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Studies on some of mechanical properties of SS304L material under different heat treatment conditions

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Abstract: In the PWR pressure water reactor (PWR), stainless steel is used in many important parts in both primary and secondary water circuits. There are not enough necessary condition to experiment in extremly conditons of nuclear reactor, such as high temperature, high pressure in radiation environment in Vietnam. Therefore, in order to study the world's technology for evaluating metal materials, it is necessary to have basic research on SS304 stainless steel objects. This study deals with SS304L stainless steel, which is low carbon steel used in nuclear power plants. The material used in this work was stainless steel 304 with low C content (SS304L). AISI stainless steel 304L plates were cut by wire-cutting machine into standard specimens and then heat-treated under different conditions. Finally, the post-treated specimens were tested by Rockwell hardness tester, tensile strength tester, and Charpy impact tester to verify the mechanical properties. The results showed that when heating the specimens in the range of 300÷900 ^{o}C, cooling in the furnace to the room temperature, the value of hardness changed insignificantly. When increasing heating temperature, the yield strength and ultimate tensile strength values of the specimens decreased while the relative elongation values were almost unchanged. It means that under tested heat treatment conditions, the higher the heating temperature is, the worse mechanical properties are. The reason for this might be the appearance of the brittle sigma phase. Heat treatment results of SS304 specimens with the normalizing conditions at 900 ^{o}C also shows the possibility to remove the sigma phase in the steel composition.

Keywords: *Rockwell hardness, tensile strength, SS304L, stainless steel heat treatment.*

I. INTRODUCTION

In metallurgy, stainless steel, also known as inox steel or inox, is a steel alloy with a minimum of 10.5% chromium content by mass. Ordinary steel when exposed to oxidizing medium (such as air, moisture, etc.) forms rust and corrosion on the surface and the inside of material. Stainless steel containing Cr, on the contrary, forms a passive chromium-oxide film which prevents the rusting and erosion of the material while also brightening the steel surface. Due to their superior mechanical properties at elevated temperature, resistance against corrosion and better creep rupture properties, austenitic stainless steel is widely used in various industries, especially as structural material for the fabrication of nuclear reactor components [1].

SS304L stainless steel with low carbon content (less than 0.03% by weight) improves anti-friction properties, increases abrasion resistance and reduces sensitivity to corrosion of grain boundaries [2]. Austenitic stainless steels are usually sensitized at 470÷750 °C due to the formation of carbide phase at the grain boundaries. Carbide precipitation affects corrosion resistance and reduces mechanical

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properties of stainless steels, particularly strength and toughness [3]. The mechanical properties of austenitic stainless steel depend strongly on the chemical composition, heat treatment conditions and cold-working processes. In addition, hydrogen embrittlement (HE), sensitization and the formation of carbide and sigma phases also affect mechanical properties [4, 5].

Karthik et al. [6] have investigated mechanical properties such as ultimate tensile strength (UTS), yield strength (Ys), % elongation, strain hardening exponent (n) and strength coefficient (K) based on the experimental data of the uniaxial isothermal tensile tests performed at an interval of 50 ^oC from 50 ^oC to 650 ^oC and at three different strain rates (0.0001; 0.001 and 0.01 s^{-1}) and then giving calculating model that predicts mechanical properties changes with excellent correlation coefficient and the significantly low error value.

Moreover, Candelaria et al. have reported on improvement of the corrosion resistance on sensitized stainless steel after solution treatment at temperature up to 1100 ^oC followed by quenching in water. It was observed that increasing the heating temperature to 1100 ^oC promotes the dissolution of carbide and enrichment of Cr in the matrix phase [7]. This dissolution increases the retained austenitic phases in structure of stainless steel with beneficial influence on pitting corrosion resistance. The increase of austenitic phase of stainless steels improved corrosion resistance of steel alloys [8].

This work is in order to study changes of some mechanical properties of SS304L material such as hardness, ultimate tensile strength (UTS), yield strength (Ys), % elongation and impact energy at the different heat treatment conditions.

