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AUTOMATED BALL INDENTATION TECHNIQUE FOR TENSILE PROPERTIES MEASUREMENT OF COLD WORKED STAINLESS STEEL AND CARBON STEEL

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ABSTRACT

In the present work, ball indentation technique (BIT) has been employed to explore the possibilities for revealing the effect of cold rolling on mechanical properties on stainless steel and carbon steel. Tests have been carried out on as-received, and cold worked (10 and 20%) materials at room temperature. The entire specimen tested, the dependence of yield strength (YS), ultimate tensile strength (UTS), strength coefficient (K) and strain hardening component (n) values on cold rolling effect were made available from the BI results and they were validated with the standard conventional mechanical test results. It was found that, with increase in cold rolling the YS, UTS and K values have increased as revealed by BIT, while n value has decreased. Overall, it is found that BIT can be effectively used to determine the change of mechanical properties after cold working by using a small amount of test materials and quite rapidly compared to conventional test. An in-house developed BI system was employed to evaluate the mechanical properties. In this work, we also presented property estimation with new methodology that is not using unloading curve data and found close approximation with earlier. We also presented the effect of indentation ball diameter on the load deflection data.

INTRODUCTION

Nuclear reactor components and power piping are generally subjected to various forms of thermal cycling. As a result, the mechanical properties of the materials of the components get degraded. It is therefore of prime importance, that the altered mechanical properties of the degraded materials be known for life assessment of the components of the nuclear and thermal power plants. A fundamental requirement to assess the mechanical properties of materials using a small amount of test materials has got tremendous importance in the research area. Among the several small specimen techniques for determining mechanical properties of material, BIT is one of the most promising techniques

The *Automated Ball Indentation* technique is capable of extracting degraded mechanical behavior and properties of thermally aged or irradiated materials from very small specimens. The objective of miniaturized specimen testing technology is to enable the characterization of mechanical behavior while using a greatly reduced minimum volume of material. In most of the cases extracting specimen from components, for conducting conventional tests for evaluation of properties of the material, is neither possible nor permissible. The significance of this technology is obvious to the nuclear industry where neutron irradiation space is limited and irradiation cost scales up with specimen volume and evaluation of property by in-situ monitoring using magnetic attachments. In addition, the substantial advantages resulting from the application of this technology in non-nuclear industries are now beginning to be realized.

For this evaluation the specimen undergoes multiple indentations by a spherical ball indenter. Furthermore, this method can be used to characterize weldments and associated Heat Affected Zone (HAZ), it also avoids the need to fabricate test specimen, and it is relatively rapid.

REVIEW OF EARLIER WORK

For evaluating mechanical properties through BIT many theories and models have been developed and some of the mechanical properties such as yield strength, ultimate tensile strength etc. were evaluated using these theories. It was Mayer [1] who first developed a relationship between the mean pressure and indentation diameter to evaluate the yield strength of materials. Tabor [2] gave an empirical relationship to find the representative strain of materials while indentation is done through a hard spherical ball. However, Tabor’s relation holds very close to the test observation when the indentation process becomes fully plastic. Haggag *et.al.* [3] developed an automated ball indentation (ABI) set-up. Using this set-up many research groups studied flow properties of different materials through the thickness variation/gradient in mechanical and fracture properties, energy to fracture in terms of new parameter indentation energy to fracture (IEF) and found good agreement with the conventional test results. They developed a field indentation microprobe to evaluate the integrity of metallic structure nondestructively.

Mok [4] and Duffy [5] worked on various indentation velocities and strain rate. Das *et al* [6] have established the effectiveness of a laboratory scale BI system. They have optimized the system to extract room temperature mechanical properties of various materials. Haggag and Nansted [7] also described a simple technique for estimating the fracture toughness by coupling the measured flow properties with a modified but empirically correlated critical fracture strain model. Mathew *et.al.* [8] studied the effects of low temperature aging (673K) up to 18 months on the mechanical and fracture properties of cast CF-8 stainless steel in the range of 173-423K. Sharma *et. al.* [9] presented simulation of technique using non-linear finite element analysis and properties estimation through neural network application. A theoretical model is proposed to estimate fracture toughness of ferritic steel in the transition region from ball indentation test data by Byun, kin, Hang [10]. The key concept of the model is that the indentation energy to a critical load is related to fracture energy of material.

