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A NOVEL METHOD OF EVALUATING FLOW CURVE FOR SS304 FROM LOW COST INDENTATION EXPERIMENTS

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ABSTRACT
Static indentation and compression tests have been conducted at a common strain rate of $10^{-3}s^{-1}$ on SS304 heated to 1273 K held there for 30 min and subsequently cooled in the atmosphere. In the present work an attempt was made in evaluating the Constraint Factor (CF) i.e., the ratio of Meyer Hardness to flow stress as a function of average strain perusing the Meyer hardness data points and flow stress data points at constant strain over a considerable strain range. An attempt was also made in converting Meyer hardness Vs average strain curve to a flow curve in uniaxial tensile/compression test by applying CF obtained from the literature. It has been observed that Meyer hardness Vs average strain curve is matching with flow curve at a CF value of 3.06 for SS304. In addition to this, an effort is made in evaluating the important properties like strain hardening exponent and strength coefficient for SS304 from static indentation and compression tests.

Keywords: static indentation, flow stress, constraint factor, mechanical properties.

1. INTRODUCTION
Advances in the field of materials science have resulted in the improvement of existing materials and the development of new materials along with a variety of new applications. Major branches of engineering, particularly those involved in the design and construction of new mechanical or structural elements, depend on the results of mechanical tests for measurement of mechanical properties. Users want to know various strengths of the materials they are considering and how that strength relates to the practical problems of forming parts. The evaluation of mechanical properties of structural elements plays an important role in material degradation under high temperature and pressure. This demands property evaluation techniques that are simple, non-destructive and suitable for materials ranging from very thin coatings to large volumes such as forged and cast components having complex geometries.

Indentation tests are the most commonly used non-destructive testing procedures in the metal industry and in research because they provide an easy, inexpensive and reliable method of evaluating basic properties of developed or new materials. Indentation hardness tests, in which a plane test surface is plastically indented, are widely used to provide quickly a measure of the flow stress of a material. Consequently, a series of indentations of different sizes can be used to estimate the stress-strain curve of a material. When, for example, there is insufficient material for a stress-strain specimen or machining and bulk deformation of the test piece is undesirable or impossible. Furthermore, for brittle materials, for example ceramics indentation can be a good alternative test because it eliminates the need for expensive tensile specimens. In view of this, an attempt was made in evaluating the CF as a function of average strain for SS304. The flow curve is evaluated using CF from published literature. Finally, important properties like strain hardening exponent and strength coefficient have been evaluated.

2. MATERIALS AND METHODS

SS304 is a versatile and most widely used alloy available in a wide range of products, forms and finishes. It has good corrosion resistance, thermal resistance, low-temperature strength and mechanical properties. The composition of SS304 is given in Table-1 and important properties are given in Table-2.

Table-1. Composition of SS304.

C	Mn	Si	P	S	Cr	Ni	N
0.08	2.0	0.75	0.045	0.03	20.0	10.5	0.1

Table-2. Properties of SS304 from literature.

ρ, Kg/m^3	UTS, MPa	0.2 % YS, MPa	Elongation, %	E, GPa
8000	515	205	40	193

T_m ^0C	C_p,J/Kg^{0}K	K W/m^{0}K	α, μm/m^{0}K
1400-1450	500	16.2	17.2

2.1 Specimen preparation
SS304 samples used in the indentation and compression tests are cut from cold extruded rods of 27mm and 16mm diameter respectively. The SS304 samples were heated to 1273 K held there for 30 min and subsequently cooled in the atmosphere. Test samples are prepared in such a way that the loading direction is same in indentation and compression tests, so that orientation effect is absent and the results are comparable. The size of

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the specimens used in static indentation test is ϕ27x23 mm^2 and compression test is ϕ16x24 mm^2. Top and bottom surfaces have been carefully ground and polished to ensure flatness and parallelism within 1μm. The indenter used in static hardness test is a non-deformable Tungsten carbide (WC) spherical ball of 5mm and 10mm diameter. The hardness of WC ball was 2020 HV, which is about a factor of five higher than the test material.

