Study of Factors Affecting on Formability of Stainless Steel Alloys

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Abstract

Factors affecting on formability of austenitic stainless steel AISI321 and two duplex stainless steels GOST A917, and SAF2205, have been studied in the as-received condition at different strain rates, testing temperatures, and directions. The mechanical properties obtained from tensile testing (strength, ductility, strain hardening index, and strain rate sensitivity), have been chosen as criteria to detect the formability. The values of these criteria are compared with stretching behavior obtained from Olsen test (peak height, maximum stretching force, and total work done). Strain hardening index, elongation, and tensile: yield ratio, were found good criteria which represent formability. Results from tensile and stretching tests of these alloys in the as-received condition, showed that the austenitic stainless steel had the best formability due to its higher ductility and work hardenability. Formability was found to be dependent on strain rate, testing temperature, and rolling direction due to the anisotropy. Stretching tests for the three alloys in the as-received condition, showed that 321 austenitic stainless steel had higher (h-value) , followed by 2205 duplex. Lubrication was found to improve formability by increasing the (h-value) for the three alloys.

Keywords: Austenitic and Duplex stainless steels, Formability, Tensile and Stretching Tests

دراسة العوامل المؤثرة على قابلية تشكيل سبائك الصلب المقاوم للصدأ

الخلاصة

تم في هذا البحث دراسة تأثير معدل الانفعال ودرجة الحرارة والاتجاهية على قابلية تشكيل ثلاث سبائك من الفولاذ المقاوم للصدأ في الحالة المستلمة. أعتمدت الخواص الميكانيكية الناتجة من أختبار الشد (المقاومة، المطيلية، دليل الاصلاد الانفعالي، وحساسية معدل الانفعال) كمعايير لتحديد قابلية التشكيل ومقارنة هذه المعايير مع سلوك السبائك أثناء أختبار المط بحساب قيمة ارتفاع القبة المحدد وأقصى قوة لازمة للمط والشغل الكلي. وأظهرت أختبارات الشد والمط للفولاذ المقاوم للصدأ الأوستينياتي(321) قابلية تشكيل أفضل بسبب قابلية الأصلاد العالية والمطيلية الجيدة. ووجد أن قابلية التشكيل تعتمد على معدل الأنفعال ودرجة حرارة الأختبار وأتجاه الدرفلة الناتج عن تباين الخواص. وأخيرا، بينت أختبارات المط ان ارتفاع القبة المحدد يكون بأقصى قيمة للفولاذ الأوستنايتي ويتبعه الفولاذ المزدوج نوع (2205) وكذلك أستخدام التزييت يحسن من قيمة أرتفاع القبة للسبائك الثلاث.

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Introduction

Formability of a stainless steel varies from one alloy to another depending on its type (austenitic, ferritic, martensitic, and duplex) [1-], and the alloying elements exist in their structure (chromium, nickel, molybdenum, carbon, nitrogen, and tungsten, etc.,) [8-10]. Generally, formability of any metal or alloy is affected by many factors such as strain rate[11-15], temperature [11,16-18], directionality or anisotropy [11, 19-20], and other factors which have no relationship with the forming process (metallurgical factors such as chemical content, microstructure, phases, grain size, and prestraining). Therefore, formability is a complicated property since it deals with intricate engineering cases. Thus, it becomes necessary to study the formability indexes of the stainless steel alloy in order to reach better conditions that yield the optimum formability.

This paper aims to study the formability of three different stainless steel alloys (SAF2205, GOST A917, and AISI321) through many affecting factors: strain rate; temperature; and directionality. While the effect of the metallurgical factors are considered to be the topic of the next paper.. Tensile tests were used as a criterion to detect the formability and to know the mechanical behavior of each alloy by obtaining the strength, ductility, strain hardening index, and strain rate sensitivity.

Also, the behavior of these three alloys has been studied during the stretching test using Olsen test which is considered as a proper criterion to evaluate and compare the stretching ability of the metallic sheets by measuring the peak height at maximum load (near failure).

Experimental Work

Material Condition

In this work, all tests were carried out on two duplex stainless steel alloys (type SAF2205 and GOST A917) and one austenitic stainless steel type AISI321 for comparison purpose since the latter is characterized with a good formability. All these alloys were supplied on the basis of their standards in form of cold rolled sheets in the solution annealed condition. Since, this study is mainly focused on the effect of the mechanical properties on the formability of the austenitic and duplex stainless steels during tensile and stretching tests, 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 [21].

Regarding their solution treatments (annealing), these alloys should first be uniformly heated and hot worked in the range of 950-1230°C, and then cold worked for better dimensional accuracy and proper surface finish, particularly for forming purposes. The austenitic stainless steel is solution annealed in the range of 950-1120°C and rapidly cooled to room temperature, then stabilized in the range of 870-900°C and air cooled, and finally stress relieved by heating to 700°C and air cooled. However, Hensley [22] previously reported that most of the austenitic stainless steel alloys are heat treated by solution treatment at 1100-1200°C and rapidly cooled to room temperature. Concerning the duplex stainless steels, the proper annealing temperatures are in the range of 925-1175°C, depending on the type of the alloy, and then rapidly cooled to room temperature [23]. Larson and Lundqvist [24] proposed that the annealing temperature is in the range of 1020-1100°C for SAF (2205) duplex steel.

The knowledge of the hardening behavior during sheet metal forming is very important since it provides a previous knowledge on the behavior of the sheets at certain forming conditions, the mechanical properties, and the extent of avoiding the stress application that might cause the failure. Accordingly, in order to know the strain hardening behavior of each alloy used in the present work during the forming process (stretching test), three criterions were used [25,26]: the uniform strain in the tensile test (strain up to the maximum load; the strain hardening index (n); and the tensile:yield strength ratio.