METHODOLOGY

The basic principle of the ball indentation technique is multiple indentations by a spherical indenter at the same test location on the test sample with intermediate partial unloading. Here, the load increases approximately linearly with penetration depth. This is due to two nonlinear but opposing processes that occur simultaneously, i.e. the non-linear increase in the applied load with indentation depth due to the spherical geometry of the indenter and non-linear increase of load with indentation depth due to the work hardening of the test pieces. During each subsequent loading the amount of materials experiencing plastic deformation increases, so continuous yielding and strain hardening occur simultaneously. For each loading cycle the total depth h_t is measured and plastic depth h_p is measured by intersecting the unloading slope line with the zero load line. The h_t , h_p and corresponding loads of the raw data used for determining the mechanical properties.

True Strain

An elastic zone surrounds a compressed plastic zone, just beneath the indenter. The plastic zone and the indentation impression will expand as the indentation load increases. The strain field produced beneath the indenter was regarded as representative strain as the total true strain $\left(\varepsilon_f\right)$ by Tabor [6]. ε_f can be expressed as a function of *d* and *D*:

$$\varepsilon_f = f\left(d / D\right) \tag{1}$$

where, *D* = indenter diameter and *d* = indentation diameter.

After analyzing empirical data Tabor [6] found that ε_f varies linearly with the ratio of d/D and found the linearity coefficient is equivalent to 0.2. Later on Haggag *et al.* [7] calculated the true plastic strain $\left(\varepsilon_p\right)$ as:

$$\varepsilon_p = 0.2\left(d_p / D\right) \tag{2}$$

where, d_p = plastic indentation diameter.

True Stress

An advancing spherical indenter generates multi-axial compressive stresses just beneath the indenter and due to these stresses an increasing volume of test material is forced to flow. Using the maximum shear stress theory as yielding criterion the uni-axial flow stress $\left(\sigma\right)$ can be expressed by

$$\sigma = p_m / \delta' . \tag{3}$$

where, δ' is a constraint factor, which increases as the plastic zone increases and reaches a maximum until the whole of the material around the indentation is in a state of full plasticity.

Evaluation of Tensile Strength

The following analytical expression was used for evaluating the engineering value of σ_{uts} :

$$\sigma_{uts} = K\left(n/e\right)^{n} \tag{3}$$

where, σ_{uts} = the engineering value of UTS, K = strength coefficient and n = strain hardening exponent.
The flow curve can be expressed as:

$$\sigma = K.\varepsilon_{p}^{n} \tag{4}$$

where, σ = true stress, ε_p = true plastic strain and these values can be obtained by fitting various data points of load and indentation plastic diameter in the following expression:

$$\varepsilon_p = 0.2\left(d_p / D\right) \tag{5}$$

$$\sigma = 4.P/\pi.d_p^2.\delta^{'} \tag{6}$$

The plastic diameter of indentation can be calculated through the regression analysis of the Hertzian equation. $\delta^{'}$ can be expressed as:

$$\delta^{'} = 1.12 + \tau \ln \phi \tag{7}$$

where, ϕ is a function of a parameter τ and its value is dependent on the flow stress and plastic strain of the test piece. Again τ is a function of τ that is dependent on strain rate sensitivity and work hardening characteristic of the test materials.

Evaluation of Yield Strength

Total penetration depth is converted to indentation diameter using spherical geometry relation. The data points from all loading cycles are fit by Meyer relation:

$$P/d_t^2 = A\left(d_t / D\right)^{m-2} \tag{8}$$

where, *m* = Meyer's coefficient, P= applied load and *A*= material parameter. The yield strength can be calculated using following equation:

$$\sigma_y = \beta_m.A \tag{9}$$

where, β_m = material constant and same for a specific class of materials irrespective of heat treatment and mechanical working. The value of β_m is determined for each class or type of materials from the various known YS value by analysis.

Indentation Energy to Fracture (IEF)

Indentation Energy to Fracture (IEF) allows the nondestructive determination of fracture energy from ABI-measured true stress-strain curves up to the controlling micromechanical fracture mechanism of the critical fracture stress or the critical fracture strain. It is given as the integration of ABI flow stress to the predicted depth to fracture.

$$IEF = \int_0^{h_f} P_m(h)dh \quad \text{where, } P_m = {4P}\Big/{\pi d^2} \tag{10}$$

Here, P_m is the mean contact pressure, P is the indentation load, h is the indentation depth, h_f is the indentation depth up to cleavage fracture stress and d is the chordal diameter of the indentation. Since indentation load versus depth curve is linear. The slope (S) of he curves can be used to calculate IEF,

$$P = Sh \tag{11}$$

$$d = 2(Dh - h^2)^{0.5} \tag{12}$$

D is the indentation diameter.

So that

$$IEF = \frac{S}{\pi}\ln\left(\frac{D}{D-h_f}\right) \tag{13}$$

In our analysis, we assume reference stress is equal to σ_{uts} .

