Use of ball indentation technique to determine the change of tensile properties of SS316L steel due to cold rolling

Goutam Das\textsuperscript{a},*, Sabita Ghosh\textsuperscript{a}, S.K. Sahay\textsuperscript{b}

\textsuperscript{a}National Metallurgical Laboratory, Jamshedpur 831 007, India
\textsuperscript{b}National Institute of Technology, Jamshedpur 831 014 India

Received 24 August 2004; accepted 24 January 2005
Available online 24 February 2005

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 a SS316L steel. The as-received steel was cold rolled up to 40%. Results are presented for 7%, 15%, 24% and 40% of cold rolling effect on the SS316L steels. For all the specimens 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.

Keywords: Cold rolling; SS316L steel; Ball indentation test; Mechanical properties; Spherical indenter

1. Introduction

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 for a long time. Among the several small specimen techniques for determining mechanical properties of material, BIT is one of the most promising techniques [1–9].

For evaluating mechanical properties through BIT many theories and models have been developed [1–9]. Meyer [5] was the first who developed a relationship between mean pressure and impression diameter to evaluate the YS of materials. Tabor [6] gave an empirical relationship to find the representative strain of materials within plastic region while indentation is done through a spherical ball indenter. Mok [7] and Duffy [8] worked on various indentation velocities and strain rate. The present authors [4,9,10–12] have established the effectiveness of a laboratory scale BI system. They have optimised the system to extract room temperature mechanical properties of various materials. Haggag et al. [1,2,13–17] developed an automated ball indentation (ABI) set-up. Using this set-up many research groups [18–20] studied flow properties of different materials through the thickness variation/gradient in mechanical and fracture properties, energy to fracture in terms of a new parameter ‘indentation energy to fracture’ (IEF) and found good agreement with the conventional test results.

In the present work, 316L grade SS steel has been chosen to establish the effectiveness of the BI system, developed in NML. Austenitic stainless steel is a single-phase structure and because of this its yield strength is low. This steel can be strengthened only by cold work or by elements in the solid solution. The aim of the work is to determine the mechanical properties of the SS steel and its cold rolled condition by using BIT. The work is aimed to establish the effectiveness of the BI system to evaluate flow properties of materials by using a small amount of test materials.
2. Methodology

The basic principle of the ball indentation technique is multiple indentation by a spherical indenter at the same test location on the test sample with intermediate partial unloading. Here, a spherical ball with a specific rate of loading indents the test materials and multiple indentations in a single position is made through loading–unloading–reloading sequences. Spherical balls of different diameters have been used to get multiple stress–strain data points. Here, the load increases approximately linearly with penetration depth. This is due to two non-linear 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. In contrast, for the case of an uni-axial tensile test the yielding and strain hardening occur simultaneously. The indenter is in highly constrained state. Using the Tresca or Huber–Mises criterion shows that the condition for plasticity is first reached at a point below the actual surface of contact. Beside normal pressure, a shear stress also acts and the maximum shear stress acts along the axis of the indenter. Calculated shear stress shows that the maximum values occur at a point about 0.5a below the center of the circle of contact. Tresca or Huber–Mises criterion indicates that the plastic deformation commences when \( p_m \geq 1.1Y \), where \( Y \) is the yield strength of the material. Two radial stresses become zero at this point. The flow stress is smaller than the mean indentation pressure as already mentioned that the plastic deformation zone beneath the indenter is in highly constrained state. Using the maximum shear stress \([3]\) theory as yielding criterion the uni-axial flow stress (\( \sigma \)) can be expressed by

\[
\sigma = p_m / \delta' 
\]  

where, \( \delta' \) 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.

2.2. 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. The region of contact is a hemisphere of radius ‘\( a \)’. The friction between the indenter and the metal surface is assumed to be negligibly small. The pressure by the spherical indenter on the contact surface is normal and has an elliptical distribution with maximum at the contact point and decreasing zero at the periphery of the indentation circle. It may be noted that the pressure across the surface of contact is not uniform. The mean pressure (\( p_m \)) over the region of contact is proportional to \( P^{1/3} \) \([6]\) (applied load). Tresca or Huber–Mises criterion shows that the condition for plasticity is first reached at a point below the actual surface of contact. Beside normal pressure, a shear stress also acts and the maximum shear stress acts along the axis of the indenter. Calculated \([6]\) shear stress shows that the maximum values occur at a point about 0.5a below the center of the circle of contact. Tresca or Huber–Mises criterion indicates that the plastic deformation commences when \( p_m \geq 1.1Y \), where \( Y \) is the yield strength of the material. Two radial stresses become zero at this point. The flow stress is smaller than the mean indentation pressure as already mentioned that the plastic deformation zone beneath the indenter is in highly constrained state. Using the maximum shear stress \([3]\) theory as yielding criterion the uni-axial flow stress (\( \sigma \)) can be expressed by

\[
\sigma = p_m / \delta' 
\]  

where, \( \delta' \) 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.

2.3. Evaluation of tensile strength (\( \sigma_{uts} \))

The following analytical expression was used for evaluating the engineering value of \( \sigma_{uts} \)

\[
\sigma_{uts} = K(n/e)^n 
\]  

where, \( \sigma_{uts} \) = the engineering value of UTS, \( K \) = strength coefficient and \( n \) = strain hardening exponent.

