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Effect of Solution Annealing Treatments on Formability of Stainless Steel Alloys

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Abstract

The effect of solution annealing treatment on the formability of three stainless steel alloys (AISI 321, GOST A917, and SAF 2205) has been studied. Properties obtained from tensile testing (strength, ductility, strain hardening index, and strain rate sensitivity) have been chosen as criteria to detect formability. The values of those criteria were compared with stretching behavior obtained from Olsen test (h-value). Solution annealing treatment, at the range 900-1350^{o}C for 30 min. followed by water quenching, showed a remarkable effect on formability for the three alloys.

Annealing the duplex stainless steels at 950^{o}C and at temperatures higher than 1050^{o}C, was found to decrease the strain hardening index (formability) due to the formation of brittle phases during annealing at 950^{o}C, and also due to increase of ferrite content when annealing at temperatures higher than 1050^{o}C. The rate of cooling (water quenching, air cooling, and furnace cooling) after annealing at 1050^{o}C showed to have an effect on the formability of the three alloys in a way that air cooling and water quenching produced better formability than furnace cooling due to formation of brittle carbides and grain growth during furnace cooling.

Increasing annealing time reduced tensile and yield strengths, while it had a little effect on Vickers hardness value. Strain hardening index was found to be increased with increasing annealing time. The results of stretching and tensile tests were conformed for the two duplex steels at different annealing temperatures and cooling rates but they did not for the austenitic steel due to the enormous crystalline growth caused by increasing the solution annealing temperature

Keywords: Austenitic and Duplex Stainless Steels, Solution Annealing, Formability, Tensile and Stretching Tests.

الخلاصة

تم في هذا البحث دراسة تأثير معاملات التلدين المحلولية على قابلية تشكيل ثلاث سبائك من الفولاذ المقاوم للصدأ (سبيكتين من الفولاذ المزدوج والاخرى من الفولاذ الاوستنايتي) بأختلاف درجة حرارة التلدين ومعدل التبريد وزمن التثبيت. اعتمد اختبار الشد كمعيار لقياس قابلية التشكيل من خلال قياس خواص المقاومة والمطيلية ودليل الاصلاد الانفعالي وحساسية معدل الانفعال.

بينت النتائج بوضوح انه عند التلدين من درجة حرارة (950) م° فان قابلية التشكيل للفولاذ المزدوج قد انخفضت بسبب تكون طور سكما والاطوار الهشة الاخرى تقل ايضاً بعد درجة حرارة تلدين (1050) م° بسبب زيادة نسبة المحتوى الفرايتي الذي يسبب زيادة في مقاومة الخضوع والصلادة ونقصان في المطيلية ومقاومة الشد القصوى. اما زيادة درجة حرارة التلدين المحلولية اعلى من (1100) م° للفولاذالاوستنايتي فد سببت نمواً بلورياً كبيراً ادى الى هبوط في قابلية التشكيل بانمط.

واظهرت النتائج ايضاً اختلاف في قابلية التشكيل للسبائك الثلاث بأختلاف معدل التبريد وابرزت ان معدل التبريد السريع والمتوسط قد اعطى افضل قابلية تشكيل من معدل التبريد البطيئ لكون الاخيرقد سبب في ترسيب الكاربيدات الهشة وزيادة النمو البلوري للحبيبات. ولوحظ ايضاً ان زيادة زمن التثبيت عند درجة حرارة التلدين يقلل من مقاومة الشد والخضوع ويزيد من دليل الاصلاد الانفعالي بينما لا تتأثر الصلادة الفكرية كثيراً بزيادته. واخيراً فقد تطابقت نتائج اختباري المط والشد بأختلاف درجة حرارة التلدين ومعدل التبريد لسبيكتا الفولاذ المزدوج بينما لم تتوافق بالنسبة لسبيكة الفولاذ الاوستنايتي بسبب النمو البلوري الهائل من جراء درجة حرارة التلدين المحلولية.

INTRODUCTION

Stainless steel alloy with 12% Cr provides a good corrosion and oxidation resistance [1-3]. There are many commercial and standard stainless steel alloys that characterized by specific mechanical and corrosion properties. And, formability of these alloys varies from one alloy to another depending on the alloy quality [4-18] and the amount of the alloying elements that exist besides the chromium [4,19-23]. Generally, the formability of the stainless steel alloys are not only affected by some factors related to the forming process as reported previously [24], but also by the heat treatments of these alloys [17,24-31] reaching for better conditions at which the optimum formability can be obtained.

The main heat treatments of the austenitic and duplex stainless steels after the working processes, is the solution annealing treatment which is often used either for relieving the stresses induced during the cold forming or to dissolve the brittle phases and precipitated carbides during the service or for both [32]. It must be mentioned that chromium carbides will decompose during the annealing treatment and since these carbides form at a temperature between the 425-900ºC, therefore, it is necessary to carry out the annealing treatment at a temperature above this range. This means that the annealing temperature is limited by the occurrence or formation of the brittle phases and carbides [29]. Most of the austenitic stainless steels can be thermally treated by the solution annealing at 1000-1200ºC and rapidly cooled to room temperature [28]. While the solution annealing temperature for the duplex stainless steels is between 925-1175ºC, depending on the type of the alloy, and followed by rapid cooling to room temperature [32]. And, it is previously proposed that the annealing temperature for the duplex alloy SAF 2205 is in the range of 1020-1100ºC [30].

It must pointed out that the solution annealing treatment plays an important role on the formability of the duplex sheet steels because of its effect on the ferrite and austenite content. Hagen and Keller [29] noted that the ferrite: austenite ratio for the duplex alloy varies at temperatures above 1050°C. They found that the proper annealing temperature is 1000 C while Mazza et al. [31] found that annealing at temperature between (950-1350°C) will cause an obvious reduction in he austenite:ferrite ratio which is (0.78) at temperatures (950-1050°C). And this ratio starts to decrease with temperature increase till it reaches (0.02) at a temperature of 1350°C. Also, they concluded that this alloy at 1350°C totally becomes ferritic and they observed that specimens annealed at 950°C failed in the tensile test at a shorter time. They attributed the reason for this rapid failure to the precipitation of carbides type (M23C6) and nitrides (Cr6N) at the grain boundaries of the alloy.

Many researchers [18,31] indicated that the importance of the solution annealing treatment and its negative influence on the mechanical properties, especially when improper temperatures and cooling rates are utilized. Thus, it becomes necessary to control the cooling rates after heating to the proper temperature since the cooling rates will help to form the brittle phases and carbides and this will lead to the reduction in the impact strength and ductility of the duplex steels.

So, this paper aims is to study the formability of three stainless steel alloys (SAF 2205, GOST A917, and AISI 321) through the effect of the metallurgical parameters such as the effect of the solution annealing temperature and holding time, rate of cooling, and phases amount. Tensile tests were used as a criterion to determine the formability and to understand the mechanical behavior for each alloy. Also, the behavior of these alloys was studied during the stretching test using Olsen test which is considered as a good criterion to evaluate and compare the stretchability of the metallic sheets.

Method

In this work all test we carried out on two type duplex stainless steels (SAF 2205 and GOST A91) and one type austenitic stainless steel alloy (AISI 321) for comparison perpose. since the latter posses a good formability. All these alloys were supplied on the basis of their standards in form of cold rolled sheets with (2) mm thickness in the solution annealed condition. Therefore, it was found necessary to check first these alloys prior to testing in the local laboratories to determine their chemical compositions, mechanical properties, and microstructures in order to ensure their conformity with those results which should be relevant for their standards.

Thus, Table (1) shows the chemical compositions for the three alloys of the present work together with those in the as-standard condition for comparison purpose. It can be seen that the compositions of these alloys are in accordance with those for standard stainless steel alloys [33]. Also, the mechanical properties for the three alloys were measured in the rolling direction at room temperature and a strain rate of (1.6x10-3) /sec as listed in Table (2). The average of five hardness measurements was taken as the Vickers hardness number (HV). The results of the mechanical tests indicated that these data are in accordance with the standard mechanical properties [33].

Tension Tests

Tensile tests were conducted on standard specimens as given in the British specification B.S.18 [34]. The specimen dimensions were chosen in a way that they are properly fitted with the sheet thickness and the gripping method in the tensile machine. The test specimens prepared from 2 mm thickness stainless steel alloy sheets, were cut into their final dimensions using a special die designed and manufactured to cut the tensile specimens [24]. Prior to testing, all specimen edges were properly smoothed using fine files and followed by a polishing process with emery paper of (320) grade to remove all existed scratches on their sides and surfaces.