Evaluation of Property Without Considering Unloading Data

We presented the algorithm of new approach for evaluation of property from BIT raw data without using unloading cycle data points.

1. Select the load P and respective h_t (total depth).
2. Evaluate d_t and consider as d_p and calculate ε_p^* and σ^* .
3. Calculate $\varepsilon_e = \sigma^* / E$ and $\varepsilon_p = \varepsilon_P^* - \varepsilon_e$
4. Recalculate d_p and σ using new ε_p, repeat the cycle until ($\left(\sigma^* - \sigma\right) \le 0.5MPa$
5. Get array of σ_t and ε_p .
6. Fit the data in the form $\sigma_t = K\varepsilon_p^n$ and obtain best estimate K & n and $\sigma_{uts} = K\left(n/e\right)^n$.

EXPERIMENTAL

To study the effect of cold rolling on stainless steel and carbon steel material, as-received material of thickness 25 mm had taken as stock. These were cold rolled in two categories 10%, and 20% of the initial thickness. For the rolling process, 2-3% reduction per pass was chosen. A linear variable differential transducer (LVDT) is clamped to the loading members. Both the plastic depth (h_p) and total depth (h_t) are measured through the LVDT. The indentation balls are made of tungsten carbide and are (0.75, 1.0 & 1.46) mm in diameter. The size of the indenting ball is depending on the type and thickness of the material to be tested. These balls are brazed into spherical groove machined at the bottom of the loading arm. The surface of the BI test specimens is ground to 800 grit emery papers. The tests are carried out at room temperature with an indenter velocity of 0.5 mm/min. All the tests are terminated when the total indentation depth measured by LVDT is less than the indenting ball radius.

RESULTS AND DISCUSSION

The mechanical properties of all the investigated steels were derived through BIT. Some of them were validated by conventional test results. It is found that there is a distinct difference among the load–deflection $\left(P - \delta\right)$ curves for as received and cold rolled stainless steel as well as carbon steel, obtained through BIT and the load increases linearly as the depth of indentation increases as shown in Fig.(1&2). An in-house developed S/W has been used to convert load-displacement data into true stress-true strain curves. Fig. 3 showed the closing matching of BIT obtained results and conventional results for as received stainless steel. The mechanical properties for other cold rolled materials were determined through BIT shown in the Table 1 along with as-received material for comparison. Table 2 showed the change in IEF and strain hardening exponent value w.r.t. to as-received material for both steel. It is seen from the table that with increasing CR, the flow stress increases sharply. It is also found that strain hardening exponent and IEF decreases but strength coefficient increases and similar result is expected from the reference. It is also noticed that the decrement of strain hardening exponent and IEF is not linear. Initially the values decrease rapidly with rolling. Since the work hardening exponent is a measure of he uniform elongation and it has influence on the deformation capability of the material, so it can be said that with the cold rolling, strength of the materials increases but its uniform strain along with the stretch ability decrease. Fig. 4 show the case study of stainless steel as received material using new approach of only using loading data and compare with unloading data theory and comparison show in Table 3. It is observed that there is no variation is yield strength because it's only used total depth data in both algorithm but other properties showed maximum difference of 4.55% in case of carbon steel and 1.71% in case of stainless steel for strain hardening exponent. Fig.5 shows the close matching in normalized load-deflection curve for different ball diameter (0.7, 1.0 & 1.46 mm).

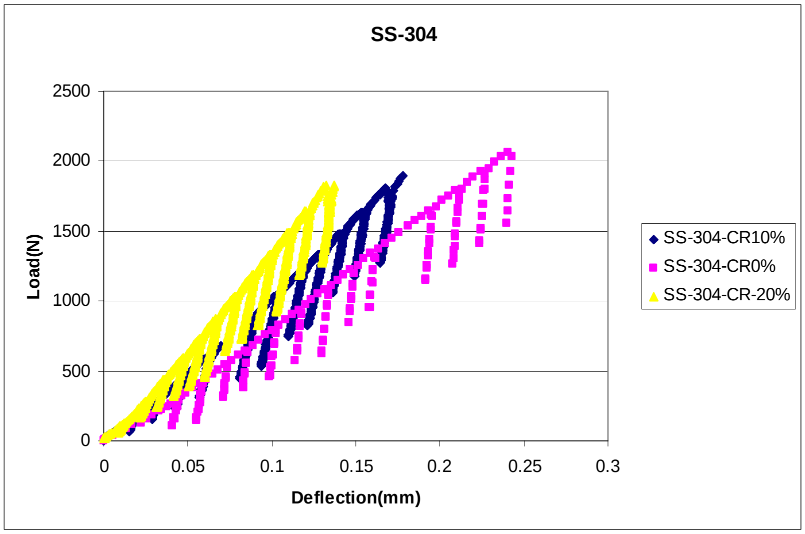

Fig. 1: Comparison of load deflection curves for as-received and cold rolled SS-304LN