II. CONTENT

A. Materials and Methods

1. Materials

The materials for this work is AISI-standard SS304L. The chemical composition (by % weight) of as-received steel SS304L is shown in **Table III.**

2. Experimentals

a. Specimen preparation

Standard test specimens were cut directly from the as-received steel plate by an electro-discharge wire cutting machine. Fig. 1 is a schematic diagram showing the shape and dimension of specimens for mechanical tests, particularly (a) for hardness test; (b) for tensile test, (c) for impact test and (d) is images of actual specimens after processing.

b. Heat treatment

Steel specimens (20 specimens) were heat-treated under different conditions before testing mechanical properties as follows:

Table I. Heat treatment conditions for tensile testing specimens ($M_K1 \div M_K5$) and hardness testing specimens ($M_C1 \div M_C5$):

Sample	Heating temp. (^oC)	Heat up rate (^oC/min)	Retention time (h)	Cooling condition
M1	30	250	2	cooled in the furnace, cooling rate: 100^0C/h
M2	300	250	2	
M3	700	250	2	
M4	850	250	2	
M5	900	250	2	

Table II. Heat treatment conditions for impact testing specimens at 0^0C (5 specimens) and room temperature (5 specimens):

Specimen	Heating temp. (^{0}C)	Heat up rate (^{0}C/min)	Retention time (min)	Cooling condition
M6	30	250	45 ÷ 60	cooled in the air, cooling rate: 80-100^{0}C/min
M7	300	250	45 ÷ 60	
M8	700	250	45 ÷ 60	
M9	800	250	45 ÷ 60	
M10	900	250	45 ÷ 60	

c. Mechanical property tests

➢ ***Hardness test***

Steel specimens were tested using Rockwell hardness testing instrument Mitutoyo ATK-600 (Japan) at RB scale, room temperature at the Institute of Materials Science and Technology (Hanoi University of Science and Technology). The treatment conditions for these specimens were shown in Table I.

➢ ***Tensile test***

Steel specimens were tested by using MTS-980 tensile testing machine at room temperature at the Institute of Materials Science and Technology (Hanoi University of Science and Technology) to determine ultimate tensile strength (UTS), yield strength (Y_s) and % elongation of material. The treatment conditions for these specimens were shown in Table I.

➢ ***Impact test***

SS304L specimens after normalizing heat treatment were tested for impact strength using impact testing machine JBW-500 (China) at the Center for Non-Destructive Evaluation (NDE).

The impact data strongly depends on the testing temperature, so the impact strength test was performed at two different temperatures: room temperature (30°C) and 0°C. The treatment conditions for these specimens were shown in Table II.

The specimens for 0 °C were prepared by being immerged in a mazut oil solution and then placed in the freezer for ~20÷24 hours. After that, the specimen's temperature was checked right before carrying out the impact test. The temperature of specimens was about 0±2 ^{o}C. After stabilizing at low temperature for a few minutes, the specimen was rapidly transferred to the machine's stripper and the impact test was performed.

Table III: Chemical composition of SS304L material (by % weight)

Element	***C***	***Mn***	***P***	***S***	***Si***	***Cr***	***Ni***	***Mo***	***Cu***	***V***
%	0,0235	1,69	0,0311	-	0,368	19,0	8,78	0,128	0,154	0,0628

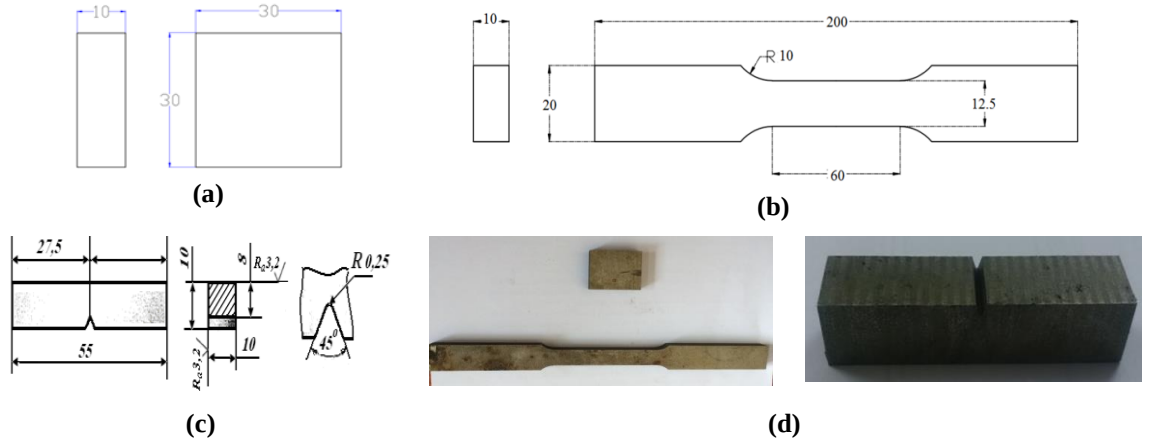

Fig. 1. A schematic diagram showing the shape, dimension of specimens and actual specimens after processing

B. Results and Discussion

1. Hardness

The results of hardness test for $M_C1 \div M_C5$ were shown in Table IV and Fig. 2.