For the solution annealing specimens, all tensile tests were achieved on a tensile testing machine type (Instron1195) at a strain rate of (3.3×10-3)/sec. The load-extension curves were then plotted to establish the engineering and true stress-strain curves in order to calculate the properties and criteria used in this work. And, these include: the ultimate and yield strengths at (0.2%) strain, total and uniform elongations, strain hardening index, strain rate sensitivity, and percentage of area reduction according to certain relationships [35].

Solution Annealing Treatment

The solution annealing process was performed for tensile, hardness, and stretching specimens from the three alloys using a computerized furnace type (Carbolated RHF/6/3) of a high heating rate. The maximum temperature that can be acquired by using this furnace was 1600°C.

All specimens were solution annealed at temperatures between (900–1350°C with an increasing step of (50°C) for different periods of holding times from (15-195) min. Three cooling and quenching medians were used and these were water, air, and furnace to obtain different cooling rates. After cooling and quenching processes, the ground, polished, and cleaned specimens were prepared for tensile and hardness tests.

Hardness Tests

Hardness tests were carried out on solution annealed specimens in form of strips with dimensions of (30) mm x (30) mm x (2) mm. Prior to annealing process, these specimens were then carefully cleaned and dried. After annealing treatment, all specimens were first wet ground by different emery papers of (120, 220, 320, 500, and 1000) grade, respectively and then entirely dried to prepare them for Vickers hardness testing using (30) Kg load. For each specimen, the Vickers hardness number was taken as average of five hardness measurements.

Stretching Test

Olsen test was chosen to evaluate and compare the formability of the three alloys and according to the American standard (E643) [36]. The die for the stretching test was designed and produced according to this specification. And, all tests were achieved on blanks from these alloys at different annealing temperatures and cooling medians.

The blanks relevant to this test, was firmly fixed above the die using a blank holder with enough force to avoid the blank from drawing inside the die. The stretching test die was then fastened on the base of the Instron machine.

The blank was formed till failure experienced and the stretching test was accompanied with plotting the load – extension (the peak height) curve which was used to calculate the limiting dome height, maximum stretching force, and the total work done necessary for the stretching process for each alloy.

Sheets of the three alloys were cut into strips of (80) mm x (80) mm size with (2) mm thickness and their edges were straightened by fine files. And, all stretching tests for these alloys were conducted after the solution annealing treatment without lubricating the blanks to be formed and at different cooling rates. All tests were performed at a punch speed of (10) mm /min.

RESULTS AND DISCUSSION

Effect of Annealing Temperature on the Mechanical Properties

The basic effect of the annealing temperature on the two duplex stainless steels was the increase of ferrite content with increasing the annealing temperature. Figure (1) reveals the change of the ferrite percentage for the duplex alloys with annealing temperature. It can be observed that the -ferrite contents for alloy (2205) at 1050 °C, 1250 C and 1350 C were 51.2% , 75% , and 92% , respectively while those for alloy (A917) at same temperatures were 53.4%, 76% , and 96%, respectively.

Figures (2a) and (2b) show the effect of the solution annealing temperature on strength properties for the specimens of the three alloys solution annealed at different temperatures followed by water quenching. It can be seen in fig.(2a) that the decrease of the ultimate tensile strength with increasing the annealing temperature for the three alloys (with exception of the two duplex alloys at 1350°C while in fig.(2b), the value of the yield strength was high at 950°C for the two duplex alloys and decreased at the annealing temperature of 1050°C and then increased at the subsequent temperatures. For alloy (321), the value of the yield strength was high and then started to decrease till the minimum value at a temperature of 1200°C and slightly increased later.

As shown in Fig.(2a) that the values of the ultimate tensile for the two duplex steels at 950 °C were too high. The reason of that was likely due to the formation of the brittle sigma phase and other carbides which resulted in an increase of the ultimate and yield strengths and a decrease in the ductility (percent elongation and area reduction) as shown in Figs.(2c),(2d), and (2e). And, this result was in agreement with that found by other investigation [12,13,16,17]. Also, at a temperature range (1050-1250°C), it was seen that the ultimate tensile strength values decreased with increasing the solution annealing temperature. And, this attributed to the increase of the ferrite content of the two duplex steels as shown in figs.(2a) and as measured also in this study (see Fig.(1)) which deduced the increase of ferrite percentage to (75%) at 1250°C.

Also, the formation of the metallurgical structure consisting of a matrix of ferrite grains with less percent of needled austenitic at annealing temperature 1350^{o}C, caused an increase in tensile strength and this was supported by a number of investigators [12], i.e., the results of the present study mean that the tensile strength decreased with increasing the ferrite from (50%) to almost (80%) and then increased due to the formation of the above metallurgical structure. Figures (2c) and (2d) exhibit the variation of the total and uniform elongations with the annealing temperature, respectively. The maximum value for these elongations was at (1050^{o}C), (1150^{o}C), and (1200^{o}C), for alloy (2205), (A917), and (321), respectively. While Fig.(2e) shows the change of the reduction in area with the annealing temperature for the three alloys. The maximum value was at (1050ºC), (1050 ºC), and (1200º C) for the alloys (2205), (A917), and (321), respectively.

The variation of the Vickers hardness with increasing annealing temperature for a holding time of (15) min is shown in Fig. (2f).The minimum hardness value was at (1050^{o}C), (1050^{o}C-1150^{o}C), and (1200^{o}C) for alloy (2205), (A917) and (321), respectively. For the two duplex steels, the combined increase of the yield strength and hardness in their values with increasing of the annealing temperature is shown in Fig. (2b) and Fig (2f), certainly ascribed to the increase of the ferrite content because of the annealing temperature increase. And, the ferrite phase led to the hardness and yield strength increase [13,14,16,37]. Also, the increase of this phase (ferrite) resulted in a decrease in the ductility [13,14,37] and this was observed in this work and as shown in Figs.(2c) and (2d).

The results of this study with respect to the variation of the mechanical properties with annealing temperature increase beyond (1050oC) for the duplex steel (i.e., the variation of these results with ferrite content increase as clarified above), were conformed to several results of other studies. And, in certain cases, there are other variables (not only the change of the phases percentage) but also, the variation of the constituents distribution within the phases them self that affect the mechanical properties.

For instance, other studies [31] referred that the ferrite content increase with increasing the annealing temperature, led to the reduction of some constituents that stabilize the ferrite such as the molybdenum. And, concerning the mechanical properties, the nitrogen element has a large effect in this field whereas, its concentration increased certainly in the austenite phase with increasing the annealing temperature due to the disability to dissolve in ferrite.

And this means obtaining a metallurgical structure containing a low percent of austenite but having a large percent of nitrogen which in this case affects actively on the yield strength [38]. According to this basis, the yield strength increase of the duplex steel could be interpreted not only depending on the ferrite increase but also on the nitrogen content increase in the austenite content, particularly some studies indicated that the existence of the lower percent of austenite with ferrite would form the distortion which centered in the austenite in addition to its distribution causing the rapid failure [13]. While for alloy (321) with the austenitic structure, the annealing temperature increase resulted in a continuous reduction in the ultimate and yield strengths, hardness, and an increase in ductility up to (1200^{o}C) as shown in Figs.(2a), (2b), (2d) and (2f).

And, this attributed to the annealing temperature increase that induced the recrystallization of the austenite grains and then form the grain growth. And, this lessened the strength and hardness and induced the increase in ductility [39]. While at annealing temperature (1350°C), the increase shown in the yield strength and hardness and the decrease in the ductility imputed to the formation of some simple phase transformation. And, this was the increase of the ferrite content type (δ) in the structure which influenced the properties [40] during annealing at this temperature.

Effect of Annealing Temperature on the

Formabi1ity Indexes

Figure (3a) illustrates the variation of strain hardening index obtained from the plotted log true stress-log true strain for the three alloys at different annealing temperatures and at a strain rate of 3.3 $x10^{-3}$ /sec. And, Fig.(3b) indicates also the change in the ultimate tensile: yield strength ratio with annealing temperature. These figures show that the maximum value of the strain hardening index (n) and tensile:yield strength ratio was at (1050ºC) for the two duplex steels and at (1200ºC) for the austenitic alloy. It was also shown from these figures, the increase of the strain hardening index and the tensile: yield strength ratio for alloy (321) that considered as the formability indexes with increasing the annealing temperature up to (1200^oC).