Tensile Tests

Tension tests were performed on standard specimens according to the British Specifications (B.S.18) [27]. Specimens of 2 mm thickness were prepared from stainless steel sheets at three directions (angles) with respect to the sheet rolling direction. All tests were achieved using a Tensile Instron 1195 machine with different strain rates(10^{-2} -10^{-5})/sec. At strain rate of (10^{-1} /sec), a tensile test was carried out on another machine type (SHINK) to plot the Load-Extension curves from which the engineering and true stress-strain curves were determined to calculate the properties and different criteria according to certain relationships [28] used in this work (i.e., ultimate tensile strength, yield strength at 0.2% strain, total elongation, uniform elongation, strain hardening index, strain rate sensitivity, and percentage of the area reduction.

Anisotropy Tests

These tests were carried out on specimens for the three steels at different directions (three angles) with respect to the sheet rolling direction at room temperature. The gage length of the test specimen was divided into five regions of 10 mm length each in order to measure the length and width of the test specimen by a measuring microscope of (0.001) mm resolution. Tension tests were then performed at strain rate from ($3.3x10^{-3}$) /sec to 20% strain for alloy SAF 2205 and AISI 321 and to 18% for alloy A917. The length and width of these specimens were measured again after machine stop and releasing their loads.

The normal anisotropy (r), planar anisotropy (Δr) [25,26,29,30] and mean normal anisotropy ($\bar{r}$) [30] values were calculated at three angles of (0^o), (45^o), and (90^o) with respect to the sheet rolling direction. In addition, another criterion (r_m) was calculated and this represents the difference between the maximum and the minimum normal anisotropy value in order to give more obvious picture for tearing direction that can be occurred. This criterion is often used instead of the planar anisotropy criterion [29,31].

Strain hardening Index

This index represents the increase in metal strength at any applied stress and it can be calculated by transferring the empirical equation which is known as Duke's relationship [25,26] to a logarithmic equation and then to a linear equation according to the American Specification (E646-78) [32], And, by using the least square method, the strain hardening index (n) and strength factor (K) were obtained. Then, the strain hardening rate (d $_T$/de) was calculated with the use of strain hardening index (n) definition [28].

Strain rate sensitivity

The effect of strain rate for three tested alloys was studied at room temperature and 100 ^{o}C using strain rates of (10^{-5}- $l0^{-4}$) /sec. After tensile testing till the fracture limit, the true stresses and strains were calculated at different used strain rates. And, a relationship between the logarithm true stress and logarithm strain rate was then plotted at different true strains to determine the strain rate sensitivity (m) [25,26]. Also, the properties and certain criteria for each test were recorded such as the total elongation, uniform elongation, strain hardening index, percentage of area reduction, yield strength, and tensile strength.

Temperature test

Tensile test were carried out at temperatures of 50, 100, 150, 200 and 250^{o}C using a strain rate of ($3.3x10^{-3}$) /sec for the three alloy specimens. A tensile testing machine type (SHINK) equipped with a furnace was used to plot the engineering stress-strain curve. A computer was also linked to this machine to know the effect of the testing temperatures on the properties and criteria used in this work.

Stretching Test

Olesn test was chosen to evaluate and compare the formability of the three tested alloys according to the American Specification (E643) [33]. A die was designed and produced according to this standard specification for the stretching test. In this test, a special blank was firmly held above the die using a blank holder with enough force to prevent the blank from drawing inside the die. The blank of the stretching test was then fixed on the Instron machine base and formed until failure occurred. The stretching process was accompanied with plotting the load-extension (represents the peak height) curve used to calculate the peak height, maximum stretching force, and total work necessary for the stretching process for each alloy.

Specimens from three tested alloys sheets were cut into strips of 80 x 80 mm size and 2 mm thickness and their acute edges were flattened using fine files. Stretching tests were performed for the three alloys by using two blanks. One blank was formed by a grease lubricated punch while the other formed without lubrication The speed of the punch was 10 mm/min during all tests, For alloy SAF2205, other stretching tests were carried out at different speeds (50, 10, 0.5, and 0.05 mm/min) to study the effect of the forming speed on the limited peak height.

Results And Discussion

Chemical compositions

Table (1) shows the chemical compositions for the three alloys tested at three different directions at room temperature 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 [21].

Mechanical properties

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 shown 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 [21].

The engineering stress-strain curves for these three alloys at strain rate
($3.3x10^{-3}$)/sec are shown in Fig.(1). This figure shows that the yield strength values were: S_y(2205) > S_y(A917) > S_y(321) while the ultimate tensile strength were as follows: S_u(A917) > S_u(2205) > S_u(321). The difference in the mechanical properties between duplex (2205) and austenitic (321) steels is due to the difference between their structures since the microstructure of the duplex steel consists of bands of austenite in a ferritic matrix with almost equal amounts of ferrite and austenite when this alloy solution annealed at 1050°C followed by water quench [5,21]. While the microstructure of the austenitic steel consists of angular grains of austenite with titanium carbides [21]. The presence of almost equal content of ferrite and austenite resulted in an increase in the yield and tensile strength more than those in the austenitic and ferritic steels and this often attributed to the Keying Effect phenomenon [34]. In addition to this reason, the nitrogen content in alloy (2205) (exists in a solid solution phase) increased the yield strength due to the solution hardening of the austenitic content [12,35].

The ductility expressed by the total and uniform elongations was lower in duplex steels than that in the austenitic type because
of the existence of the ferrite phase in the duplex steel structure. For same above reason, the hardness of steel (2205) was higher than that for austenitic type (321) and also, the nitrogen content in alloy (2205) induced a higher hardness than that for alloy (A917).

