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Yield Strength Estimation For Stainless Steel Using Plane Strain Compression Test

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Abstract: Plane strain compression test data for various stainless steel materials (AISI316SS, AISI316L, AISI304 and HCSS316) were analysed with the aim of obtaining the relationship describing the yield strength of each material as a function of the deformation variables (strain rate and temperature). Previous results of hot plane strain compression tests at the temperature range of 900ºC to 1200ºC and strain rate of $0.001s^{-1}$ to$100s^{-1}$ were used as input data for the FORTRAN program developed. The program generated stress-strain equations, and determined the yield strength due to load and torque for t he different materials. Stress-Strain linear equations for peak stress (σ_p) and stress to 0.1 or 0.15 strain were obtained to describe all the materials of different compositions while their peak strain ($\in_p$) equations were peculiar to these materials. The yield strength values obtained when plotted against $\log_{10}Z$ started from specific values of Zener-Hollomon parameter (Z) and rose to a peak before decreasing to a specific value (for that due to load and torque).

Key words: yield strength, stainless steel, plain strain compression, Zener-Hollomon parameter.

INTRODUCTION

Yield strength is the stress required to produce a small specified amount of plastic deformation, which is considered as not having impaired useful elastic behaviour and which represents the practical elastic strength for materials having a steady rise to a peak value and a slight gradual knee decrease. In yield strength estimation, the flow stress needs to be considered. The flow stress of a metal is influenced by two factors: factors unrelated to the deformation process such as chemical composition, metallurgical structure, phases, grain size, segregation, prior strain history; factors explicitly related to the deformation process such as temperature of deformation, strain and strain rate.

Stainless steel is a generic name commonly used for that entire group of iron-based alloys, which exhibits phenomenal resistance to rusting and corrosion because of chromium content. The metallic element chromium (Cr) was formerly used in small amount to strengthen steel until it was later discovered that contents of Cr exceeding ten percent, with carbon (C) held suitably low, makes iron effectively rust proof. Other alloy elements, notably nickel (Ni) and molybdenum (Mo), can also be added to the basic stainless composition to produce both variety and improvement of properties. The change in mechanical properties with carbon content separates steel into low, medium, and high carbon classifications that are related to the need for formability in manufacturing and strength and toughness for good performance in service.

The two main hot working tests used to determine the resistance to deformation is scaled down test such as rolling, extrusion, forging etc and mechanical test viz, tension, compression, torsion and bending. Tension, compression and torsion have all been adapted for high temperature deformation. Hot torsion testing in which a twisting moment is applied to a solid or tubular sample has been accepted worldwide. At strain rate of 10^{-3} to$10^{2}s^{-1}$, measurements of flow stress were obtained (Aiyedun, 1999).

Plane strain compression test is more suitable for hot working studies since the stress system is closer to those found in deformation processing (McQueen and Jones, 1975). It offers the advantage of having the same mode of deformation as in rolling (Sellars and Whiteman, 1979). The error introduced into the stress and strain calculations during the use of this method is small due to the small change of geometry in contact with the working tools.

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Research shows no instability associated with dynamic recrystallisation for the plane strain tests (Sellars and Whiteman, 1979). Results by Barbosa (1983) showed that the kinetic of recrystallisation after deformation in plane strain compression are strongly position dependent.

Other research (Dieter, 1986) on titanium alloys suggests that a very strong strain gradient developed in plane strain compression. Work by Hand, *et al* (2000) described the creation of high angle boundaries, in specific regions, after high strains in aluminium and tantalum (Gray *et al*, 2005) deformed under plane strain compression at high temperature.

In this work, experimental data from hot compression testing is used to obtain the hot strength of stainless steel because it covers adequately the deformational range of interest, strain rate (0.001-$5.0s^{-1}$) and the temperature range (600-1201°C) at constant rate. Computer program was developed to generate stress-strain equations which are used to determine the yield stress and yield strength due to load and torque for the different materials.

1.2 Stress-strain Theory:

These are related terms used to define the intensity of internal reactive forces in a deformed body and associated unit change of dimension, shape, or volume caused by externally applied forces.

Stress is a measure of the internal reaction between elementary particles of a material in resisting separation, compaction, or sliding that tends to be induced by external forces. Total internal resisting forces are resultants of continuously distributed normal and parallel forces that are of varying magnitude and direction acting on elementary areas throughout the material. These forces may be distributed uniformly or non-uniformly. Stresses are identified as tensile, compressive, or shearing according to the straining action.