And, this is due to that the annealing temperature and, as explained previously, leads to the recrystallization and then the growth of the austenite grains. While annealing at (1300^oC), induced a slight reduction in these two values (i.e., reduction in the formability and this interprets also accordingly that this temperature results in an increase in ferrite content type (δ) [40]. The ferrite phase is one of the phases that reduce the formability since the degree of its strain hardening is lower than that in the austenite [41]. Whereas, for the two duplex stainless steels, the formability was measured on the basis of the value of both strain hardening index and tensile: yield strength ratio.

The maximum value for them was at the annealing temperature (1050°C) and then decreased with increasing the annealing temperature. And, this interprets that the annealing temperature at (1050°C) caused the formation of a metallurgical structure with about (51%) ferrite as calculated and the ferrite percentage was then increased with increasing the annealing temperature. This increase in the ferrite phase resulted in a reduction of the formability because of the low strain hardening for this phase [41].

Figure (3c) exhibits the change in the normal anisotropy values with solution annealing temperature for the three alloys (water quenched) and the maximum value was at (1050^oC) for the duplex steel. And, the reason was owing to the almost equal ferrite and austenite contents in the two duplex alloys while the maximum value was at (1000^oC) for alloy (321) since the crystalline structure at this temperature was in the recrystal1ization condition.

Effect of Cooling Rate on Mechanical Properties

Cooling rate has a considerable influence on the mechanical properties of various metals and alloys through its effect on phases quantity and precipitation ratio of the brittle phases. Figures(4), (5), and (6) show the effect of the annealing temperature on yield and tensile strengths, uniform and total elongations, tensile:yield strength ratio, and strain-hardening index at three cooling medians for alloys (321), (2205), and (A917), respectively.

For alloy (321), Figs.(4a-4f) exhibit the influence of cooling rate on the mechanical properties and it also indicates that the cooling rate reduction from cooling by water, then air, and then inside the furnace cooling, led to ductility reduction. And, this is in contrast to the anticipated behavior of the single phase alloys, which form an increase in strength and a decrease in ductility with increasing the cooling rate [38.]. This attributed to the precipitation of the brittle phases which are in this case carbides along the grain regions when the cooling rate is lowered such as furnace cooling.

That is obviously appeared in the microstructure of alloy (321) where the brittle phases (precipitated carbides) are on the grain boundary regions when furnace cooling at all annealing temperatures whereas, the precipitancies which would reduce the ductility cooling by water are not appeared. This carbide precipitating affects also on the yield and tensile strengths. Thus, Figs.(4a) and (4b) manifest the increase of yield and tensile strengths when furnace cooling is more than that when cooling by air because of the carbides precipitation effect in this case.

While, concerning the change of the tensile strength with cooling rate when annealing at temperatures higher than 1100°C, the effect of carbide precipitation is less since cooling from these higher temperatures results in giving higher cooling rate than that when cooling from lower temperatures. And, in this case, the change in tensile strength with cooling rate as known, is increasing the strength with increasing this rate as shown in Fig.(4b) when cooling from temperatures higher than 1100°C.

With respect to alloy (2205), the cooling rate reduction from water, to air, and then furnace cooling leads to obtain of metallurgical changes even when cooling from the annealing temperature itself. It is seen from the microstructure of this alloy that the cooling rate reduction induces the ferrite transformation to austenite, particularly when cooling from higher annealing temperatures that result in the formation of a high amount of ferrite when cooling by water. Also, it is noted that the increase of the austenite content when cooling by furnace and air at temperature of 1350°C for instant, is more than that when cooling by water from the same temperature [42].

In addition to that, the cooling rate reduction leads to the brittle phases precipitation such as sigma (σ) and ferrite (α) phases and as this is evident when cooling by furnace. The effect of increasing the austenite amount with cooling rate reduction certainly causes the ductility increase and yield strength reduction since the strain-hardening of this phase is large in comparison with the ferrite phase and this is what actually obtained in the present study and as seen in Figs.(2f), (5a), and (5d), especially when cooling from high annealing temperatures at which the cooling rate has a great influence on the mechanical properties. The effect of the brittle phase precipitation always leads to ductility reduction and these carbides form due to lower cooling rates and have not experienced a mechanical effect on tensile properties in these tests.

While, the mechanical behavior of alloy (A917) is similar to that of alloy (2205) and as indicated by Figs (6a-6d) when cooling from higher annealing temperatures. Whereas, on cooling from lower annealing temperatures, their behavior was different and this is likely due to precipitation of the brittle phases that form in all types of duplex steel on slow cooling. And, these brittle precipitancies are noted in the microstructure of this alloy. The transformation from ferrite phase to austenite is also appeared in this alloy, particularly on slow cooling from higher temperatures.

Effect of Cooling Rate on the Formability Indexes

The metallurgical changes at various cooling rates that manifested with respect to alloy (321), led to obtaining formability by calculating the formability indexes. And, these are strain-hardening index and tensile:yield strength ratio as shown in Figs.(4e) and (4f) which exhibit that air cooling imparts higher formability through these two indexes. And, the reason for high formability in air cooling is probably because of no occurrence of the distortion which often induced at higher cooling rates [32] and this would influence these two indexes. Also, the furnace cooling as mentioned earlier, results in precipitating brittle phases on grain boundary regions in addition to the crystal1ine growth and these would reduce the formability

Regarding the duplex steel alloy (2205), the slow cooling from all annealing temperatures gives a greater value for strain-hardening index and tensi1e:yield strength ratio as shown in Figs (5e) and (5f), ascribed as previously indicated, to the greater amount of the austenite that form at lower cooling rate. And, this behavior is also demonstrated in the duplex steel (A917) as shown in Figs (6e) and (6f), and in similar form for the changes that occurred in the mechanical properties at varying cooling rates.

Effect of Holding Time

Figure (7) reveals the effect of holding time on Vickers hardness for the three alloys at their optimum annealing temperatures. While, the hardness values slightly decreased with increasing the annealing time for the two duplex alloys, it can be seen that the hardness values for alloy (321) was increasing, especially at a holding time of 195 min. And, this imputed to the probability of both increasing the ferrite content and probability of carbides precipitation in this alloy with increasing the holding time as well as the crystalline growth induced by the holding time increase.

Whereas, the reason of the hardness values reduction for duplex steel alloys attributed to enormous crystalline growth for ferrite phase and this would reduce the tensile and yield strength values and increases the ductility as shown in Table (3). This table exhibits the effect of the holding time on the mechanical properties of the duplex alloy (2205) solution annealed at 1050^{o}C and water quenched. The increase of the strain hardening values with increasing the holding time is also noted in this table.

Figure (8) demonstrates the changes of Vickers hardness values for alloy (2205) with various holding times and annealing temperatures. It can be seen that the increase of the holding time at annealing temperature of 950°C leads to the hardness increase. And, this is owing to the occurrence of the brittleness and increasing of the rate of sigma phase formation with increasing the holding time [12,13,14,16,17]. While at consequent temperatures, it is indicated that the hardness values dropped due to the occurrence of the crystalline growth of ferrite phase [37]. The microstructures for these three alloys at three holding times (30, 60, and 195 min.), exhibit also the occurrence of the crystalline growth with increasing the holding times for these three alloys.

Mechanical Behavior during the Stretching Test

Figure (9a-9c) show the effect of the solution annealing temperature on the value of each of the limiting dome height (h-value), maximum stretching force, and total work done for the three alloys which solution annealed at different annealing temperatures and then water quenched. It can be observed that the limiting dome height values are low at a temperature of 950°C for the two duplex steels because of sigma phase formation and brittle carbides.

And, it has a higher value at annealing temperatures 1050°C and 1150°C for alloy (2205) and alloy (A917), respectively and then reduced as pointed out earlier, due to the increase of ferrite content for these two alloys with increasing the annealing temperature. While, for alloy (321), the highest value for the limiting dome height (h-value), maximum stretching force, and total work done, is at a temperature of 900°C and this value reduced at the consequent annealing temperatures. The reason of nonconformity of the total and uniform elongations and strain hardening index value for the tensile with stretching test, can be interpreted by the huge crystalline growth that took place in the crystals and this would reduce the stretchability while, its effect in the uniaxial tensile test has not shown.