Formability of the Used Alloys:

Effect of Strain Rate:

Figure (2) shows the variation of yield strength, ultimate tensile strength, total elongation, uniform elongation, strain-hardening index, and ultimate tensile:yield strength ratio with strain rate for the three stainless steel alloys at room temperature, respectively. Fig.(2a) exhibits the increase of the yield strength for these alloys with an increase in strain rate [28]. This increase was in a ratio of (12.2%), (11%), and (5.7%) for alloy (2205), (A917), and (321), respectively when the strain rate increased from ($1.6x10^{-5}$)/sec to ($1.6x10^{-2}$)/sec. While for the value of the ultimate tensile, the behavior was different for these alloys and this value slightly increased with increasing the strain rate for alloy (2205) whereas it decreased for alloy (321) as shown in Fig.(2b).The increase of the yield strength with strain rate was proved and interpreted in many studies [13,17,25,26,36] and at different temperatures. Whereas, the ultimate tensile strength variation showed, a decrease with an increase of the strain rate for alloy (321) of the austenitic structure. And, this attributed to the tendency of the strain hardening in this alloy became larger at lower strain rates whereas this trend became smaller at higher strain rates. While the strain hardening in this case implied, the transformation of the austenite to martensite was higher at lower strain rates due to the presence of enough time available for this transformation [17,36]. In such case, the decrease in tensile strength with increasing the strain rate was proved in other studies on the austenitic steel type (304) almost similar to what brought in the present study [17]. And, this interpretation is clearly shown in Figs.(2a) and (2b). The behavior of the duplex steel type (2205) was different and the tensile strength did not show great response by increasing the strain. This was ascribed to the nature of the metallurgical structure containing an amount of austenite and ferrite and the saturation stage of the martensitic transformations was not attained in this case [37].

Figures (2c) and (2d) demonstrate the effect of strain rate on the total and uniform elongations, respectively. The elongations for the duplex alloy (2205) and austenitic (321) alloys increased up to their maximum value at a strain rate of ($1.6x10^{-4}$)/sec and then decreased at the subsequent strain rates. Whereas for alloy (A917), the maximum value of these elongation was at a strain rate ($1.6x10^{-3}$)/sec and decreased later as shown in Figs.(2c) and (2d). The increase of the ductility at lower strain rates followed by a decrease at higher rates for alloys (321) and duplex (2205), could be explained at higher strain rates limits at which the ductility decreased with increasing strain rate due to the thermal effect as interpreted by other researchers who observed in their studies [15,36]. The same phenomenon appeared only at these rates. While, the increase perceived in this study at lower strain rates, as noticed in figures (2c) and (2d), could be interpreted on the basis of inefficient thermal effect at these rates which reduced the ductility by increasing the strain. But, the increase in the ductility accompanied with the strain rate increase, could be generally explained according to many interventions related to the material type and its metallurgical structure and the mode of the dislocations movement

Figures (2e) and (2f) reveal the variation of the strain hardening index value and tensile: yield strength ratio for the three alloys. It can be seen that the maximum value of strain hardening index for alloys (2205) and (321) was at a strain rate of ($1.6x10^{-4}$)/ sec while the maximum value for alloy (A917) was at a strain rate of ($1.6 x10^{-5}$)/sec. And, it is noted that these values were higher at lower strain rates while they decreased with increasing the strain rate. This attributed to the effect of strain rate on the yield strength which led to decrease the strain hardening index [28]. In addition, the low rate of phase transformations from the austenite to the martensite in alloy (321) at higher strain rates resulted in the reduction of the strain hardening index.

Effect of the Temperature

Figures (3a) and (3b) show the variation of the yield and ultimate tensile strengths with the temperature, respectively. It can be seen that the decrease of these strengths with increasing the temperature (except alloy (A917) whose yield strength increased beyond a temperature of 150°C). The behavior of alloy (A917) is thought to be that this alloy is more liable to the temperature embrittlement with temperature increase than the other two alloys due to the brittleness of its higher ferrite content. This means that with increasing the temperature, the brittle sigma and other solid phases initiate to form at 150°C. Thus, the limited temperature for the duplex steel in use must be less than 300°C in order to prevent the brittleness of the ferrite phase [6]. These figures also exhibit the effect of the temperature on the yield and tensile strengths for the three alloys at a strain rate of $(3.3x10^{-3})$/sec where the yield strength decreased in a range of (31.8%), (31.5%) for alloys (2205) and (321), respectively. The reduction of these strengths with the temperature increase, attributed to the temperature effect on the sliding (dislocations movement) since the resulted deformation in the tensile test occurred by the sliding (dislocations movement along the sliding planes) whereas the energy of the thermal activation such as the multiple sliding and the intersecting sliding, allowed the concentrated strains to relieve and then to decrease the strength [28].

Figures (3c) and (3d) reveal the effect of temperature on the total and uniform elongations where each of them reduced with temperature increasing except alloy 2205 whose uniform and total elongations were not significantly affected. And, this was due to the presence of the austenite phase type (FCC) which was sensitive for the ductility increment (increasing the easiness of the dislocations movement in the sliding planes) with increasing the temperature more than that was in the crystalline structure type BCC [28,38], i.e. the existed ferrite in alloy (2205). Regarding the two alloys (321) and (A917), the results of this study are found in agreement with those obtained in previous work by Hecker et al [17] in their testing the austenitic steel at different temperatures. They found that the strain hardening and total elongation decreased when the temperature increased from room temperature (22°C) to 50°C. They attributed that to the large martensitic transformation at 50°C and a 0.25 strain but at higher strains, the saturation of the martensite transformation becomes a reason for the reduction of the strain-hardening rate, leading suddenly to thinning formation at earlier stage and thus causing a reduction in the total elongation. A similar result was determined by Semiatin et al [18] for the austenitic steel. They also noted that the flow stress, strain-hardening rate, and total elongation were high at room temperature and then decreased with the temperature rise.