Strain is a measure of deformation such as linear strain and shear strain. The strain associated with stress is characteristic of the material. Above a critical stress, both elastic and plastic strain exists. Inelastic strain reflects internal changes in the crystalline structure of the metal. Increase of resistance to continued plastic deformation due to more favourable arrangement of the atomic structure is called strain hardening.

1.3 Flow Stress Versus Strain Rate:

Following an examination of stress- strain behaviour over a wide range of different hot working conditions, it is usual to report a number of curves as typical examples and characteristic values of the flow stress as functions of temperature and strain rate. In order to correlate data at different temperature, the Zener-Hollomon parameter (Z) is used which is found to be related to strain rate and temperature by the equation

$$Z = \dot{\varepsilon} \exp(\frac{Q}{RT}) \tag{1}$$

where

$\dot{\varepsilon}$ - strain rate

Q - activation energy kJ/mol
R - gas constant= 8.13J/°K
T - absolute temperature, °K

If the same value of activation energy is found for both creep and hot working as in aluminium, this parameter can be used to correlate data over many orders of magnitude of strain rate. However, if the activation energy varies, such a parameter can only be used in a limited range. A relationship which is particularly useful for correlating stress, temperature and strain rate under hot working conditions was proposed by Sellars and Tegart (1972) as

$$\dot{\varepsilon} = A(\sinh\alpha\sigma)^n \exp(-Q/RT) \tag{2}$$

where A,α and n are experimentally determined constants and Q is an activation energy. At low stresses ($\alpha\sigma < 0.8$), Eq.2 reduces to a power relation such as is used to describe creep behaviour.

$$\dot{\varepsilon} = A_1\sigma^n \exp(-Q/RT) \tag{3}$$

and at high stresses ($\alpha\sigma$ > 1.2) it reduces to an exponential relation

$$\dot{\varepsilon} = A_2 \exp\beta\sigma \, e^{(-Q/RT)} \tag{4}$$

The constant α and n are related by

$$\beta = \alpha n \tag{5}$$

so that α and n can be simply determined from tests at high and low stresses.

Strain-rate experiments with steel have shown a semilogarithmic relationship between the lower yield point and the strain rate (Aiyedun and Lawal,2002).

$$\sigma_0 = k_1 + k_2 \log_{10} \dot{\varepsilon} \tag{6}$$

MATERIALS AND METHODS

Based on equations (1-6) and from the data obtained from the plane strain compression test as given in Table 1-4 (Colas, 1983; Sellars and Tegart,1972; Aiyedun, 1984), equations were generated which describe the peak stress ($\sigma_{p)}$, stress at 0.1 strain ($\sigma_{0.1)}$ against $\log_{10}$ Z and peak strain ($\in_p$) against Zener-Hollomon parameter respectively for all values of Z. Set of data obtained for each strain level was fitted by a straight line using the least square method. FORTRAN codes were developed to generate the relationships.

2.1. Experimental Data Obtained From Plane Compression Tests:

Table 1: Stress-Strain Data for AISI 316SS (Colas, 1983) (D1).

Temperature(K)	Stress-0.1 Strain(MPa)	Peak Stress(MPa)	Peak Strain	Strain Rate (S^{-1})	Stress-0.15Strain(Mpa)
1223	227	245	0.33	5.24	185
1223	228	245	0.45	5.24	196
1223	220	251	0.45	5.22	198
1228	212	237	0.45	2.89	198
1228	186	206	0.41	0.50	183
1228	155	168	0.37	0.05	153
1228	180	192	0.36	1.00	160
1228	206	224	0.38	5.28	182
1228	205	221	0.38	5.16	170
1228	189	206	0.35	5.00	180
1228	195	208	0.35	5.00	182
1228	184	200	0.44	5.00	189
1228	186	206	0.38	5.00	166
1228	185	208	0.41	5.42	175
1228	114	128	0.36	0.05	112
1228	151	166	0.37	0.5	145
1228	188	207	0.43	5.37	174
1373	135	152	0.38	1.00	115

Table 2: Stress-Strain Data for AISI 316L (Colas, 1983) (D2)

Temperature(K)	Stress-0.1 Strain(MPa)	Peak Stress(MPa)	Peak Strain	Strain Rate (S^{-1})
1183	219	295	0.37	5.30
1183	248	284	0.40	2.14
1183	268	270	0.41	1.04

Table 3: Stress- Strain Data for AISI 304 (Sellars and Tegart,1972) (D3)

Temperature(K)	Stress-0.1 Strain(MPa)	Peak Stress(MPa)	Peak Strain	Strain Rate (S^{-1})
1373	153	216	0.70	100.0
1373	138	189	0.60	40.0
1373	99	162	0.55	8.0
1373	92	130	0.45	1.5

The plane strain compression tests experimental data for different materials over a range of 900^{o}C to 1200^{o}C and strain rates from 0.001 to 100s^{-1} as shown in table 1- 4 were analysed and used to obtain the Zener-Hollomon parameter (Z), its logarithm and the peak strain logarithm.