Figure (10a-10c) show the effect of annealing temperature on the limiting dome height at various cooling medians for the alloys (2205), (A917), and (321), respectively. It is indicated that the influence of cooling rate on the limited dome height for these alloys and it is clearly appeared that the h-values are affected by cooling rate. And, these values are in conformity with the results obtained from the tensile test for the two duplex steels while, these values did not conform, at all cooling rates, with the tensile test values for alloy (321) due to the enormous crystalline growth caused by increasing of the annealing temperature.

CONCLUSIONS

1. The formability of the duplex stainless steel decreased with increasing the solution annealing temperature where, the optimum annealing temperature in this case is 1050°C. Whereas, the formability of the austenitic stainless steel (321) increased with increasing annealing temperature up to 1200°C and decreased afterward.

2. Similar heat treatment effects (obtained from tensile and stretching tests) were found in (2205) and (A917) alloys.

3. The formability is influenced by cooling rate change where, this formability is higher than it can be when cooling by air, water, and furnace.

4. Increasing annealing time reduced tensile and yield strengths, while it had a little effect on Vickers hardness value. Strain hardening index was found to be increased with increasing annealing time.

5. The 321 austenitic stainless steel exhibited grain growth during annealing at temperatures above 1100oC and this affected the limiting dome height (h-value), which was found to be decreased in the stretching test.

Table (1): Chemical composition for the three stainless steel alloys compared with those of the standard alloys.

Element (wt %)	SAF (2205)	Standard SAF (2205) [35]	GOST (A917)	Standard GOST (A917) [35]	AISI (321)	Standard AISI (321) [35]
C	0.025	0.03	0.055	0.1	0.072	0.08
Cr	22.6	22	20.5	20-22	17.5	17.5
Ni	5.31	5.5	4.95	4.8-5.0	10.7	10.5
Mo	2.9	3.0	0.12	--	0.19	--
Si	0.408	Max 0.8	0.53	Max 0.8	0.35	Max 1.00
P	0.033	Max 0.03	0.027	Max 0.035	0.018	Max 0.04
S	0.005	Max 0.02	0.004	Max 0.025	0.008	Max 0.03
Cu	0.16		0.18		0.178	
Ti	0.005	--	0.31	0.25-0.5	0.49	> 5 x C%
Mn	1.55	Max 2.0	0.67	Max 0.8	2.06	Max 2.0
W	0.024		0.05		0.037	
Al	0.01		0.02		0.036	
V	0.097		--		0.05	
N		0.14		--		--
Fe	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.

Table (2): Mechanical properties for the three stainless steel alloys in the rolling direction , at room temperature at strain rate of 1.6 x 10^{-3} /sec.

Property	Alloy		
	SAF (2205)	GOST (A917)	AISI (321)
Yield Strength (MPa)	545.6	444.4	245.6
Tensile Strength (MPa)	807.5	825.6	617.1
Total Elongation (%)	36.6	20.6	72.8
Uniform Elongation (%)	31.6	18	69.2
Strain Hardening index (n)	0.208	0.365	0.37
Strength Factor (K) (MPa)	1369.7	1901	1220
Hardness (HV)	265	210	165

Table.3: Effect of holding time on the mechanical properties of the duplex alloy (2205) solution annealed at 1050 °C.

Property	Holding Time(hours)		
	0.5	1	2
Yield strenght (MPa)	580	471.7	472.4
Tensile strength(MPa)	820.5	751	748
Total elongation(%)	35.4	35.8	37.2
Uniform elongation(%)	30.6	30.4	31.6
Reduction of Area(50) (%)	30	32	34.4
Strain Hardening Index(n)	0.216	0.23	0.238
Strength Factor(K)(MPa)	1412	1308	1321

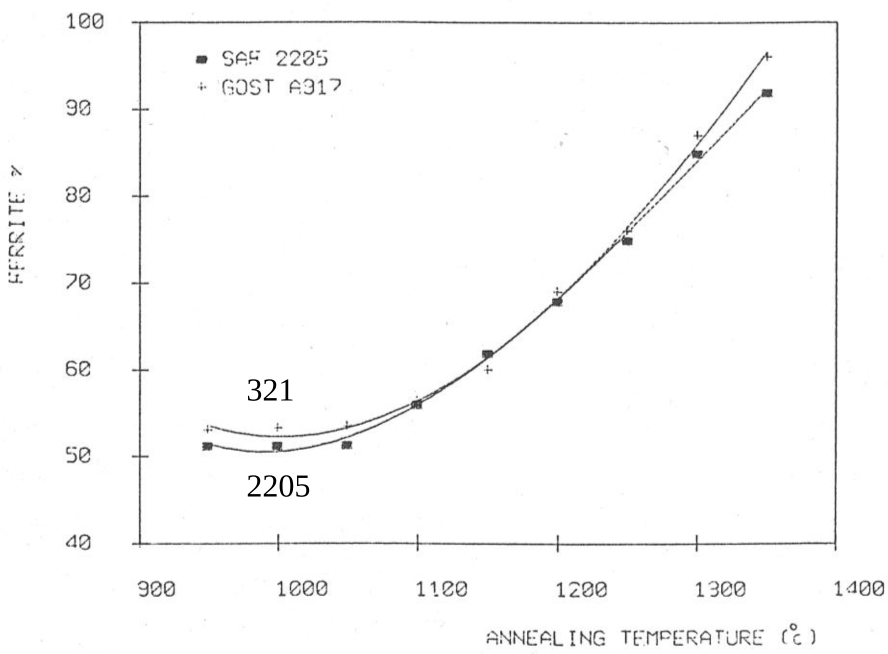


Fig. (1) Effect of solution annealing temperature on ferrite content for the two duplex alloys (2205) and (A917) after water quenching.