The change of strain hardening index and the ultimate tensile:yield strength ratio with the temperature are shown in Figs.(3e) and (3f), respectively where the temperature increase caused an evident increase in the strain hardening index value for alloys (2205) and (321) while the reverse induced for alloy (A917) as in Fig.(3e). The similar behavior for alloys (2205) and (321) with increasing the temperature, was also perceived and the value of the strain hardening index and the tensile: yield strength ratio was higher for alloy (321) at all temperatures. The strain hardening index for alloys (321) and

(2205) increased with the temperature because of the higher values of their tensile:yield ratio than that for alloy (A917) over the temperature rise. This means that both alloys exhibited more resistance to deformation (higher strain induced at higher stress) and thus their flow stresses increased owing to the short range obstacles (such as foreign atoms, lattice friction, critical dislocations, etc.) inside the material [25]. The reason of the strain hardening is the stored dislocations inside the material that forms when they pass through other dislocations inside the crystal lattice [25,26]. While for alloy (A917), the strain hardening index reduction with temperature increase indicates less plastic material deformation occurred and the thinning started earlier. This can obviously be explained by the increase of its yield strength as shown in Fig.(3a), a decrease of the uniform and total elongations as depicted in Figs.(3c) and (3d), respectively, and a decrease of the tensile:yield ratio as illustrated in Fig.(3f). The annihilation, rearrangement, and cross slip of the dislocations reduce the hardening rate where they become in equilibrium state with thinning rate [25].Therefore, the alloy (917) appeared to be more brittle at the temperature of 250°C and led this alloy to have a lower formability (which mainly depends on the ductility of the material) in comparison with the alloys (321) and (2205) over the same temperature range. In other words, the brittle behavior of alloy (A917) can be more possibly caused by the precipitation of brittle sigma and phases due to the temperature influence.

Figure (4a) shows the variation of the strain rate sensitivity with the true strain at room temperature. The decrease in the strain rate sensitivity for the three alloys was noted with increasing the true strain. This figure also illustrates that the values of the strain rate sensitivity were lower at all true strains. While, the values of (m) for alloys (321) and (2205) were closer at lower true strains whereas for alloy (2205), these values decreased more than those for alloy (321) at higher strains. It can be seen that at very high strains which the alloy (2205) did not attend, the alloy 321 has a negative value of (m) and this was also observed in other research works in their studies for the behavior of the austenitic steel type (304). Also, this ascribed to the higher amount of the martensite formation for alloy (321) at higher strain rates and this would not be occurred for alloy (2205) which contains a lower amount of ausenite.

The change of the strain rate sensitivity with the true strain at a temperature of 100°C is indicated in Fig.(4b) which reveals a closer behavior for alloys (321) and (2205) but different manner for alloy (A917). At this temperature, the (m) values for these alloys were positive at all true strain values. The reason of this increase is attributed to the limitation of the austenite transformation to martensite at this temperature and it is well known that the amount of transformation is higher as the temperature decreases [17].

The effect of temperature on the true stress for alloys (2205) and (A917), is demonstrated in Fig.(5), respectively, It can be seen that the temperature increase resulted in a reduction in the true stress for these alloys except for alloy (A917) at a temperature of 250 °C at lower true strain (0.0676). It was also observed that the true stress decreased with the temperature increase [13,25,26,28]. And, this attributed to above same reason while the increase of the true stress at 250 °C for alloy (A917) imputed to the occurrence of the brittleness at this temperature. And, this was seen in Fig.(3) as well. Whereas, pitting for voids at 250°C was less as compared with that at 100°C.

Effect of the Directionality (Anisotropy)

Table (3) shows the tensile properties at different angles with respect to the sheet rolling direction for alloys (2205), (A917), and (321) at a strain rate of $(3.3x10^{-3})$/sec and at room temperature. The mean value of these properties was calculated at angles (0^o), (45^o), and (90^o) with respect to the rolling direction. While, tables (4) and (5) clarify the values of the normal anisotropy (r), the planar anisotropy (Δr), the mean normal anisotropy ($\bar{r}$), and the criterion (r_m) for alloys (2205), (A917), and (321). Figure (6) reveals the true stress-strain curve for the three alloys at different directions (angles) with respect to the sheet rolling direction.

According to Tables (3), (4) and (5) and Fig.(6), the values of these properties slightly varied at the different angles with respect to the sheet rolling direction and it was more likely expected that the mechanical properties for the duplex steel might be dissimilar at different direction [39]. But, the results of the tensile tests indicated that there was less directionality in the properties for the two duplex alloys of this study (Figs.(6a) and (6b)) while the alloy (321) pointed out no directionality as shown in Fig.(6c), And, this little difference in this manner when varying the direction for the two duplex alloys ascribed to the difference in the metallurgical structure for each of them since the austenite affected by the directionality more than in the ferrite phase [36] and owing to this duplex structure, this directionality appeared [12].

Formability Indexes

Concerning the values of the normal, the planar, and the mean anisotropy for the three alloys which provide a good conception on the drawing formability [40,41] for these alloys as given in Tables (4) and (5). It can be seen that the values of the normal anisotropy for alloys (2205) and (A917) were $r_0{}^o > r_{90}{}^o > r_{45}{}^o$ while for alloy (321) $r_0{}^o > r_{90}{}^o > r_{45}{}^o$. And, as clarified in Table (5), the best value of the mean normal anisotropy ($\bar{r}$) was for alloy (321) followed by the value for alloy (A917) and finally for alloy (2205). According to the priority sequence for these alloys, the values of the planar anisotropy were as follows: alloy (321), (A917), and eventually (2205). This was owing to the high strain hardening for alloys (321), and (A917) and this increased the formability in drawing [41].