Table 4: Stress- Strain Data for HCSS 316 (Aiyedun, 1984) (D4)

Temperature(K)	Stress-0.1 Strain(MPa)	Peak Stress(MPa)	Peak Strain	Strain Rate (S^{-1})
1373 96.5	105.6	0.24	0.063	
1223 177.8	207.6	0.53	0.680	
1413 110.0	122.0	0.37	0.680	
1250 222.0	250.0	0.41	0.690	
1223 250.7	300.0	0.49	6.460	
1223 192.0	224.0	0.53	0.680	
1223 185.0	220.0	0.43	0.074	

RESULTS AND DISCUSSION

The following equations were generated which describe the peak stress ($\sigma_{p)}$, stress at 0.1 strain ($\sigma_{0.1)}$ against $\log_{10}Z$ and peak strain ($\in_p$) against Zener-Hollomon parameter respectively for all values of Z. Equations 7(a,b,c) to 10(a,b,c) were obtained from the least square method.

$$\sigma_{p\,=\,-486.78\;+\;36.15}\ \log_{10}Z \tag{7(a)}$$

$$\sigma_{0.1\,=\,-447.2668\;+\;33.14160}\ \log_{10}Z \tag{7(b)}$$

$$\in_p\ {}_{0.1643}Z^{0.196} \tag{7(c)}$$

$$\sigma_{p\,=\,-456.11\;+\;35.75}\ \log_{10}Z \tag{8(a)}$$

$$\sigma_{0.1\,=\,-1224.3339\;+\;71.070015}\ \log_{10}Z \tag{8(b)}$$

$$\in_p\ {}_{0.0172}Z^{0.0657} \tag{8(c)}$$

$$\sigma_{p\,=\,-677.69\;+\;45.63}\ \log_{10}Z \tag{9(a)}$$

$$\sigma_{0.1\,=\,-541.5595\;+\;35.458750}\ \log_{10}Z \tag{9(b)}$$

$$\in_p\ {}_{0.0084}Z^{0.0981} \tag{9(c)}$$

$$\sigma_{p\,=\,-601.33\;+\;43.33}\ \log_{10}Z \tag{10(a)}$$

$$\sigma_{0.1\,=\,-471.1501\,+\,34.825923}\ \log_{10}Z \tag{10(b)}$$

$$\in_p\ {}_{0.0208}Z^{0.0699} \tag{10(c)}$$

Since $\in_p = kZ^m$

where k and m are constants, the values of these constants were found to be peculiar to each material (D1 to D4).

The dependence of the maximum stress, stress to strain equal 0.1 or 0.15 and peak strain on the Zener-Hollomon parameter are shown in figures 1, 2, and 3 respectively. Also dependence of the peak stress and stress to 0.1 or 0.15 strain on $\log_{10}Z$ are illustrated in figure 4 and 5. It was observed that the plots of stress versus $\log_{10}Z$ for all the materials have their points lying within a bounded region which is in consonance with work of Aiyedun *et al* (2002).

3.1 Yield Stress and Yield Strenght Determination:

Yield stress is the stress value at which behaviour of the metal changes from elastic to elastic-plastic. The yield stress of a material depends on current strain and strain rate as well as the temperature. The yield stress varies from point to point throughout the plastic material.

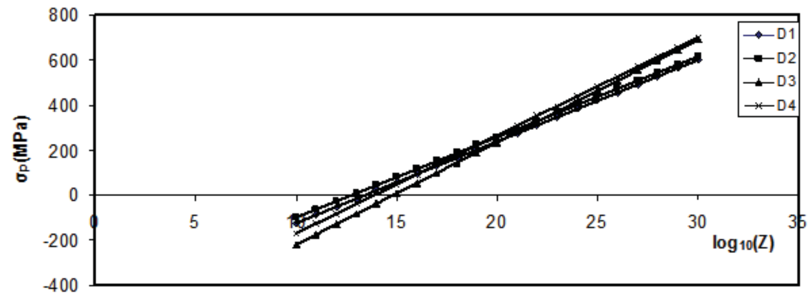

Fig. 1: Dependence of the maximum Stress on the Zener-Hollomon parameter.