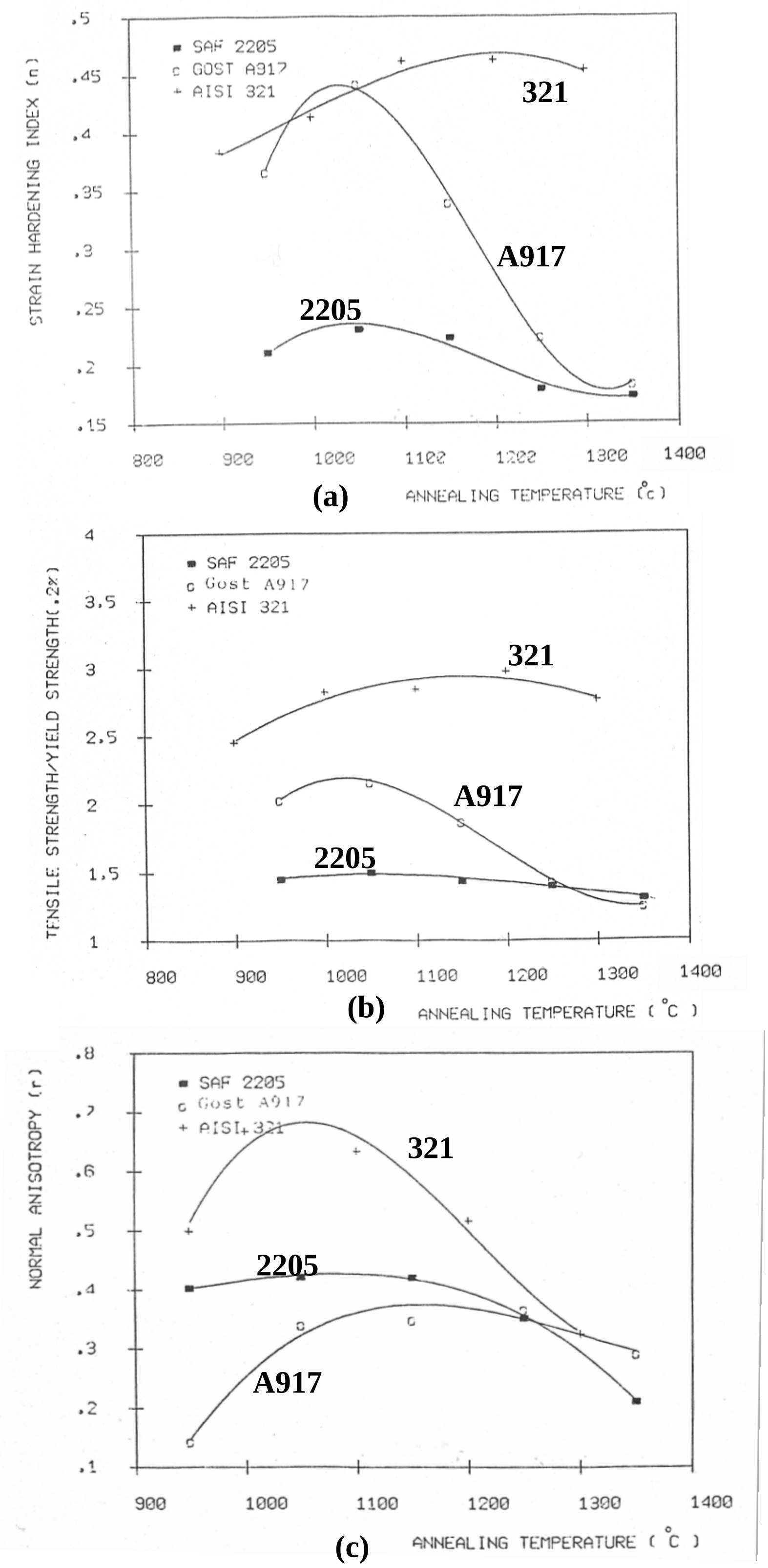


Fig.(3) Variation of (a) strain-hardening index(n), (b) tensile :yield strength ratio, and (c) normal anisotropy (r) with the solution annealing temperature for the three stainless steels at a strain rate of 3.3*10^{-3}/sec.

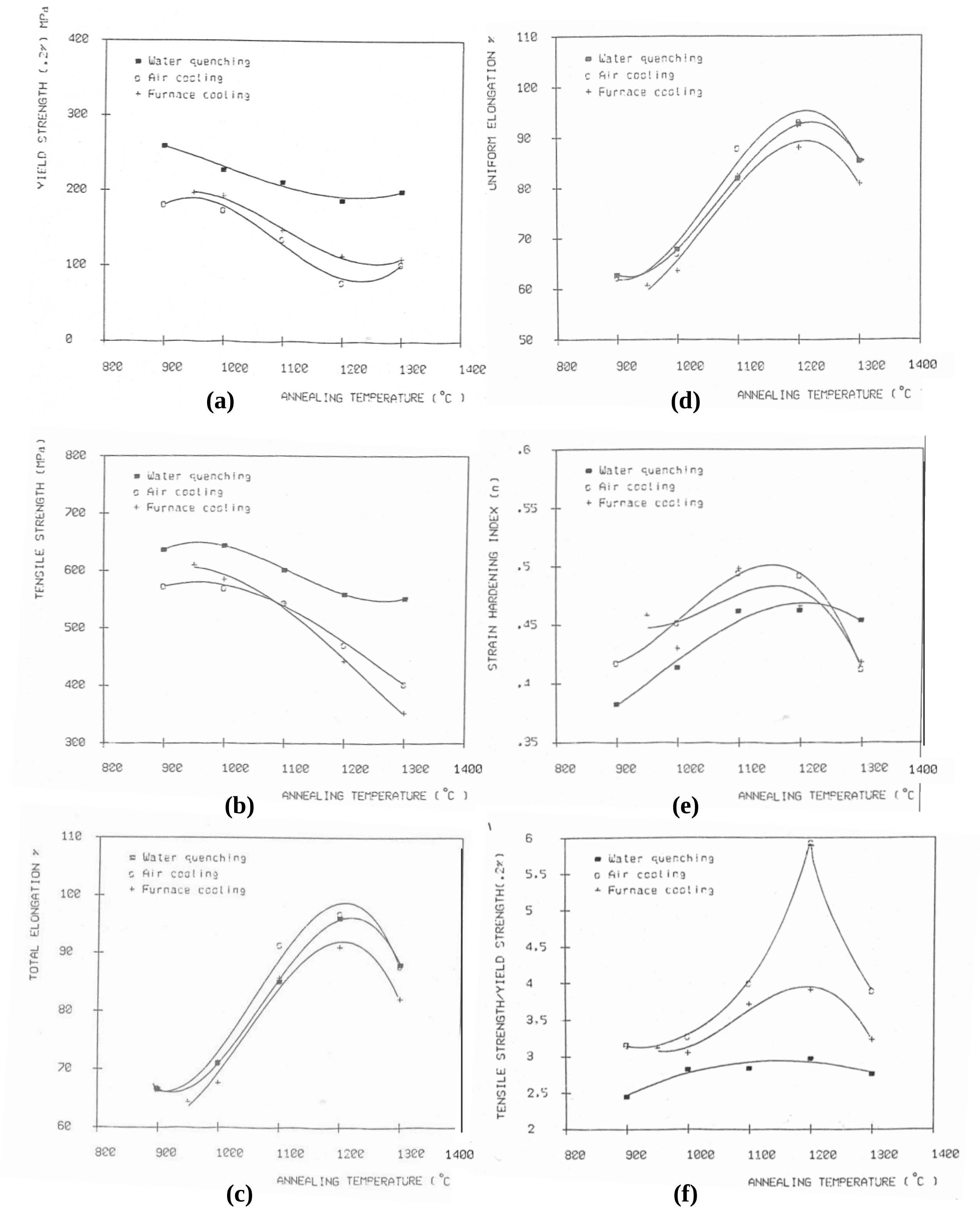


Fig.(4) The effect of solution annealing temperature on of (a) yield strength, (b) tensile strength, (c) total elongation, (d) uniform elongation, (e)strain hardening index (n), and (f) tensile: yield strength ratio for the duplex alloy (SAF 2205) cooled by three medians.