The Mechanical Behavior during the Stretching Test

Table (6) shows the variation of the limit peak height (h-value), the maximum stretching force, and the total work done for the three alloys with and without using lubrication during the stretching test. It was appeared that the increase in the limited peak height and the total work done for all alloys was in using the

lubrication but the reverse occurred with the maximum stretching force. The reason of this was due to the reduction of the resulted in friction between the punch and the blank surface. Therefore, it can be said that the stretching formability improved by using the lubrication during the stretching test as well as the decrease of the required stretching force [26]. Figure (7) reveals the force-extension (representing the instantaneous peak height) curve for the three alloys in the as-received condition. And according to this figure, it was observed that the values of the limited (h-values) for the three alloys were as follows: $h_{(321)} > h_{(A917)} > h_{(2205)}$.
The reason of that can be interpreted to the high strain hardening and high ductility of the austenitic steel [37] while the cause for the decreasing the values of the limited peak height (h-value) for alloy (A917) was due to the lower ductility of this alloy.

Table (7) illustrates the effect of the forming speed on the mechanical behavior of alloy (2205). It can be seen that for alloy (2205), the values of the limited height, maximum stretching force, and the total work done for this alloy were slightly affected with the forming speed [26].

Conclusions

1- The values of the strain hardening index, the tensile:yield strength ratio, and the percentage of the elongation, can be considered as good criteria for the formability of the stainless steel alloy.
2- The yield strength of duplex steel alloys is higher by an amount of (2) to (3) of that for the austenitic stainless steel.

Also, the yield strength of the duplex 2205) is higher than that for other duplex type (A917) while the ductility of the duplex steel is lower by an amount of(2) to (3) of that for the austenitic steel.

3- The mechanical properties of the three alloys vary with the change of strain rate, where the percentage of elongation decreases with increasing the strain rate while the reverse takes place for the yield strength of these alloys. Both values of strain hardening index and tensile: yield strength ratio decrease by increasing the strain rate.
4- The yield, tensile strengths, and the percentage of elongation decrease with temperature increase for the three alloys whereas the value of the strain hardening index for alloys (321) and (2205) increased by increasing the temperature.
5- Stretching test shows a good formability of the austenitic steel (321) followed by that for the duplex steel (2205) and then the duplex (A917) steel

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

Element (wt %)	SAF (2205)	Standard SAF (2205) [21]	GOST (A917)	Standard GOST (A917) [21]	AISI (321)	Standard AISI (321) [21]
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 and 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) Mechanical properties for the three stainless steel alloys at different angles with respect to the sheet rolling direction , at room temperature , and strain rate of 3.3 x 10^{-3} /sec.

Angles (Deg.)	Yield strength S_y (MPa)	Tensile strength S_u (MPa)	Total Elong. (%)	Uniform Elog. (%)	Strain hardening Index (n)	Strength factor (MPa)
Alloy SAF (2205)						
0	580.6	820.5	35.4	30.6	0.216	1412.3
45	564.5	786.3	34.8	29.2	01959	1308.4
90	614.7	841.2	33	26.6	0.1883	1381.3
Average	586.6	816	34.4	28.8	0.2	1367.3
Alloy GOST (A917)						
0	521.9	828.3	19.2	17.4	0.333	1696.8
45	505.8	796.3	22.3	18.4	0.324	1682.7
90	543.2	839.1	19.6	17.2	0.334	1826.3
Average	523.6	821.2	20.3	17.6	0.33	1768.6
Alloy AISI (321)						
0	243.2	595	65.6	62	0.3542	1157.1
45	242.5	582	71.2	66.8	0.3594	1141.7
90	260	596	71.2	66.8	0.3547	1161.4
Average	248.5	591	69.3	65.2	0.3561	1153.4

Table (4) Normal anisotropy for the three stainless alloys at different angles with respect to the sheet rolling direction.

Angles (Deg.)	Alloy SAF (2205)	Alloy GOST (A917)	Alloy AISI (321)
0	0.42058	0.358713	0.84157
45	0.64479	0.49204	0.893665
90	0.47087	0.472588	0.99047

Table (5) Values of the planar and mean anisotropy for the three stainless steel alloys.

Alloy	Planar anisotropy (Δr)	Mean anisotropy ($\bar{r}$)	$r_{(max)} - r_{(min)}$
SAF (2205)	-0.19906	0.38406	0.2242
GOST (A917)	-0.076389	0.453845	0.1333
AISI (321)	-0.06564	0.90254	0.1588

Table (6) The limit peak height, maximum stretching force, and the total work done with and without using lubrication during the stretching test.

Alloy	Limited peak height, (mm)	Max. stretching force, (KN)	Total work done, (N-m)
With lubrication			
SAF (2205)	**16.3**	**138.8**	**1140.8**
GOST(A917)	**14.8**	**119.75**	**943.4**
AISI (321)	**19.3**	**120**	**1195**
Without lubrication			
SAF (2205)	**15.23**	**139**	**1008.3**
GOST (A917)	**13.3**	**119.75**	**804.5**
AISI (321)	**18.6**	**120**	**1123.8**

Table (7) The limited peak height, maximum stretching force, and total work done for alloy SAF (2205) at different forming speeds

Forming speed (mm/min)	Limited peak height, (mm)	Max. stretching force, (KN)	Total work done, (N-m)
50	**15.06**	**138.5**	**1010.2**
10	**15.23**	**139**	**1008.3**
0.5	**14.72**	**131.75**	**921.7**
0.05	**15.2**	**134**	**964.4**

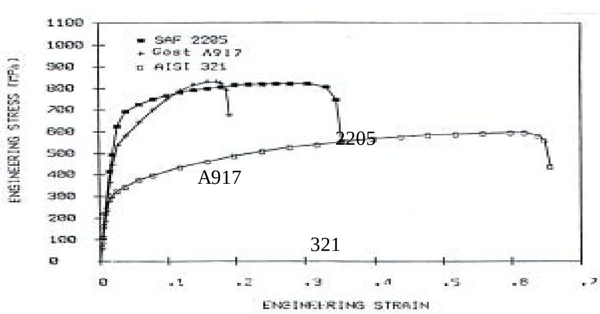

Figure (1) Engineering stress-strain curves for three stainless steel alloys at a strain rate of (3.3x10^{-3})/sec.