2.2. Static indentation test

The Static Indentation tests were carried out over a range of loads from 5kN to 30kN on a standard Brinnel hardness tester using a non-deformable Tungsten carbide spherical ball of 10mm diameter. The hardness of the Tungsten carbide ball was HV2020, which is about four times higher than the alloy i.e., SS304 used as a test material to be indented. The diameter of the residual impressions formed during static indentation test was measured using Tool Makers Microscope to an accuracy of ±1μm. The depth of the crater was evaluated using the relation, d = P/ (πW*BHN), in which BHN corresponding to impression dia and applied load is read from standard tables. The Meyer hardness, H_M in MPa based on projected area of the crater and the average strain ε_{av}, equivalent to true strain in uniaxial tensile/compression test experienced by the test material during the process of indentation were evaluated as,

$$H_M = \frac{P}{\frac{\pi}{4}(W)^2} \tag{1}$$

and

$$\varepsilon_{av} = 0.2\,\frac{W}{D} \tag{2}$$

Where, P is load applied in Newton, W is diameter of the crater in mm and D is diameter of the spherical indenter in mm.

2.3. Compression test

In compression test, cylindrical specimens machined to Ø16x24 mm size are compressed at a strain rate of $10^{-3}s^{-1}$ on a floor model computer controlled universal testing machine To minimize friction at the platen-compression specimen interface, graphite powder of 0.1mm thick is used as the lubricant. The load-compression data generated by the testing machine is converted to true compressive stress-strain (σ-ε) data using the following relations,

$$\sigma = \frac{4Pl}{\pi D_0^2 l_0} \tag{3}$$

and

$$\varepsilon = \ln\frac{l_0}{l} \tag{4}$$

Where, P, l are instantaneous load and height and D_0, l_0 are original diameter and height of the compression specimen respectively. Then, stress-strain curves are plotted and true plastic strain, ε_p (also referred as true strain, ε) corresponding to each true stress, σ are noted by drawing number of lines parallel to linear elastic portion of the curve as shown in Figure-1.

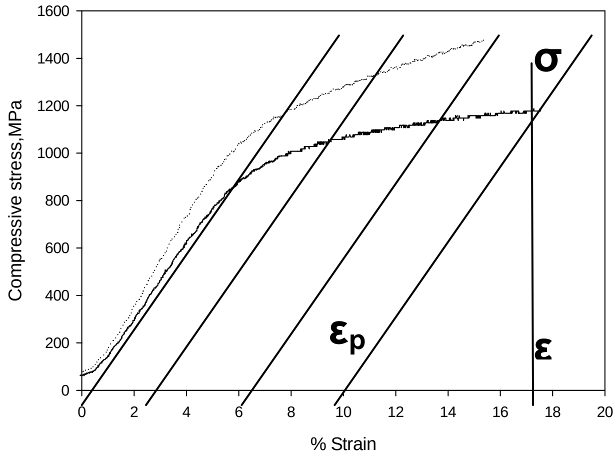

Figure-1. Measurement of plastic strain (ε_p) from true stress-strain curve.

3. RESULTS AND DISCUSSIONS

It is well known that the indentation hardness (Meyer hardness) of ductile materials is about 2.8 to 3.0 times their uniaxial tensile/ compressive flow stress. The above increase in the resistance to plastic flow, under indentation conditions, arises mainly because of plastic zone underneath the indenter is continued within a larger volume of the material which is either elastic or rigid. The plastic deformation underneath is constrained unlike in the uniaxial tension or compressive tests and the factor by which the resistance to plastic flow under indentation condition (i.e., hardness) is higher than the uniaxial flow stress value is defined as the constraint factor (CF) of the material.

3.1. Microstructural observations of SS304

The heat treated specimen was polished, etched using $HCl+HNO_3+CH_3COOH$+Glycerol and examined under optical microscope at 50X. The optical Micrograph shown in Figure-2 reveals grains and grain boundaries. It has been observed that, there is no significant change in microstructure after heat treatment (heated to 1273K, held there for 30 minutes followed by air cooling). It is similar to as in received condition.

3.2. Meyer's hardness Vs average strain

Hardness tests were conducted in the manner described in section 2.2 to obtain H_M - ε_{avg} behavior that is shown in Figure-3. The Meyer's hardness was 1400-2800 MPa, the hardness was found to increase due to strain hardening during the indentation process. The indentation strain hardening index 'p' was estimated perusing the

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Figure-3 using a relation, Meyer's hardness, $H_M = A\varepsilon^p$. The value of was found to be 0.484 and strength coefficient was 3008MPa as mentioned in Table1. During the indentation process, under the application of the load the material undergoes both elastic and plastic deformation. The plastic deformation results in the formation of a permanent impression while the stored elastic energy is released, once the load is removed. The release of elastic energy manifests itself as the relaxation of the indentation shape, once the load is removed.