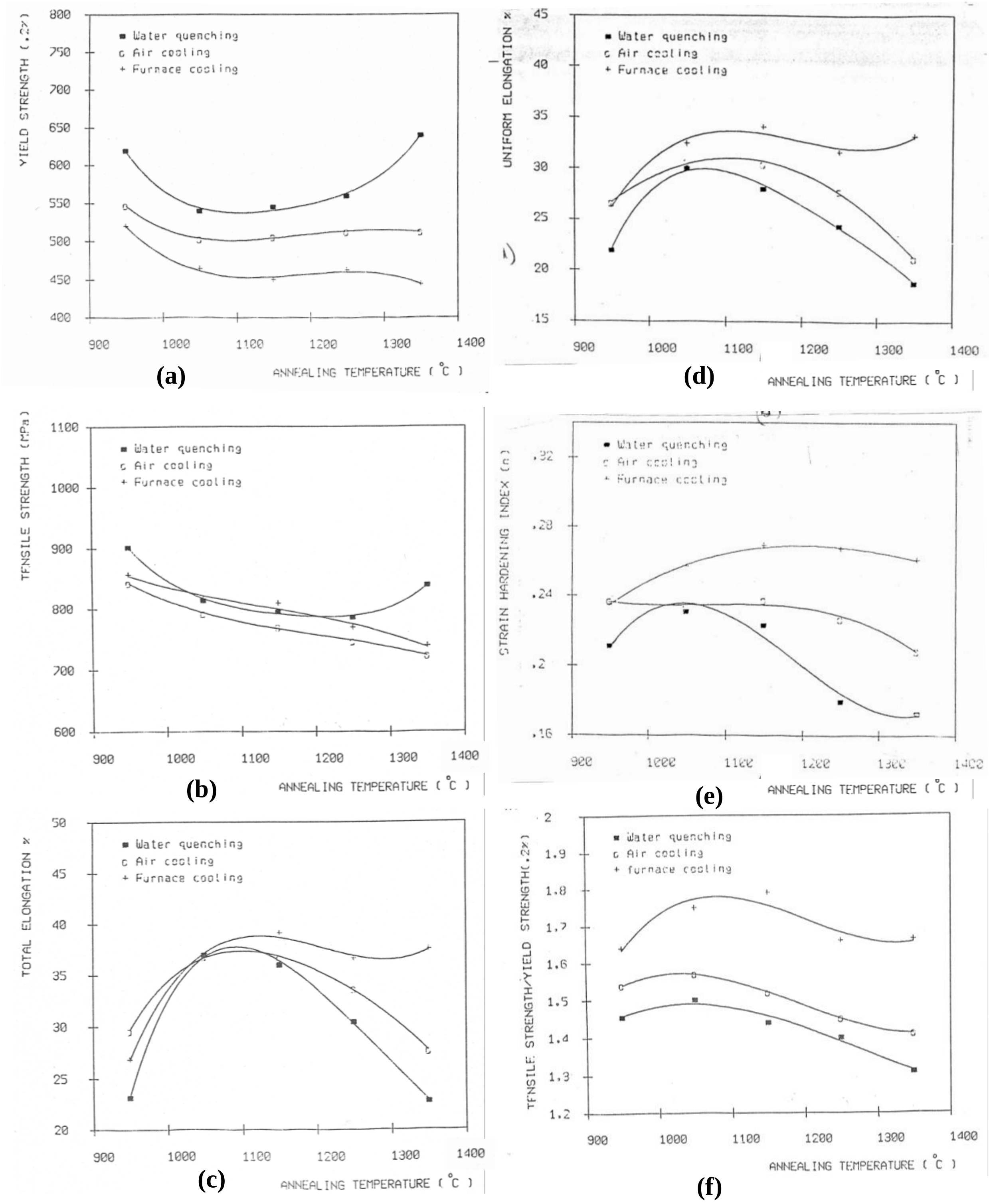


Fig.(5) The effect of solution annealing temperature on of (a) yield strength, (b) tensile strength, (c) total elongation, (d) uniform elongation, (e) strain hardening index (n), and (f) tensile: yield strength ratio for the duplex alloy (GOST A917) cooled by three medians.

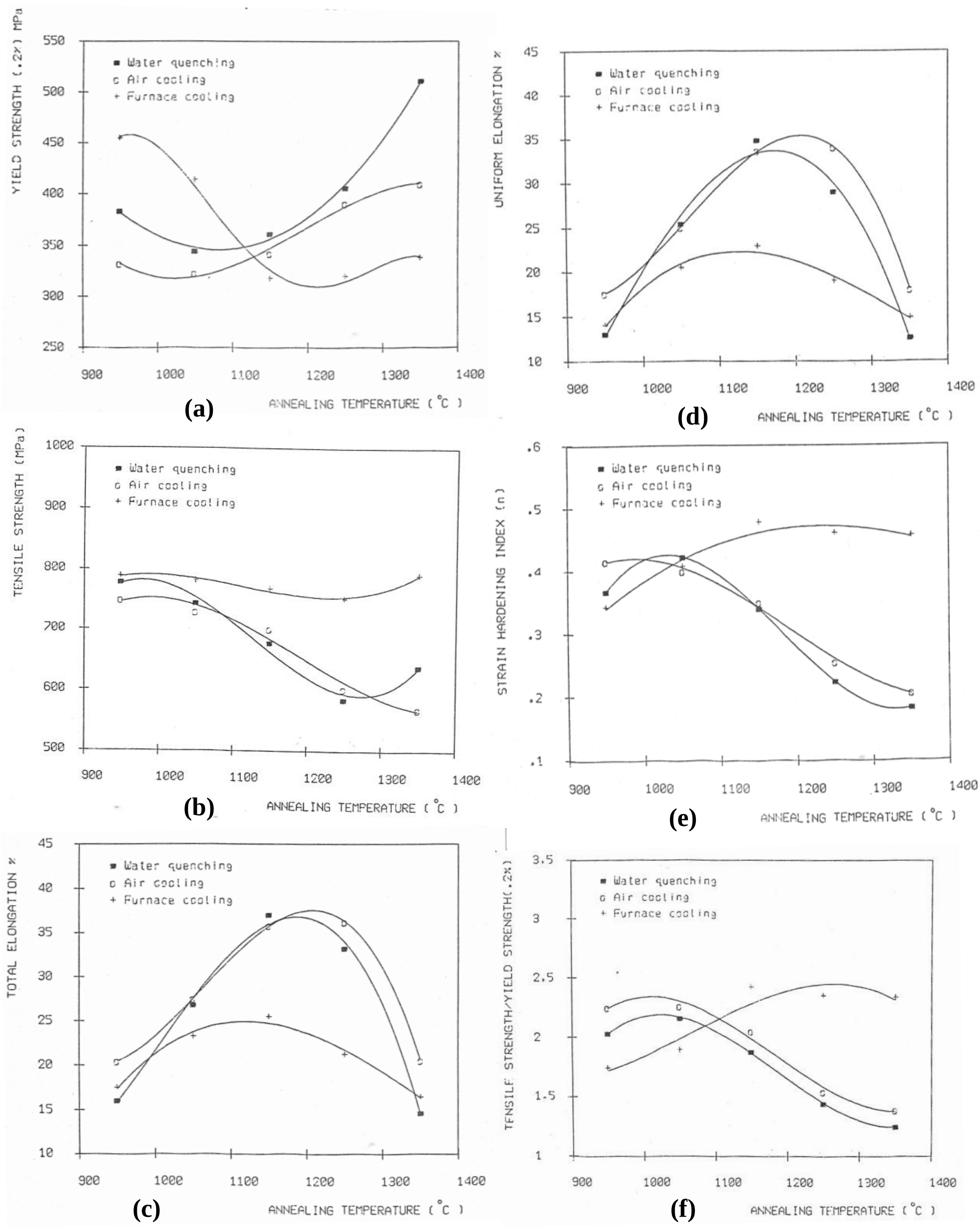


Fig.(6) The effect of solution annealing temperature on of (a) yield strength, (b) tensile strength, (c) total elongation, (d) uniform elongation, (e) strain hardening index (n), and (f) tensile: yield strength ratio for the for the austenitic (AISI 321) cooled by three medians.

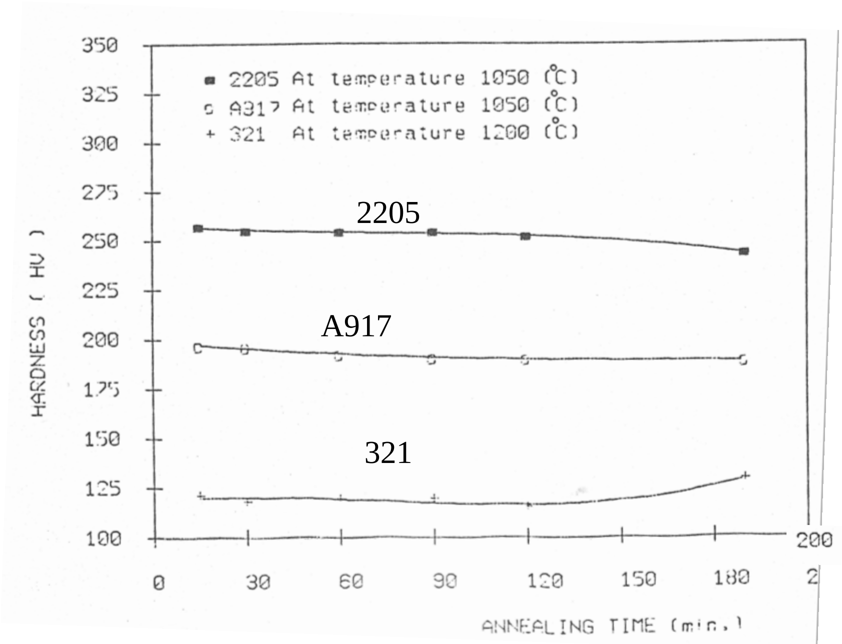


Fig.(7) Effect of the holding time on Vickers hardness for the three stainless steels at their optimum annealing temperatures.