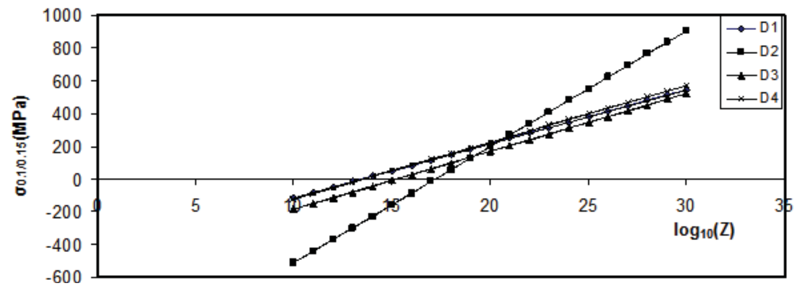

Fig. 2: Dependence of the Stress to strain equal 0.1 0.15 on the Zener-Hollomon parameter.

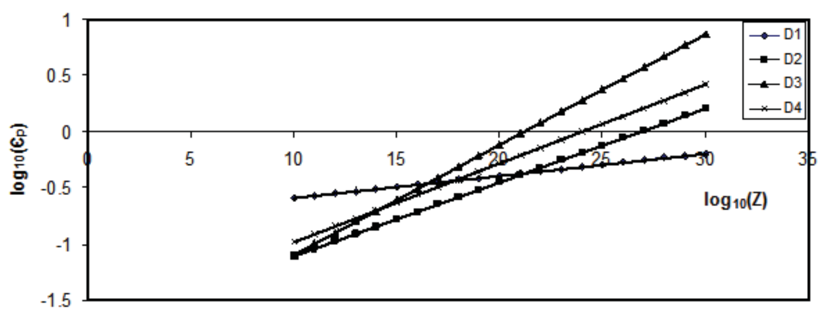

Fig. 3: Dependence of the peak strain on the Zener-Hollomon parameter.

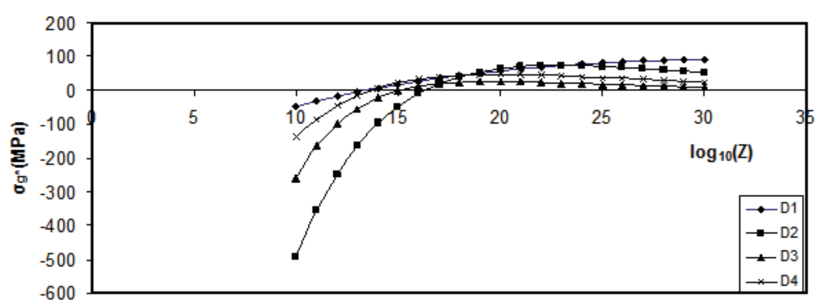

Fig. 4: Dependence of the Yield strength due to load on the Zener-Hollomon parameter.

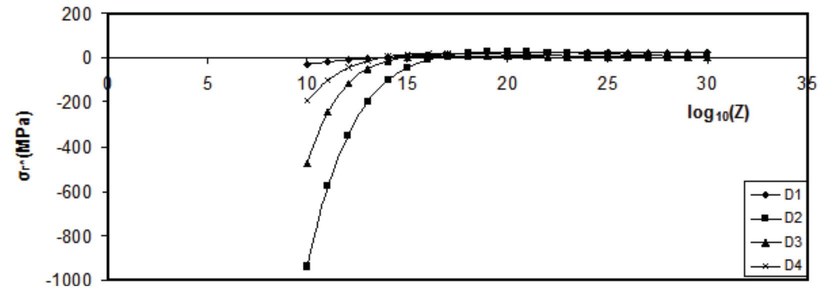

Fig. 5: Dependence of the Yield strength due to Torque on the Zener-Hollomon parameter.

The true yield stresses are defined as
Yield stress due to load

$$\bar{\sigma}_G = 1/\in_m \int_0^{\in} \sigma d \in \tag{11}$$

where:

$$\int_0^{\in} \sigma d \in = 1/2(\sigma_1 + \sigma_2)(\in_2 - \in_1) + 1/2(\sigma_2 + \sigma_3) + 1/2(\sigma_{n-1} + \sigma_n(\in_n - \in_{n-1})$$

Yield stress due to torque

$$\bar{\sigma}_T = 2/\in_m^2 \int_0^{\in} \sigma \in d \in \tag{12}$$

where:

$$\int_0^{\in} \sigma \in d \in = 1/2(\sigma_1 \in_1 + \sigma_2 \in_2)(\in_2 - \in_1) + 1/2(\sigma_2 \in_2 + \sigma_3 \in_3)(\in_3 - \in_{2)} + 1/2(\sigma_{n-1} \in_{n-1} + \sigma_n \in_n)(\in_n - \in_{n-1})$$