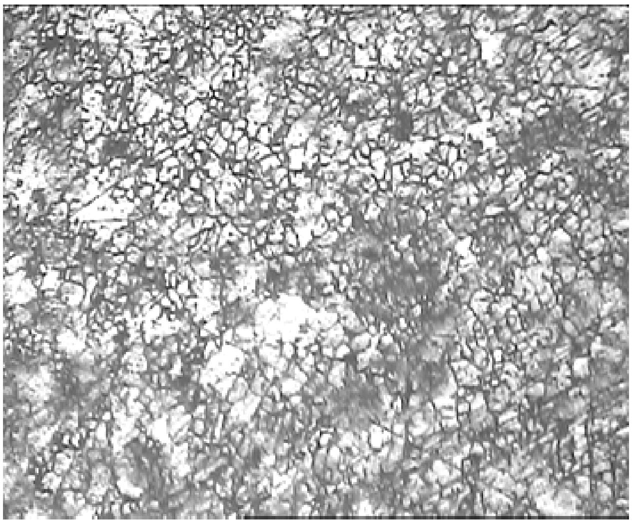

Figure-2. Optical micrograph of SS304.

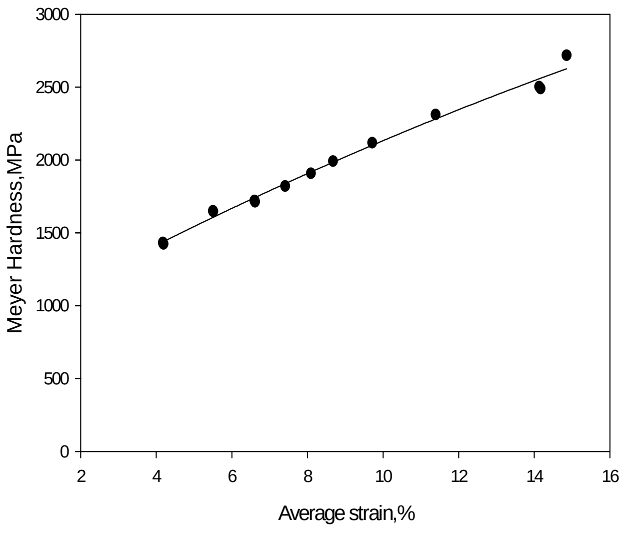

Figure-3. Meyer hardness Vs average strain for SS304.

There are two possible ways in which the indentation can relax to its final shape as shown in Figure-6. Case 1 represents a situation in which the indent relaxes to its final shape, maintaining its geometric similarity, i.e. both the indent diameter W_{ur} and indent depth d_{ur} decreases to new relaxed values W_r and d_r, releases the stored elastic energy on the other hand, case 2 represents the other extreme where all the relaxation occurs only in depth direction, i.e. $d_r<d_{ur}$ while $W_r=W_{ur}$. The actual case most appropriate under the experimental conditions can be identified by calculating the indent diameter W_{cal} from the experimentally determined value of indent depth (which equals d_r) using

$$W_{cal} = D\left\{1-(1-\frac{2d_r}{D})^2 1\right\}^{1/2}$$

The actual case is studied considering the ratio W_r/ W_{cal} where W_r is the measured diameter. If the ratio $W_r/ W_{cal} = 1.0$, case 1 is valid. However, if $W_r/ W_{cal}>1.0$, case 2 is valid and the indent relaxes mainly in the depth direction.

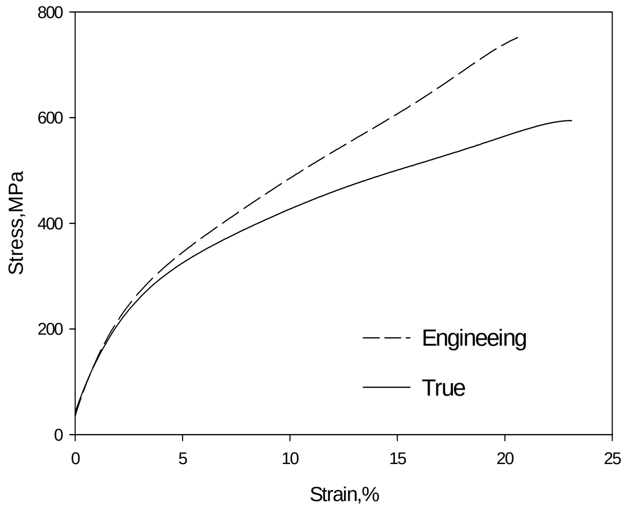

Figure-4. Stress - strain behavior for SS304.