It can be seen that, when the heating temperature increases, the hardness of the steel decreases from M_C2 to M_C5. However, the hardness value generally does not change significantly, because the austenitic steel is a kind of soft steel, the change in the hardness value of steel under different heat treatment conditions is not considerable. Typically, low tempering (incubation temperature is less than 300 ^oC) usually reduces the residual stress without the mechanical property changes of the material.

2. Tensile test

The results of tensile test for $M_k1 \div M_k5$ were shown in Table V and Fig. 3.

It has been shown that at the heating temperature 300÷900 ^oC, the elongation value of SS304L steel was almost unchanged (63÷65%).

However, the values of ultimate tensile strength and yield strength vary considerably. Tensile strength decreases from $M_K1 \div M_K5$. The ultimate tensile strength of M_K1 specimen was 440 MPa at room temperature, after heat treatment at 900 ^oC, this value of M_K5 specimen reduced sharply to approximately 300 MPa.

The yield strength value also tends to decrease similarly, slightly decreasing from 175MPa (M_K1) to 150MPa (M_K2). Especially, when the heating temperature increased to 700 ^oC and higher, the yield strength value reduced sharply to 40MPa (M_K3), 45MPa (M_K4) and then slightly increased to 60MPa (M_K5). This is consistent with the trend of most steel materials, the yield strength decreases when the heating temperature increases. The microstructure analysis data in the following section may explain this trend.

Table IV. Rockwell hardness data of M_C1-M_C5

Specimen	Heating Temp. (^oC)	First test (HRB)	Second test (HRB)	Third test (HRB)	Average (HRB)	Convert to HV
M_C1	30	89.4	88.9	89.0	89.1	188
M_C2	300	90.7	89.1	89.9	89.9	193
M_C3	700	86.2	86.6	87.9	86.9	178
M_C4	850	81.7	81.3	81.7	81.6	160
M_C5	900	80.6	80.4	79.8	80.3	155

Table V. Yield strength, Ultimate tensile strength and elongation of $M_K1 \div M_K5$

Specimen	Heating Temp. (°C)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)
M_K1	30	175	440	64
M_K2	300	150	295	64
M_K3	700	40	295	63
M_K4	850	45	310	65
M_K5	900	60	300	65

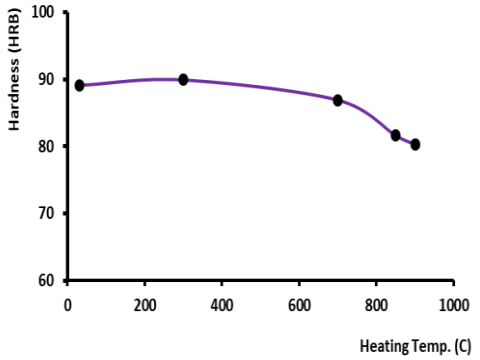

Fig. 2. Hardness values (HRB) of the specimens at different heating temperatures.

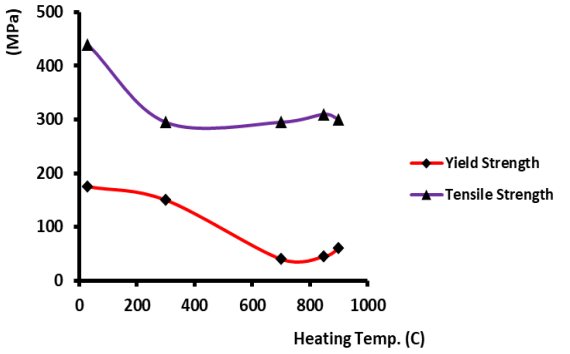

Fig. 3. The ultimate tensile strength and yield strength values of specimens at different heating temperatures

3. Charpy impact test

The results of impact energy for M6÷M10 specimens were shown in **Table VI** and **Fig. 4, 5.**

After heat-treatment, in terms of the impact strength, the mechanical properties of specimens have changed. Specimens performed at room temperature have a higher impact energy than those performed at 0 °C. When heating temperature increases, the impact energy decreases. The presence of chromium narrows the austenite zone , while the presence of nickel expands the austenitic zone. As a result, SS304L has a wider austenitic phase than the corresponding carbon steel does.

