to various heat treatment sequences, consisting of Sensitization at 660°C, followed by air cooling and solution annealed at five different temperatures: 1010°C, 1050°C, 1090°C, 1140°C and 1190°C, followed by water quenching. Heat treated samples were then mechanically tested for Hardness and Tensile properties. The influence of heat treatment process and temperature on mechanical properties of as-received, sensitized and solution annealed 304 stainless steels were evaluated. The investigation reveals that the sensitized samples give the highest hardness value at 666^0C while highest hardness value was obtained on temperature of 1090^0C for solution annealed 304 stainless steels. This temperature is found to be the optimum to avoid grain growth on solution annealed 304 stainless steels.

Keywords: Solution-Annealing, Sensitization, Mechanical Properties, Chromium carbides and Heat Treatment

I. INTRODUCTION

Stainless steel was first invented in the beginning of the 20th century [1] where the use of conventional carbon steels were restricted to their strong susceptibility to corrosion and oxidation [2]. In August 1913, Harry Brearley in Sheffield (UK) melted stainless steel for the first time which was microstructurally martensitic with a carbon content of 0.24% and chromium content of 12.8% [3]. However, Strauss and Maurer in Germany produced the first austenitic grade during the same year by adding an austenite stabilising element, nickel. Moreover, in the United States, Dansitzen was investigating the invention of Brearley with a lower carbon content which led to the discovery of ferritic stainless steel [4]. Generally, the austenitic, martensitic and ferritic stainless steel grades had been discovered prior to World War I [5]. Nowadays, considering the global warming, environmental pollution and life cycle costs, the need for durable materials is continuously increasing stainless steel production. Carbon and alloy steels are the most widely produced metallic materials in the world, and approximately 2% by weight of all produced steels are stainless steels [1]. Austenitic stainless steels due to their superior corrosion resistance, excellent mechanical properties and good weldability are consistently used in oil and gas production and power generation industries [4, 6, and 7]. The chemical composition, the proportion of constituents and exposure temperature range determine the response of austenitic stainless steels to

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thermal treatments at room temperature [8]. The austenite phase is a supersaturated solid solution which cannot accommodate more than 0.006wt% carbon in an equilibrium state. However, austenitic stainless steels can contain approximately 0.05% carbon. Exposure to elevated temperatures can therefore cause carbide precipitations, which are mostly chromium carbides in the 300 series stainless steels [9, 10]. Carbide precipitation can have deleterious effects on the resistance to intergranular corrosion and reduces the tensile properties of stainless steels, specifically strength and toughness [11]. Mechanical properties of austenitic stainless steels strongly depend on chemical composition, heat treatment and the amount of cold work. However, hydrogen embrittlement, sensitisation and formation of different carbides and sigma phase can also influence the mechanical properties [34]. In austenitic stainless steels, the addition of alloying elements increases the lattice parameters of the austenite, as a function of the atomic diameter of the added element. The changes in the austenite lattice parameter introduce strain into the austenite lattice, which is then accompanied by an increase in yield strength due to the increased resistance to dislocation glide [9, 6]. These sensitized steels, when subjected to load, experience crack propagation through the boundary, leading to even faster failures, and mostly responsible for the premature collapse of several engineering components [12].
In order to prevent the precipitation of the deleterious $M_{23}C_6$ at the grain boundaries, additional alloying elements such as Ti or Nb is added to the stainless steels [9, 11]. Moreover, Candelaria et al, reported improved the corrosion resistance on sensitized stainless steels after solution treatment at temperature up to 1100°C followed by quenching in water. It was observed that increasing the austenitizing temperature to 1100°C promotes the dissolution of carbide and Cr enrichment in the matrix [13]. This dissolution increases the retained austenitic phases in stainless steel's structure with beneficial influence on pitting corrosion resistance. The increase of retained austenitic in the structure of stainless steels improved corrosion resistance of steel alloys [14]. Although, previous studies have investigated the influences of the corrosion resistance on sensitized stainless steels after solution treatment on stainless steel, but limited literature was observed on investigation of optimum heat treatment strategy for solution annealing of AISI 304 stainless steel for a judicious combination of hardness, yield strength, ultimate strength and ductility after sensitization. The objective of this study is to evaluate an optimal heat treatment temperature for solution annealing of AISI 304 stainless steel.