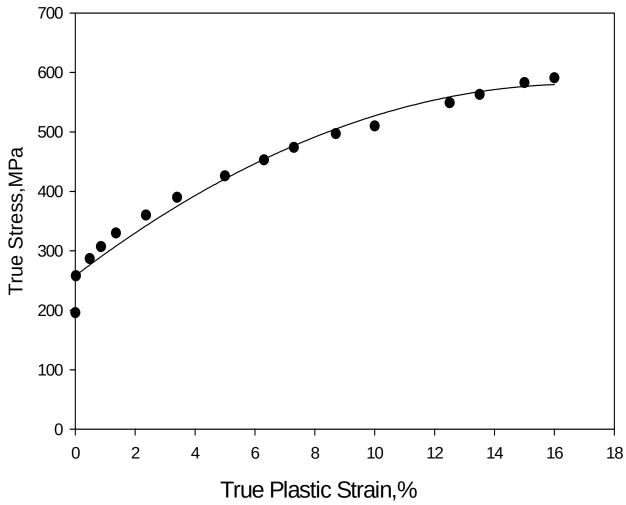

Figure-5. Flow curve for SS304.

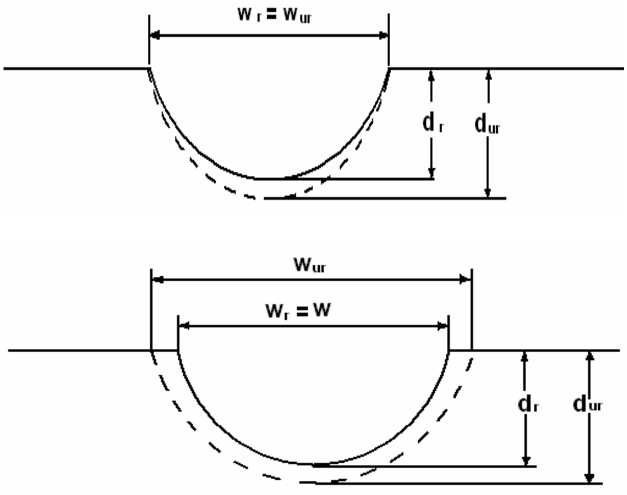

Figure-6. Representation of two modes by which the indentation can relax its shape during the elastic unloading phase.

3.3. Stress-strain behavior

The compression tests were conducted for SS304 on computer controlled UTM in the manner described in section 2.3 and stress-strain data obtained from experiments were plotted in Fig4 & 5. In order to ensure the repeatability of the experimental data, tests were carried out on two different samples and the stress-strain data was analyzed. It has been found that, the repeatability of the data is within ±1%. It reveals that, the slope of the linear portion of the stress-strain curves for SS304 is similar up to elastic limit. It is important to note that, the stress as a function of strain was increasing beyond yield point, indicating strain hardening behavior of the alloy. The experimental yield strength values of the alloy are given in Table 3

3.4. Compressive flow stress Vs true strain

The load- compression data for SS304 presented in the previous section was converted to Flow stress- true plastic strain (σ-ε) as explained in section 2.3 and the σ-ε behavior of an alloy has been plotted in Figure-4. The flow stress was increasing as a function of true plastic strain indicating strain-hardening nature of the test materials.

Table-3. Properties of SS304 obtained from the present investigation.

Indentation test			Compression test			
Strain range %	p	C, MPa	Strain range %	0.2% Yield stress MPa	n	K MPa
5-16	0.48	3008	0-23	197	0.187	333.5

The flow curve obtained was fitted to *Holloman* constitutive equation, $\sigma=K\varepsilon^n$ and best fit values of strain hardening index, 'n' and strength coefficient, 'K' are listed in Table-3.

3.5. Variation of CF with true strain

The pressure required for plastic flow under indentation condition is much larger as compared to uniaxial deformation conditions as the deformation beneath the indenter is 'constrained' by the surrounding material, which is either elastic or rigid. The constraint factor (CF) is defined as the ratio of Meyer's hardness representing mean contact pressure, P_m beneath the rigid ball indenter when the indentation is made, to the uniaxial flow stress. The CF may be evaluated by conducting a ball indentation test at different loads on number of samples as mentioned in section 2.2 and uniaxial tension/compression test at strain rates comparable with that of static indentation test.