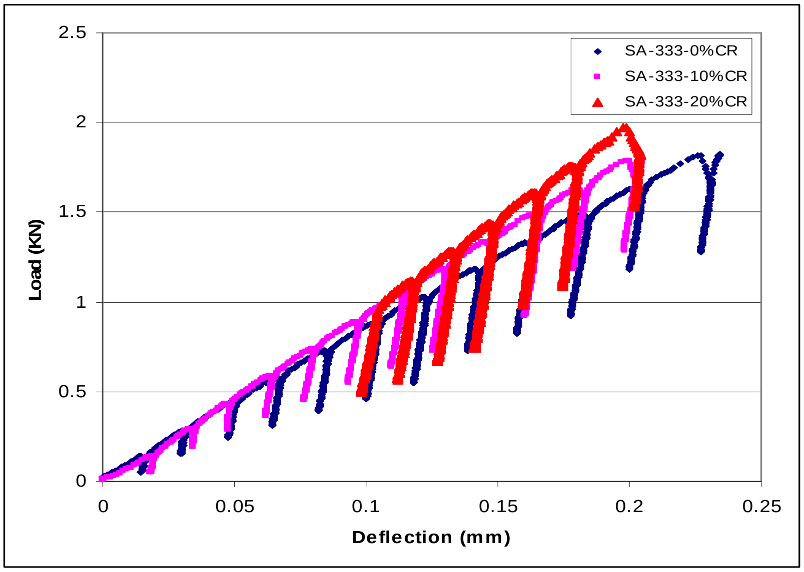

Fig. 2: Comparison of load deflection curves for as-received and cold rolled SA-333 grade 6

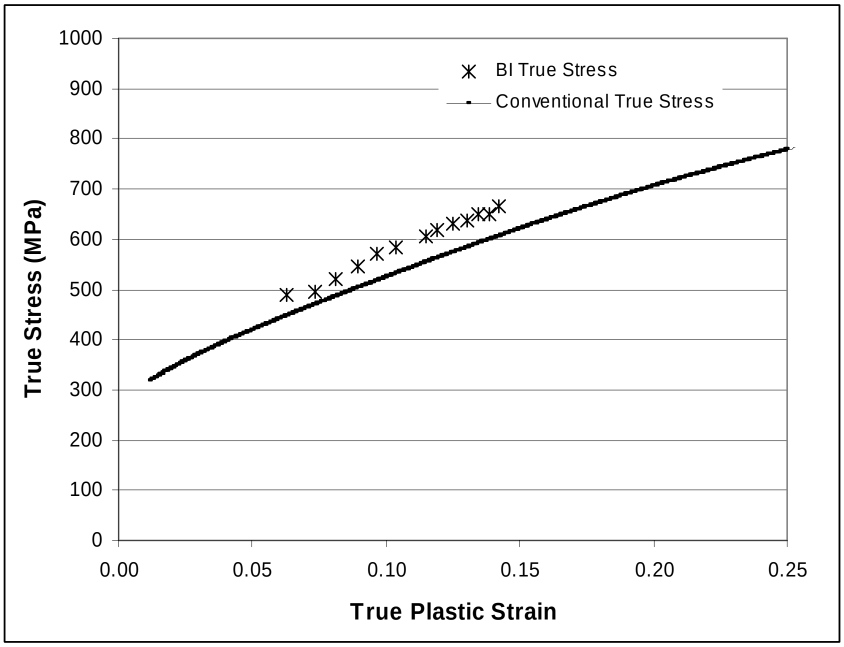

Fig. 3: Validation of true stress-true plastic strain curve obtained through BI and conventional test

Table 1: Effect of cold working on properties of stainless steel and carbon steel

Stainless Steel 304 LN				
% Rolling	Strain hardening exponent	Strength coefficient (MPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)
0	0.41	1529	290	713
10	0.23	1691	390	958
20	0.18	1790	438	1098
Carbon Steel 333 grade 6				
0	0.22	763	294	447
10	0.15	935	352	605
20	0.11	1023	460	717