II. MATERIALS AND METHOD

Samples 304 stainless steel with billet number 123744 was obtained from Quality and Assurance Mechanical Laboratory of Delta Steel Company, Alakija, Lagos, Nigeria. The chemical composition of as-received steel consists of C: 0.08%, Cr: 18.75%, Si: 1.0%, Ni: 10.5%, Mn: 2.0%. The chemical composition of the received grades steel confirmed to AISI-304 standard specification [6].

A) Heat Treatment

Twelve samples were subjected to sensitization using a high temperature furnace at 660^0C for 30 minutes dwell time. Sensitized samples were cooled to ambient temperature in an open air environment. Solution annealed treatment was conducted immediately on ten selected sensitized samples a at different temperatures of 1010°C, 1050°C, 1090°C, 1140°C and 1190°C with dwell time 30 minutes inside the furnace environment.

B) Mechanical Testing

Tensile and hardness specimens were machined from AISI 304 stainless steels based on ASTM standard. Mechanical tests were conducted on as-received, sensitized and solution-annealed samples to evaluate their tensile and hardness properties. A HV-1000 Rockwell type digital microhardness testing machine was used to conduct the hardness test measurements Hardness values were determined by taking the average of five HRC readings at different positions on the test samples. Similarly, tensile test was conducted on sensitized, as-received and solution-annealed samples at room temperature using a 600kN Avery-Denison universal testing Machine. The ends of the specimen were gripped in the machine, and load was applied until failure occurred.

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III. RESULTS AND DISCUSSION

A) Hardness

Fig. 2 shows the micro hardness values of as-received, as-sensitized and solution-annealed samples. Sample sensitized at 660°C give the highest hardness value (41HRC) compare to as-received and solution annealed counterpart. This increase in hardness can be attributed to precipitation of chromium carbides in the grain boundaries of the sensitized sample. The precipitated chromium carbides impede dislocation movement and reduce the defects within the crystal's lattice of sensitized sample. Moreover, dislocation movement is often referred as the dominant carriers of plasticity and material's ductility largely depends upon the ease its crystal lattice dislocation could be propagated [3]. Hardness value of solution annealed samples drastically decreases from heat treated temperature of 1010°C and 1050°C with slight increase at 1090°C. This decrease in hardness could be because of dissolution of the carbide and Cr enrichment in the matrix at these temperatures. However, the hardness value increases from 20.4HRC to 24HRC at 1090°C. This indicated that more chromium carbides' dissolution in the crystal's lattice at 1090°C. This signified that the samples matrix has been stretched, which result to an increase in sample strength. Moreover, since it is desirable for all carbides to be homogenously in solution prior to start of cooling stage and the need to dissolve the chromium carbide slowly. Based on the above consideration, the highest practical temperature to obtain a limited grain growth on solution annealed 304 stainless steel was found to be at 1090°C. Sample heat treated above this temperature (temperature of 1140°C and 1190°C) shows a decrease in hardness values. Beyond the temperature of 1190°C, further reduction of hardness was observed, which could be associated to sample grain growth phenomenon. This result indicates that high solution annealed treatment temperatures on AISI 304 stainless steels removed the formed alloy segregation and sigma phase after sensitization treatment, which resulted to an increased in ductility of the 304 stainless steel materials. This was achieved as a result of the dissolution of the chromium carbides at the grain boundaries which in turn hindered dislocation movement. Therefore, the matrix becomes less stretched, and dislocations were found to be relative to crystal movement, which give rise to a softer material. Grain growth occurs during heat treatment when recovery and recrystallization stages are completed, and further reduction in the internal energy can only be achieved by reducing the total area of grain boundary.

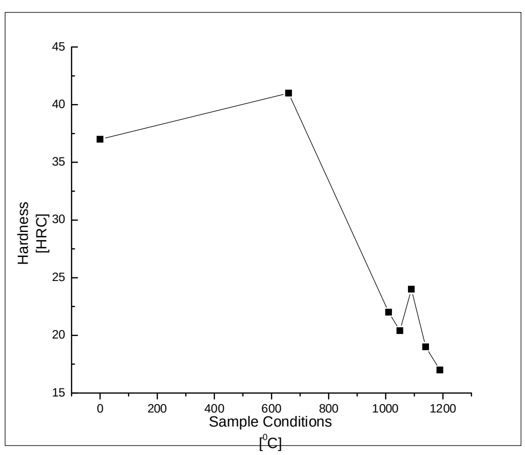

Fig.2: Variation of Hardness value of as-received, as-sensitized and Solution-annealed samples against temperatures