In general, the degraded area will be expanded in the temperature range of 500 ÷ 800 °C. Sensitivity depends on the process of chromite-rich carbide precipitation along the grain boundary due to the fact that when the carbide phase is precipitated, the carbon diffuses rapidly to the particle boundary. At higher temperatures, faster chromium diffusion also causes degradation at the grain boundaries.

Table VI. The impact energy of M6÷M10 after impact test.

Specimen	Heating temp. (°C)	Energy at 0 °C (J)	Energy at 30 °C (J)
M6	30	355	375
M7	300	350	355
M8	700	320	330
M9	800	315	335
M10	900	305	327.5

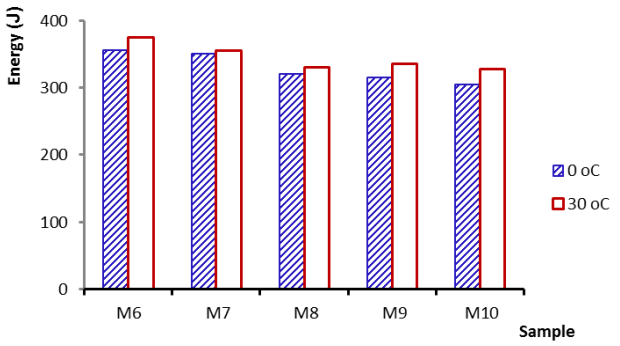

Fig. 4. The impact energy of M6-M10 specimens

Fig. 5. Specimens after impact test

4. Microstructure

Material microstructure was analyzed by Axio-vert 25CA microscope (Carl Zeiss - USA) to determine the composition and distribution of phases. It has been shown that phase composition changes corresponding to different heat treatment conditions.

It can be seen that in M1, delta-ferrite (δ) phase is seamlessly distributed across the austenite matrix (γ) (Fig. 6a). M2 also exhibited the delta ferrite (δ) phase distribution on the austenite matrix (γ), but the delta ferrite phase in M2 was more fragmented and finer than in M1 (Fig. 6b). At the temperature of 700 °C, the phase composition of M3 exhibited the presence of sigma (σ) phase. It can be seen in M3 that there are 3 phases: delta ferrite (δ) + austenite (γ) + sigma (σ). The sigma phase is a dark phase, located on the delta phase and a small part of the austenitic grain boundary (Fig. 6c-6d). In M4, there are 3 phases: delta ferrite (δ) + austenite (γ) + sigma. However, the sigma phase appears much more on the austenitic grain boundary than in M3 (Fig. 6e). In M5, the sigma phase (σ) is smaller and more fragmented than in M4 (Fig. 6f).

On the basis of phase theory, it can be seen that, in M1 as-received specimen, the delta-ferrite phase was large, seamless. In M2, the delta phase was dispersed, showing better material properties. The reason for this is when the boundary between the matrix and delta ferrite phase is long, the steel material is more susceptible to damage. M3 showed large distribution of sigma phase on the delta ferrite phase. The sigma phase is composed of Fe-Cr, leading to brittleness of material. In M4, the more the sigma phase was produced at the grain boundaries, the more negatively mechanical properties were changed. In M5, it can be shown that the grains become bigger. Sigma phase presence still occurs, making material more brittle. When comparing microstructure data to yield strength results, it can be seen that the microstructure data were able to explain trend of yield strength. Forming brittle sigma phase is responsible for the reduction of the yield strength. A slight increase of yield strength in M5 compared to that in M4 may be due to less sigma phase density (Fig. 6f).

Fig. 7 is the microstructure of normalizing specimens M7-M10. In M6 (M1)-as-received specimen, delta-ferrite phase exists on austenite matrix phase (Fig. 6). After normalizing treatment, the sigma phase appears in M7, M8, M9 with different densities and locations. However, sigma phase is still mainly concentrated on delta ferrite phase or austenite boundary. It is important that the sigma phase

density in the M9 decreases, comparing to M7 and M8, especially, in M10, the sigma phase does not appear (Fig. 7). It is known that the sigma phase is brittle, causing mechanical properties of the material degraded. Therefore, eliminating the sigma phase is very important to improve the mechanical properties of the material.