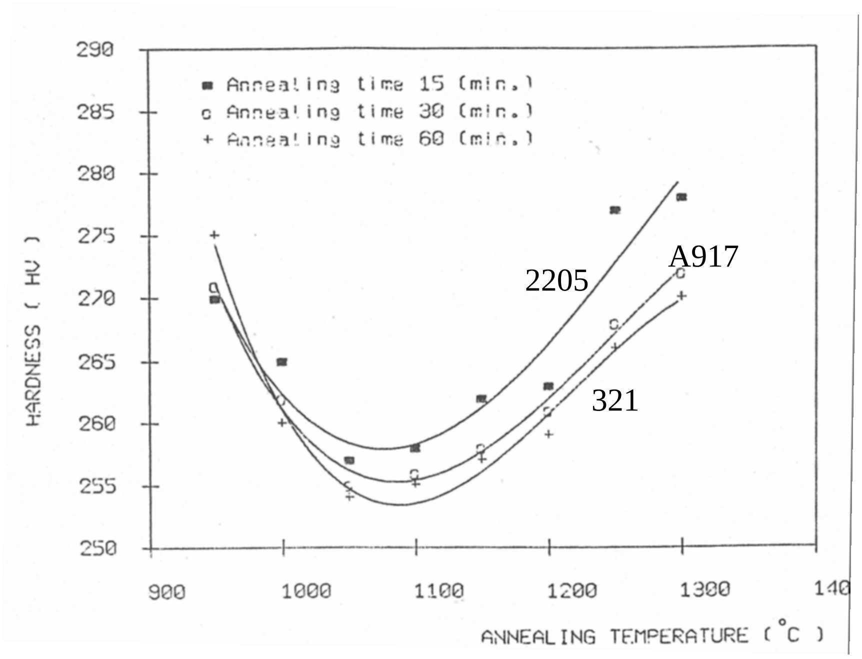


Fig.(8) Effect of the annealing temperature on Vickers hardness for the duplex stainless steel (2205) at various holding times.

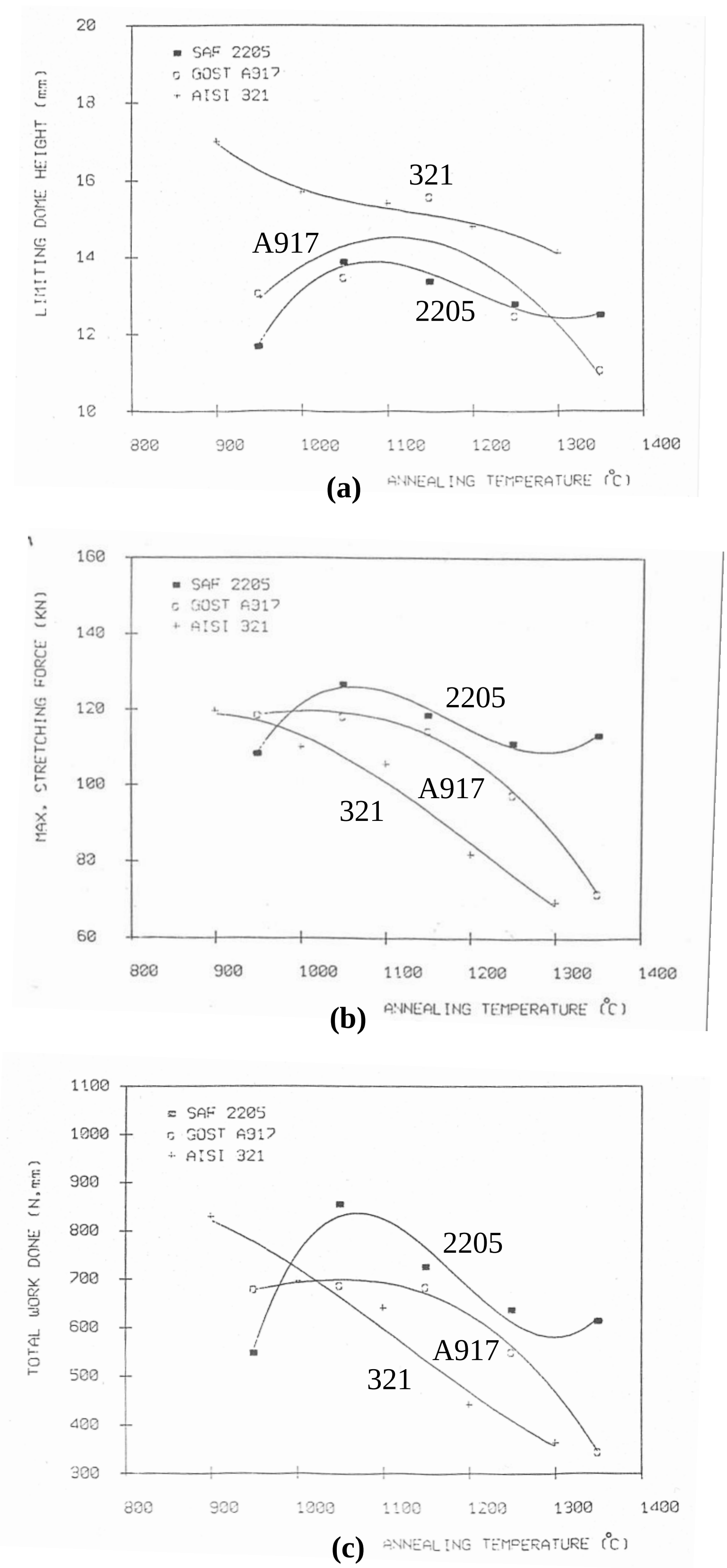


Fig.(9) The effect of the solution annealing temperature on the (a) limiting dome height, (b) maximum stretching force, and (c) total work done for the three alloys quenched by water.

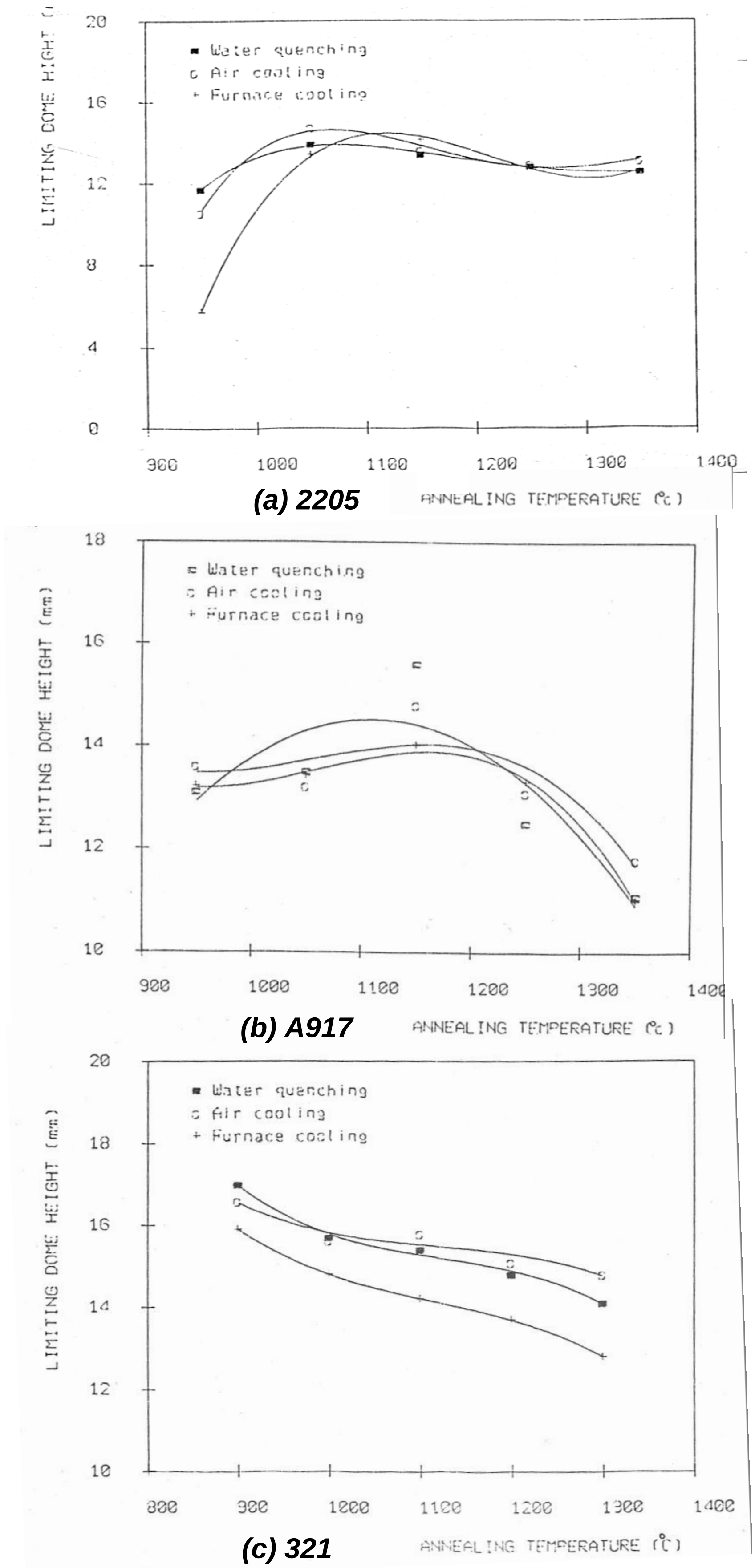


Fig.(10) Effect of the annealing temperature on the limiting dome height for the three alloys at various cooling medians

REFERENCES

1. PLAUT, T. L., HERREA, C., MARIBEL, D. E., RIOS, P. R., and PADILHA, A., F.,"A Short Review on Wrought Austenite Stainless Steels at High Temperatures: Processing, Microstructure, Properties, and Performance", Materials Research (Brazil), vol. 10, N0.4, 2007.