B) Strength

The relationship between material hardness and Strength is considered to be approximate a linear form. Fig. 3 shows compare the measured results of yield strength and ultimate tensile strength of as-received, as-sensitized and solution-annealed samples. Sensitized sample shows the maximum increase in strength compares to as-received and solution annealed samples. This could be attributed to the formation of a chromium carbide precipitate at the sample's grain boundaries which restrict dislocation movement and cause an increase in yield stress on the material. Previous

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investigation has reported that lattice distortion and modulus effect has significant influence on the observed increase in material strength after heat treatment [3]. A sharp decrease in strength was observed on solution annealed samples at 1010°C and 1050°C heat treated temperatures. This could be due to the dissolution of carbide and chromium enriched region in the matrix, which results in decrease in sample's strength.
Similarly, at solution annealing temperature of 1090°C, a slight increase of strength was observed, which followed with a rapid decrease of strength at higher solution annealed temperatures. As mentioned earlier, the observed decrease in strength at higher solution annealing temperatures could be associated to treated sample's grain growth phenomena.

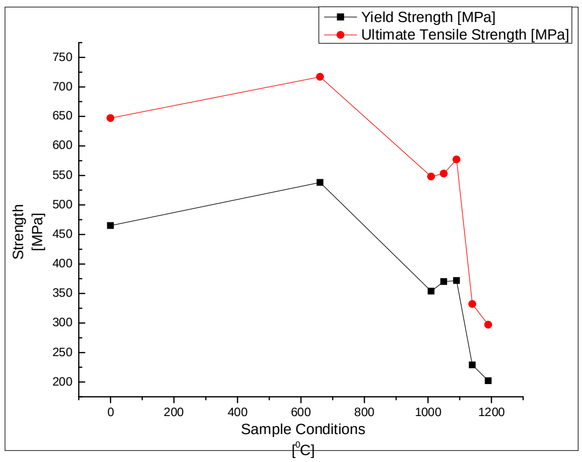

Fig 3: Variation of Strength of as-received, as-sensitized and Solution-annealed samples against solution annealing temperature

C) **Ductility**

Fig. 4 shows the results of measured ductility of tested samples, against heat treated temperatures. The ductility of sensitized samples decreases as compare to as-received sample, but increases on samples with higher solution annealed temperatures, with slight decrease at sample annealed at 1090°C. Lowest ductility value of about 50.4% was obtained on sensitized sample. This could be due to dislocations movement impeded by the chromium carbides precipitated at the grain boundaries. The highest value of ductility of about 72.3% is obtained on the sample with highest solution annealed temperature (1190^{0}C). This is because solution annealed treatment at elevated temperature is able to increase the number of planes on treated sample for dislocation movement to occur.

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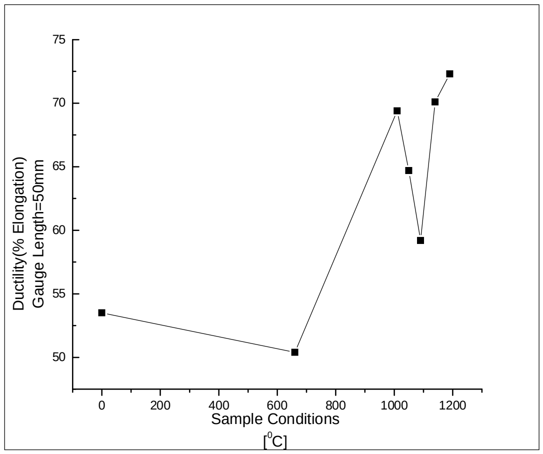

Fig.4: Variation of ductility of as-received, as-sensitized and solution-annealed samples against temperatures

IV. CONCLUSION

The influence of heat treatment process and temperature on mechanical properties of as-received, sensitized and solution annealed 304 stainless steels were evaluated. The investigation reveals that the sensitized samples give the highest hardness value at 666^0C while highest hardness value was obtained on temperature of 1090^0C for solution annealed 304 stainless steels. This temperature is found to be the optimum to avoid grain growth on solution annealed 304 stainless steels.

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