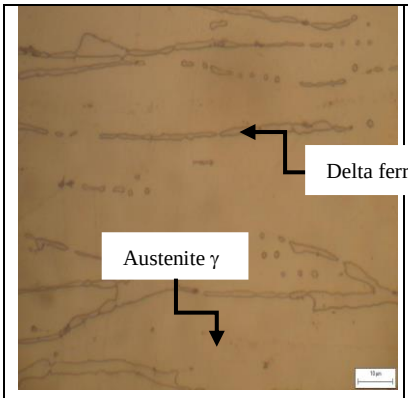

Fig. 6a. The microstructure of the M1 specimen

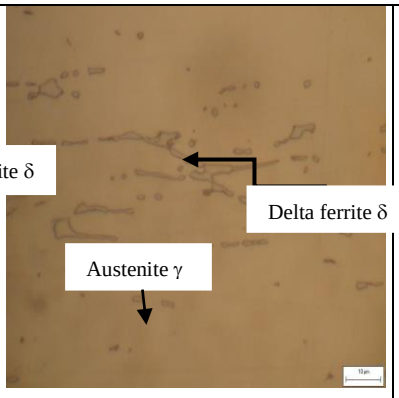

Fig. 6b. The microstructure of the M2 specimen

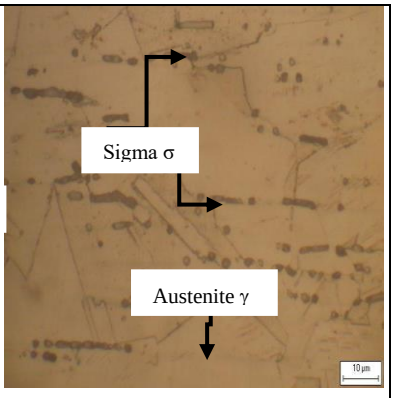

Fig. 6c. The microstructure of the M3 at the first point

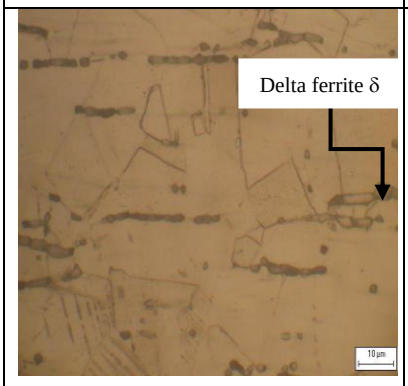

Fig. 6d. The microstructure of M3 at second point

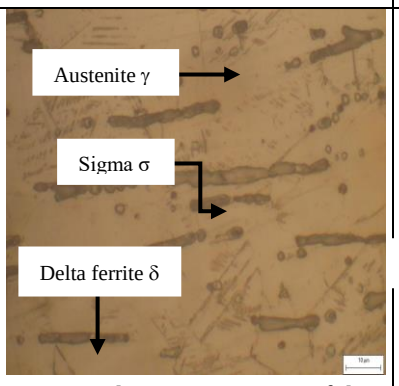

Fig. 6e. The microstructure of the M4 specimen

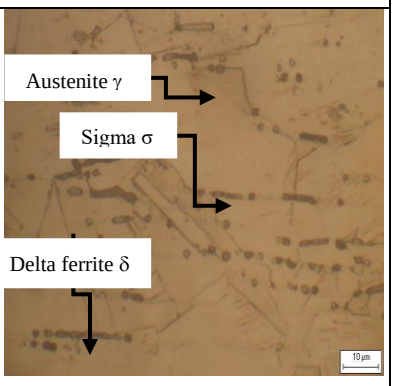

Fig. 6f. The microstructure of the M5 specimen

Fig. 6. The microstructure of M1, M2, M3, M4 and M5 specimens (x1000)