Table 2: Change in strain hardening exponent and IEF due to cold working

Material	△ (n)/n (%)		△ (IEF)/IEF (%)	
	10% CW	20% CW	10% CW	20% CW
SS-304 LN	-43.9	-56.0	54.6	71.2
SA-33 Grade 6	-30.9	-45.9	51	57.9

Table 3: Comparison of estimated properties by both methodology

	Stainless Steel				Carbon steel			
	n	K	YS	UTS	n	K	YS	UTS
Using unloading data	0.410	1518	296	698	0.22	763	294	447
Using loading data	0.417	1532	296	701	0.228	781	294	442.5
% Difference	1.71	0.92	0.0	0.43	4.55	2.36	0.0	1.01

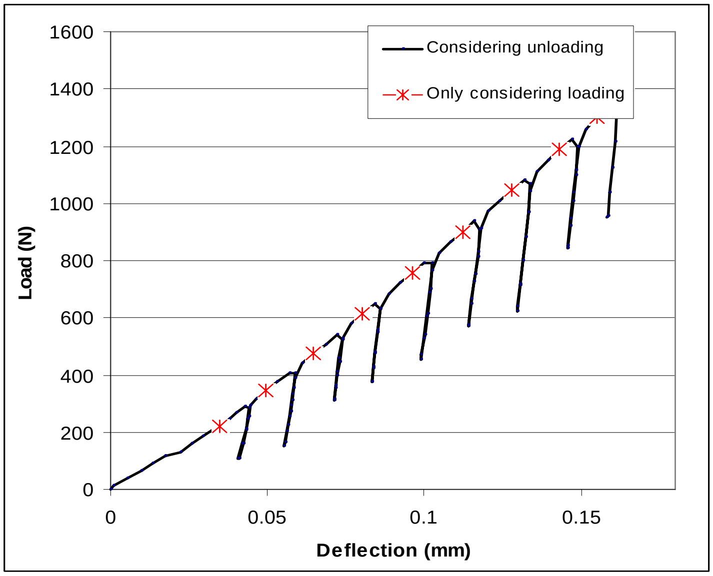

Fig. 4: Data point selection for both methodologies

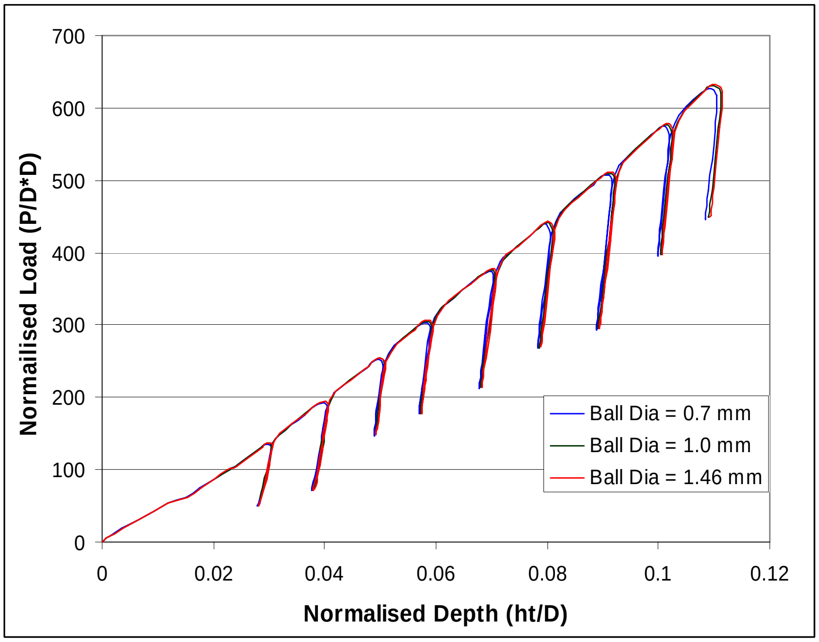

Fig. 5: Comparison of normalized load and depth for different ball diameter

CONCLUSION

It is found through BIT that with increasing the percentage of cold rolling of stainless steel and carbon steel, UTS and YS both were increased. But the increment rate of YS is much higher than the increment rate of UTS. After a certain percentage of cold rolling, the increments of flow properties are less. The value of strain hardening exponent and IEF has decreased as with the percentage of cold rolling. The formability of the steel decreases as the percentage of the cold rolling increases, as indicated by BIT. The flow properties obtained through

BIT were validated by conventional test results, which prove the effectiveness of the present BI system in which a small amount of test material will be sufficient for the entire test. It is also found that we can use new approach, which is not dependent upon unloading data points and less than 5% deviation from previous approach. It is also found that there is no significant variation in normalized load vs normalized depth curve for different ball diameter.

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