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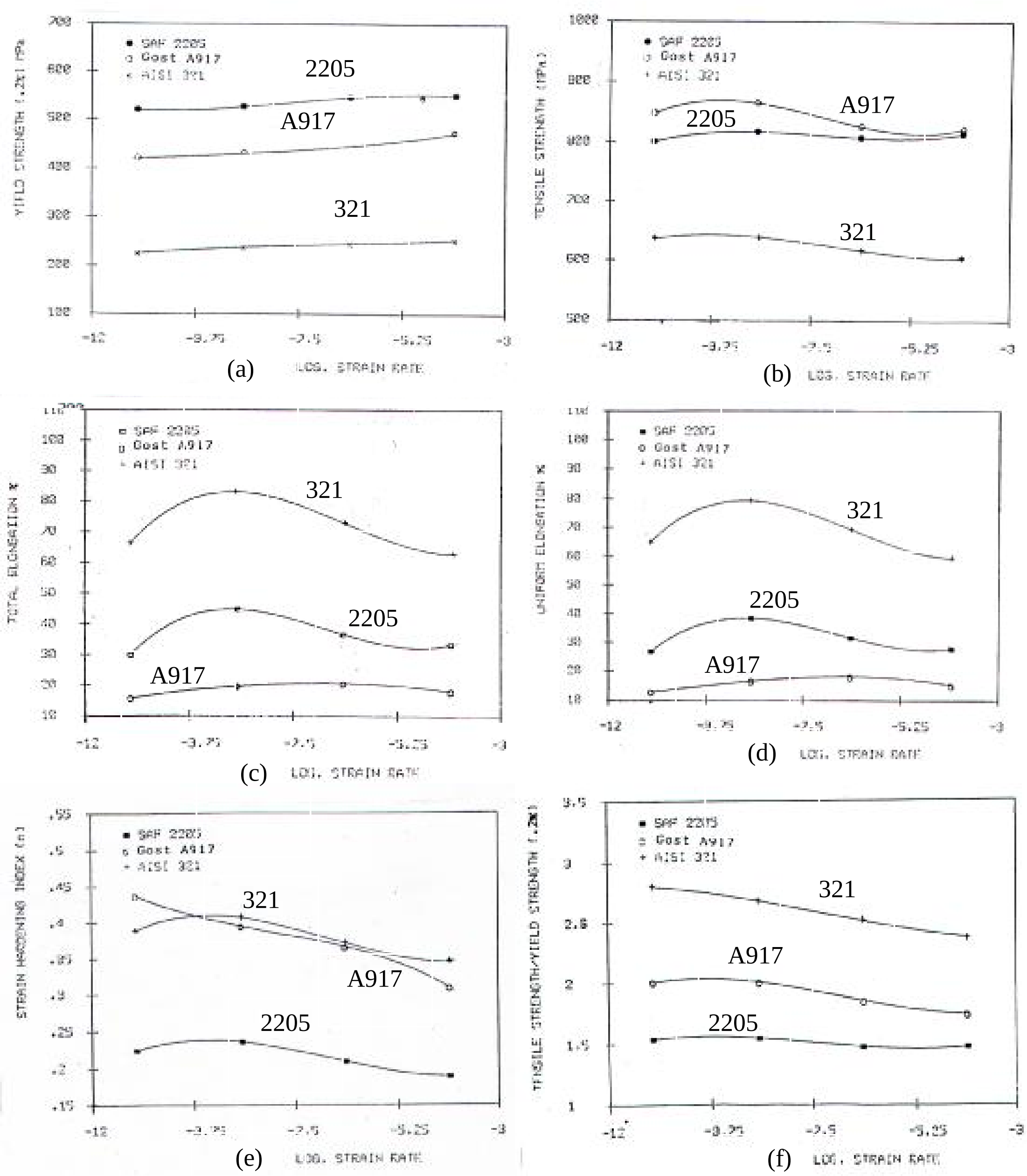

Figure (2) Variation of (a) yield strength, (b) ultimate tensile strength, (c) total elongation, (d) uniform elongation, (e) strain-hardening index, and (f) ultimate tensile: yield strength ratio with strain rate for three stainless steel alloys at room temperature.