2. ALVAREZ-ARMAS, I., "Duplex Stainless Steels :Brief History and Some Recent Alloys", Recent Patents on Mechanical Engineering, pp.51-57, 2008.

3. Stainless Today, Stainless Steel Back to Basics, Materials Reports, 1987.

4. METALS HANDBOOK, ASM, vol.3, pp.l 138, 1985.

5. PETERSON, S. F, MATAYA, M. C., and MATLOCK, D. K., "Formability of Austenitic Stainless Steels", JOM Journal of the Minerals, Metals, Materials Society, vol.49,pp.54-58, 2008.

6. ANDRADE, M. S., GOMES, O. A., VILELA, J. M. C., SERRANO, A. T. L., and de MORAES, J. M. D., "Formability Evaluation of Two Austenitic Stainless Steels", Journal of the Brazilian Society of Sciences and Engineering, vol. XXVI, No.1, pp.47-50, 2004.

7. ALVAREZ-ARMAS, I., "Formability of High-Alloy Dual-Phase Cr-Ni Steels", Steel Research International, vol.75, No.4, pp.266-273, 2004.

8. TALYAN, V., WAGONER, R. H., and LEE, J. K., "Formability of Stainless Steels", Metallurgical and Materials Transactions A, vol. 29, No.8, pp.2161-2172, 1998.

9. ERIKSSON, L., HARJU, E., KORHOEN, A., and PISCHOW, K.,"Formability and corrosion resistance of TiN-coated stainless steels", Surface and Coating Technology, 53,pp.153-160,1992.

10. MARQUES, M. J. M. B., and BAPTISTA, R. M. S. O., "Formability Characterization of Austenitic Stainless Steel"Journal of Materials Processing and Technology, vol. 32, 1-2, pp. 233-242, 1992.

11. Schedin, E.," Forming Stainless Steel", www.outokumpu.com

12. WEIBULL, I., Material and Design, 8, pp.35, 1987.

13. SOLOMON, H. D. and DEVINE, T. M., JR, Proc. Conf. on "Duplex Stainless Steel", (ed. LULA, R. A.), Metals Park, Ohio, ASME Paper No. 8201-089, pp.693, 1983.

14. ECKENROD, J. J. and PINNOW, K. E., Proc. Conf. on "New Development in Stainless Steel Technology", (ed. LULA, R. A.), Metals Park, Ohio, ASM, Paper No.8410-029, pp.77,1985.

15. FLOREEN, S. and HAYDEN, H. W., Trans. ASM, 61, pp. 489-499,1968.

16. DEVINE, T. M., Acta. Metall., 36, pp. 1491, 1988.

17. SLEB, G. H. and SCHWAAB, D., Proc. Conf. on "Duplex Stainless Steel", (ed. LULA, R. A.), Metals Park, Ohio, ASM, Paper No. 8201-002, pp.15, 1983.

18. REDMOND, J.D., Chemical Eng., 24, pp.103, 1986.

19. MATYHEWS, M. J., the Metallurgist and Materials Technologist, 14, pp.205,1982.

20. MYERS, L. P., "Handbook of Stainless Steels" McGraw – Hill Book Co., Chapter 11, 1977.

21. JOHN, C., and TVERBERG, P. E., "The Role of Alloying Elements on the Fabricability of Austenitic Stainless Steels", www.csidesigns.com/tech/fabtech.pdf

22. ABBASI, S. M., and .SHKUHFAR, A., "Improvement of Mechanical Properties of Cr-Ni-Mo-Cu-Ti Stainless Steel with Addition of Vanadium", Journal of Iron and Steel Research, International, vol.14, 6, pp. 74-78, 2007.

23. GONZALAEZ, B. M., B, CASTRO, C. S. B., BUONO, V. T. L., VILELA, J. M. C., MORAES, J. M. D., and MANTEL, M. J., "The influence of Copper addition on the Formability of AISI 304 Stainless Steel", Marterials Science and Engineering A, vol. 343, 1-2, pp. 51-56, 2003.

24. ABDULLAH, M. A., M.Sc. Thesis, Department of Engineering Production and Metallurgy, University of Technology, Baghdad, Iraq, 1990.25

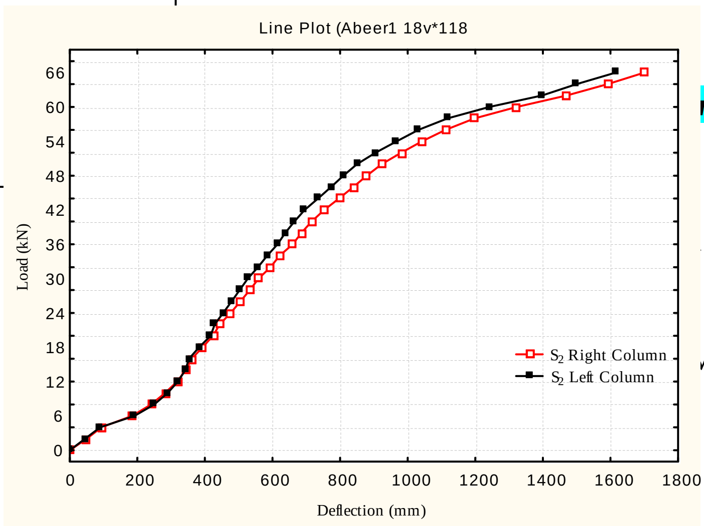
25. FARGAS, G., ANGLADA, M., and MATEO, A.,"Effect of Annealing Temperature on the Mechanical Properties, Formability, and Corrosion Resistance of Hot-rolled Duplex Stainless Steel", Journal of Materials Processing Technology, vol. 209, Issue4, pp.1770-1782, 2009.

26. PADILHA, A.F., PLAUT, R. L., and RIOS, P.R., "Annealing of cold-worked austenitic stainless steels", The Iron and Steel Institute of Japan (ISIJ), vol. 43, No.3, pp.135- 143,2003.

27. LAI, J. K. L., WONG,K.W., and LI, D.J., "Effect of Solution Treatment Transformation Behaviour of Cold-rolled duplex Stainless Steels", Journal of Materials Science and Engineering A, vol. 203, 1-2, pp.356-364,1995.

28. HENSLEY, W. E., "Handbook of Stainless Steels", McGraw-Hill Co., Chapter 12, 1977

29. HAGEN, I., and KELLER, M., Proc. Conf. on "Duplex Stainless Steels", (ed LULA, R. A.), Metals Park, Ohio, ASM, paper No.8201-017, 1983.



B., Materials and Design, 7, pp.33, 1986..

RZGGIANI, R. C., Corrosion, 88, Paper' No.291,

Vol.4, pp.621-650, 1985.

1989.

35. METALS HANDBOOK, ASM, vol.8, pp.20-45, 1985.

36. ANMUAL BOOK OF ATOM STANDARDS, vol.03.01E643-49, pp.627- 629, 1988.

37. UNNIKRISHNAN, K. And MALL, A. K., Mat. Sci. Eng., 94 PP157-181, 1987.

38. HUTCHINSON, W. B., USHIUDA, K., and RUNES, G., Mat. Sci. and Tech., vol. l, pp.728-731, 1985.

39. BERNSTEIN, M. L.and AZAIMŨVSKY, V., Mechanical Properties of Metals", Mir Publishers, Moscow, Chapter5, 1983.

40. NOVAK, C. J., "Handbook of Stainless Steels", McGraw-Hill Co., Chapter 4, 1977.

41. DAVIDSON, R. M., DEVEIL, H. E., and REDMOND, J. D., Process Industrie Corrosion, pp.427-443, 1985.

42. CLOMBIER, L. and HOCHMANN, J.,"Stainless and Heat Resistance Steels", Edward Arnold (Publishers) Ltd., 1967.