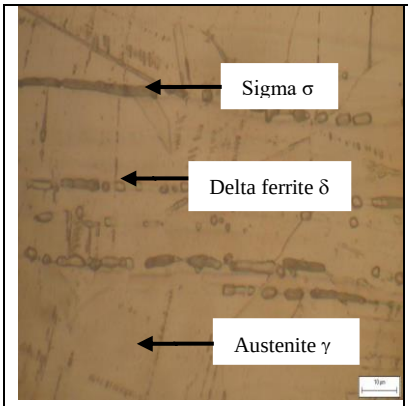

Fig. 7a. The microstructure of the M7 specimen

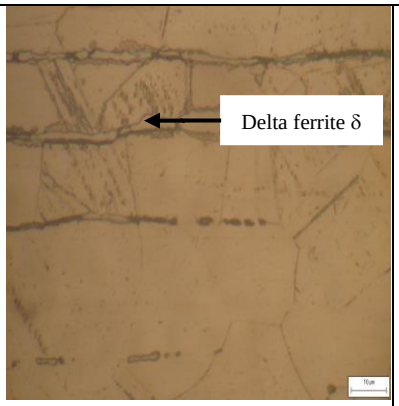

Fig. 7b. The microstructure of the M8 at the first point

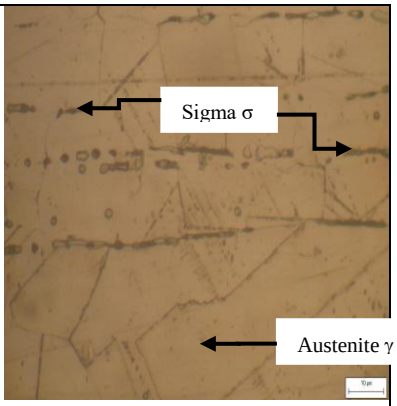

Fig. 7c. The microstructure of the M8 at the second point

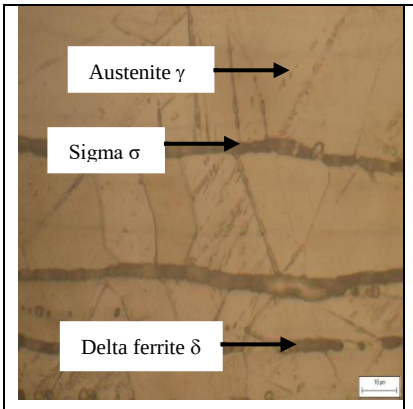

Fig. 7d. The microstructure of the M9 specimen

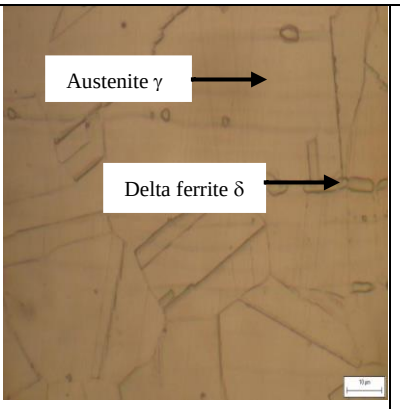

Fig. 7e. The microstructure of the M10 at the first point

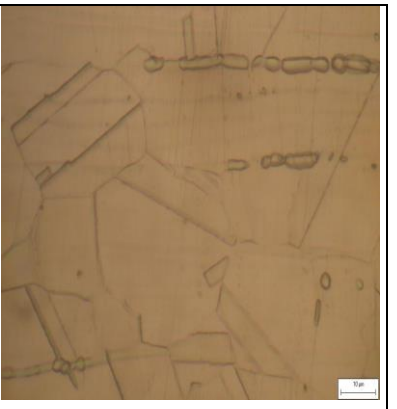

Fig. 7f. The microstructure of the M10 at the second point

Fig. 7. The microstructure of M7, M8, M9, M10 specimens (x 1000)

The results of SS304 metal microstructure is disscussed to provide some of quanlitative evidences for composition and distribution of phases. It has been shown that phase composition changes corresponding to different heat treatment conditions

III. CONCLUSIONS

Experimental results of some mechanical properties of SS304L at the selected heat treatment conditions show that the higher the heating temperature is, the worse mechanical properties are. When increasing the heating temperature, the hardness increased slightly firstly, then decreased but the differences in hardness values were not really significant due to SS304L is a kind of soft steel. When the heating temperature increased, the ultimate tensile strength and yield strength of specimens decreased while the elongation values were almost unchanged. When increasing the normalizing treatment temperature, the impact energy decreased. The impact energy of specimens performed at room temperature was higher than that of specimens performed at 0 ^{o}C. Besides, the microstructure analyzing results also showed the presence of sigma phase at high treatment temperature, causing brittle property and this work also showed the possibility to remove this sigma phase. These experimental results are just initial for further studies on NPP materials and material degradation in high temperature-working conditions of NPPs.

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