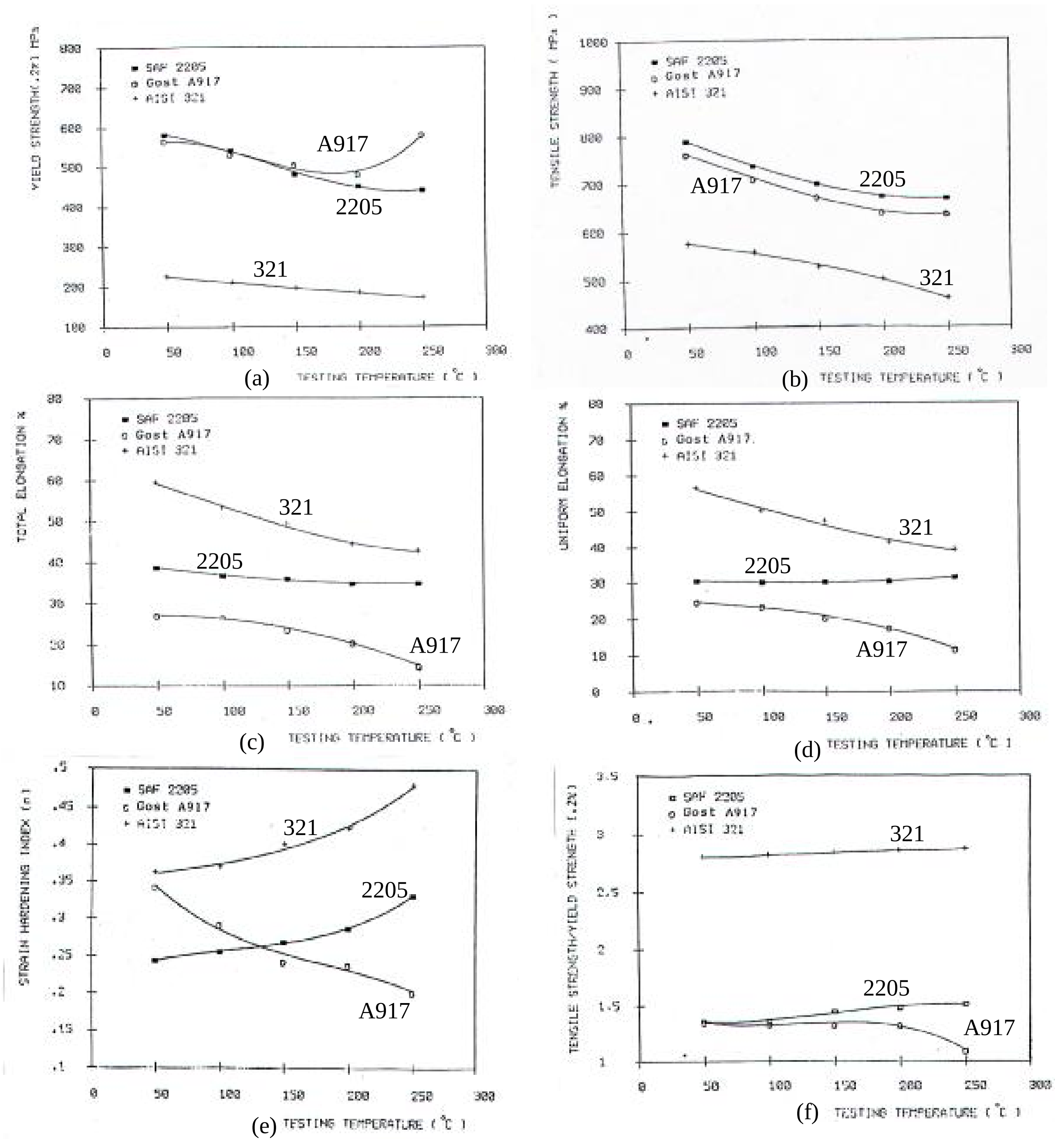

Figure (3) Variation of (a) yield strength, (b) ultimate tensile strength, (c) total elongation, (d) uniform elongation, (e) strain-hardening index, and (f) ultimate tensile: yield strength ratio with the testing temperature for three stainless steel alloys.

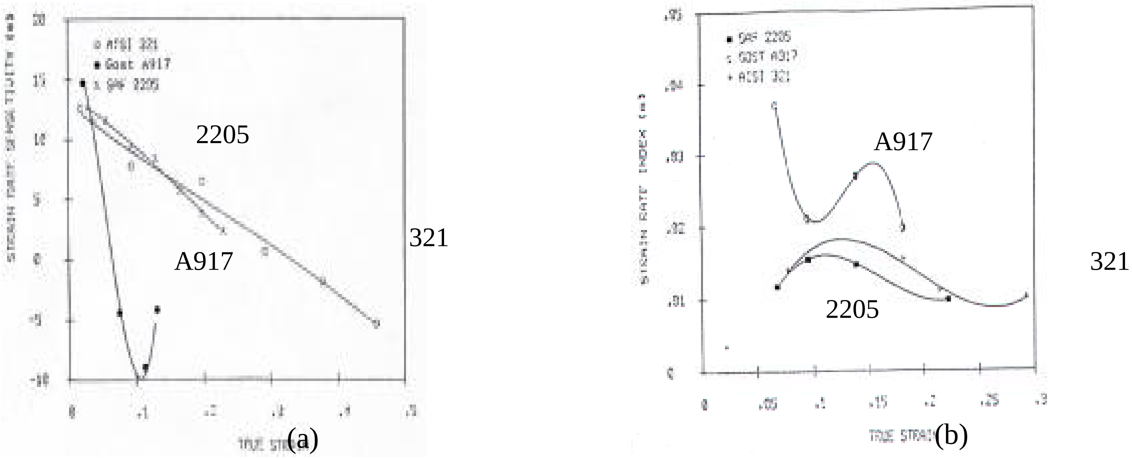

Figure (4) Variation of strain rate sensitivity with true strain for three stainless steel alloys at (a) room temperature and (b) 100°C.