The CF values SS304 were estimated as a function of strain using H_M–ε_{av} data points and σ-ε flow curves plotted on a common scale as shown in Figure-7. At each strain, Meyer's hardness H_M was divided by corresponding flow stress, σ at the same strain to obtain the CF. the CF values are plotted as a function of true strain as shown in Figure-8. The CF value was found to increase with increase in strain up to a certain strain called transition strain (ε_{tr}), beyond which the CF value was found to be independent of strain. The ε_{tr} was observed to be at a strain of 8.5%. The CF at fully plastic regime for SS304 was 4.5. The flow curve obtained from the present investigation is matching with the flow curve from the literature as shown in Figure-9.

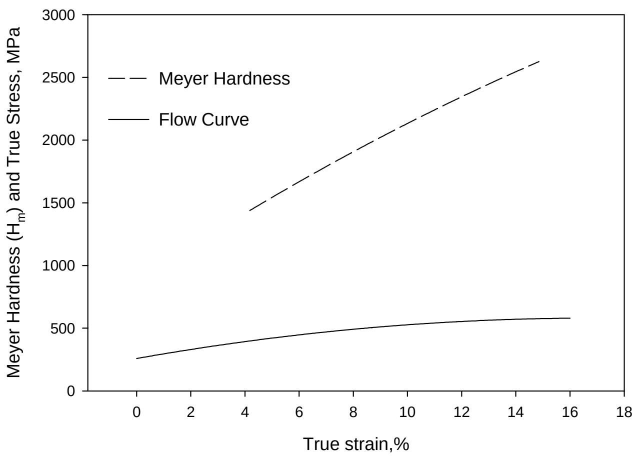

Figure-7. HM -εavg and σ-ε curves to find CF.

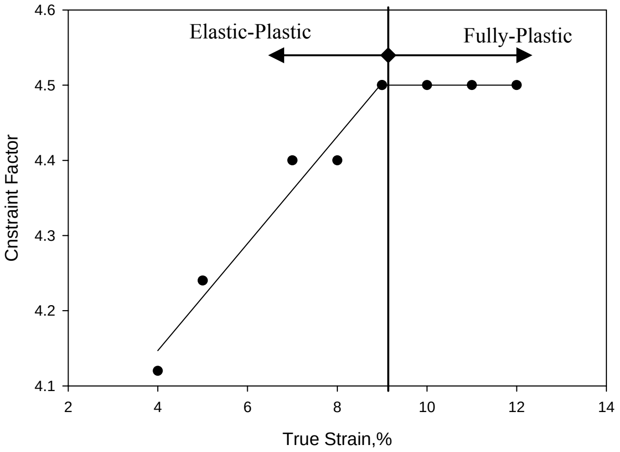

Figure-8. Variation of CF as a function of true strain for SS304.

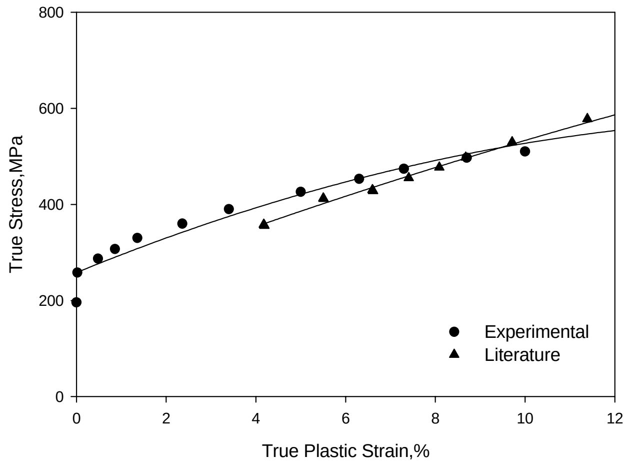

Figure-9. Flow curves of SS304.

CONCLUSIONS

- The flow stress and Meyer hardness are increasing with true strain due to strain-hardening Coefficient;
- The Meyer hardness (Hm) Vs average strain (εavg) is 3 to 4 times higher than Flow Stress Vs True strain due to constrained flow during indentation;
- The Meyer hardness (Hm) Vs Strain curve is matching with the Flow curve at a CF value of 2.4 for SS304; and
- Indentation test is a best substitute to the uniaxial Tensile and Compression test whenever material is available in small volumes.

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