The obtained equations (7(a,b,c) to 10(a,b.c)), through the computer program, can be used with reasonable value of Zener-Hollomon parameter (Z) to get $\sigma_{0.1}$ or $\sigma_{0.15}$ and σ_p values. These can consequently be used to plot stress-strain curve in order to predict the equivalent strain to each stress value which is then used to calculate the yield stress value due to load and torque as given in equations (11) and (12). Considering the graphs that relate the yield strength due to load and torque to the logarithm of Zener-Hollomon parameter as shown in figure 4 and 5, these gave almost similar pattern that is expected of any stress-strain curve. It can therefore be said that yield strength Vs $\log_{10}Z$ starts from a specific value of $\log_{10}Z$ and gave plots that rises to a peak value steadily and then decreases to a steady state value.

Aiyedun (1999) obtained that yield strength is related to yield stress by ratio 1: 1.36 in hot rolling at low strain rates (0.0036 - 1.4 sec^{-1}) and temperature range of 600ºC to1200ºC for HCSS316 material. Assuming that this ratio of 1: 1.36 is equally applicable to the other materials by virtue of their rolling temperatures, strain and strain rate, and their observed curve, therefore, the yield strength for the calculated yield stress can be determined using the relationship

$$\bar{\sigma}_{g*} = 1.36\bar{\sigma}_G \tag{12}$$

for yield strength ($\bar{\sigma}_{g*}$) due to load; and

$$\bar{\sigma}_{t*} = 1.36\bar{\sigma}_T \tag{13}$$

for yield strength ($\bar{\sigma}_{t*}$) due to torque

Conclusions:

From this work, the following conclusions can be made:

- for various materials considered in this work, the peak stress (σ_p), stress to 0.1 or 0.15 strain ($\sigma_{0.1\ or}\ \sigma_{0.15}$) and peak strain ($\in_p$) were expressed in terms of the Zener-Hollomon parameter as shown in equations 7(a,b,c) to 10(a,b,c).the stress-strain curve for any value of Z for the individual material can be obtained using these derived equations.
- The peak strain of these materials were peculiar to them i.e $\in_p = kZ^m$ where the constant k and m are peculiar for the different materials compositions.
- Yield strength Vs $\log_{10}Z$ starts from a specific value of $\log_{10}Z$ and gave plots that rises to a peak value steadily and then decreases to a steady state value.
- The calculation of yield stress due to load and torque through the computer program provides a means of predicting experimental rolling loads and torque "through either Sims theory or Bland and Fords theory" for hot rolling at low strain rates. This can be found very useful when comparing the theoretical determination of load and torque to experimental measurement of load and torque.

REFERENCES

Aiyedun, P.O., 1984. A study of loads and torque for light reduction in hot flat rolling at low strain rates. Ph.D Thesis, Sheffield University.

Aiyedun, P.O., 1999. Yield Stress Variation across Thickness for Steel (HCSS316) Specimen Hot Rolled at low Reduction and low Strain Rates. N.S.E Transactions,1st ed., pp: 46-70.

Aiyedun, P.O. and J.B. Lawal, 2002. Yield Strength Estimation for Stainless Steel using Torsional Test, NJEM., 3(1): 69-79.

Barbosa, R.A.N., 1983. Simulation of Hot Working of Austenitic Stainless Steels. Ph.D Thesis, Sheffield University.

Colas, R.O., 1983. High strain rate, High temperature deformation of stainless steel. Ph.D Thesis, University of Sheffield.

Dieter, G.E., 1986. Mechanical Metallugy. 3rd ed. Mc Graw-Hill Book Company. New York.

Gray III, G.T., P.J. Maudlin, L.M. Hull, Q. Kenzuo and S.R. Chen, 2005. Predicting Material Strength, Damage, and Fracture. Los Almos Science, 29: 80-93.

Hand, R.J., S.R. Foster and C.M. Sellar, 2000. Temperature changes during hot plain strain compression testing, Materials Sciences and Technology, 16(9): 442-450.

McQueen, H.J. and J.J. Jones, 1975. Plastic Deformation of Materials, Treatise on Material Science and Technology, Vol.6, ed. Arsenaut. Academic. New York, 395.

Sellars, C.M. and W.J. Tegart, 1972. Hot Workability, International Metallurgic Reviews, 17(158): 1-23.

Sellars, C.M. and J.A.Whiteman, 1979. Recrystallization and grain growth in hot rolling, Metal Science, pp: 187-189.