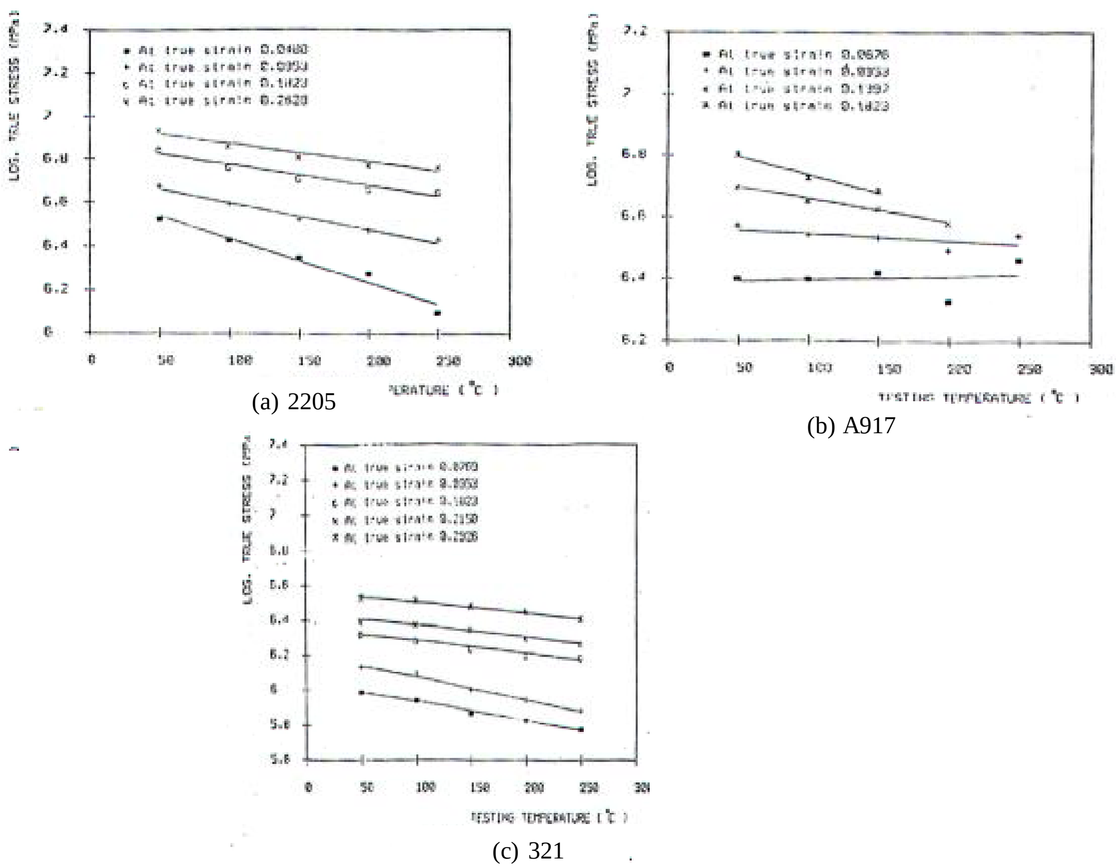

Figure (5) Variation of true stress with testing temperature for three stainless steel alloys for different true strains at a strain rate of ($3.3x10^{-3}$)/sec for: (a) Alloy (2205) b) Alloy (A917) (c) Alloy (321).

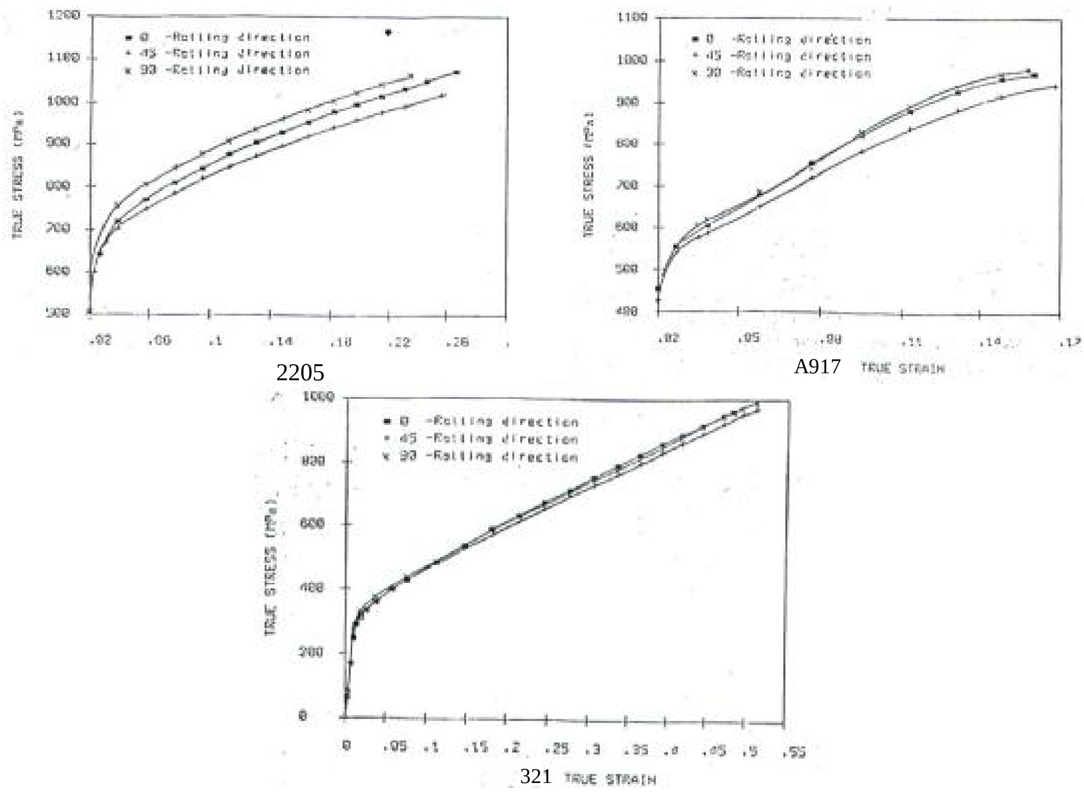

Figure (6) True stress-strain curves for three stainless steel alloys at different rolling directions (angles) and at a strain rate of ($3.3x10^{-3}$) /sec for : a) Alloy (2205) b) Alloy (A917) c) Alloy (321).

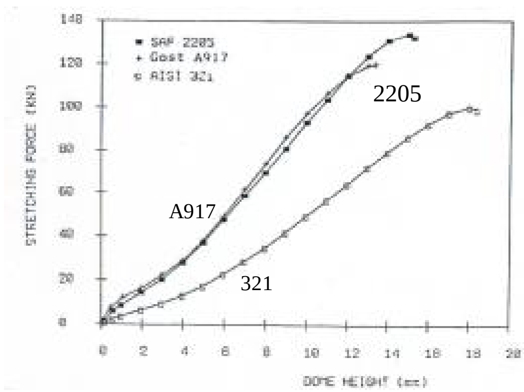

Figure (7) Force-displacement (instantaneous peak height) for three stainless steel alloys.