The \( K \) and \( n \) values can be determined through the regression analysis of the following power law equation for different values of \( \sigma \) and \( \varepsilon_p \) from Eqs. (2) and (3). The flow curve may be expressed as:

\[
\sigma = K \varepsilon_p^n 
\]  

where, \( \sigma \) = true stress, \( \varepsilon_p \) = true plastic strain and these values can be obtained by fitting various data points of load (\( P \))
and indentation plastic diameter ($d_p$) in the following expressions:

$$
e_p = K_1 \left( \frac{d_p}{D} \right)$$

(6)

$$\sigma = 4 \cdot \frac{P}{\pi \cdot d_p^2} \cdot \delta'$$

(7)

where, $P$ = applied load, $d_p$ = plastic indented diameter.

The plastic diameter of the indentation can be calculated through the regression analysis of the following Hertzian equation [6]:

$$d_p = \sqrt{\frac{2.735P}{\left( \frac{1}{E_1} + \frac{1}{E_2} \right)D \left( \frac{h_p^2 + 0.25d_p^2}{h_p^2 + 0.25d_p^2 - \delta d} \right)}}$$

(8)

where, $E_1$ and $E_2$ are the Young’s modulus of the indenter and the specimen tested, $h_p$ is plastic depth of the indentation.

$$\delta' = 1.12 + \tau \ln \phi$$

(9)

where, $\phi$ is a function of a parameter $\tau$, and its value is dependent on the flow stress and plastic strain of the test piece. An iteration method has been utilised to determine $\delta'$ values by using BI software developed by the present author [4,10]. Again, $\tau$ is a function of $\sigma$ that is dependent on strain rate sensitivity and work hardening characteristic of the test materials.

### 2.4. Evaluation of yield strength (YS)

Here, the total penetration depth ($h_t$) is measured while the load is applied and the depth is converted to a total indentation diameter ($d_t$) using following equation:

$$d_t = 2 \left( h_t \cdot D - h_t^2 \right)^{0.5}$$

(10)

where, $d_t$ = total indentation diameter, $D$ = diameter of the indenter and $h_t$ = total penetration depth.

The data points from all loading cycles are fit by linear regression analysis to the following relationship of Meyer relation [5]:

$$\frac{P}{d_t^2} = A(d_t/D)^{m-2}$$

(11)

where, $m$ = Meyer’s coefficient, $P$ = applied load and $A$ = material parameter.

The yield strength can be calculated using the following equation:

$$\sigma_y = \beta_m A$$

(12)

where, $\beta_m$ = material constant and can be calculated with a known value of $\sigma_y$. Then this $\beta_m$ will be the same for a specific class of materials irrespective of heat-treatment and

---

Fig. 1. Comparison of load–deflection curves for as-received and 40% cold rolled SS316L steel along with the SEM micrographs.
mechanical working. The value of $\beta_m$ is determined for each class or type of materials from the various known YS values by using BI analysis software.

2.5. Hardness measurement (HB)

The Brinell hardness number (HB) can also be determined from the BI test by using the following equation:

$$HB = \frac{2P}{\pi \cdot D \left( D - (D^2 - d_i^2)^{0.5} \right)}$$

where, $P$=indentation load in kgf, considering $P/D^2$ ratio is equivalent to 30 for steel and 10 for brass.

3. Experimental

To study the effect of cold rolling on SS316L material, as-received material of thickness 10 mm had taken as stock. These were cold rolled in four categories 7%, 15%, 24% and 40% of the initial thickness. For the rolling process, 5% reduction per pass was chosen. After the cold rolling the thickness of the samples reduced to 9.3, 8.5, 7.6 and 6 mm.

Standard tabletop mechanical testing machine of 10 kN capacity with a 5 kN-load cell is converted to the present BI test set-up. A PC is attached to the machine to control the test and store the digital data. Software on BASIC was developed for test control and data acquisition. 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 1–2 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 software has provision to input the diameter of the indenter ball, maximum load, maximum crosshead displacement, number of cycles and the rate of data acquisition. The displacement rate and extent of unloading are also provided as user input. The test coupons employed are 5 mm in length, 5 mm in width and the thickness in the range of 2–6 mm. The surface of the BI test specimens is ground to 800-grit emery papers. A pair of spring loaded clamps hold the test specimen on the test bed. At the start of the test, the LVDT and the load cell readings are zeroed through software. The tests are carried out at room temperature with an indenter velocity of 0.5–1.0 mm/min. All the tests are terminated when the total indentation depth measured by LVDT is less than the indenting ball radius. Using an INSTRON mechanical testing machine, the conventional tests were performed to get mechanical properties of the materials.

4. Results and discussions

The mechanical properties of all the investigated steels were derived through BIT. They were validated by conventional test results. It is found that there is a distinct difference among the load–deflection ($P$–$\delta$) curves for as-received and cold rolled steel, obtained through BIT and the
load increases linearly as the depth of indentation increases (Fig. 1). The microstructure of as-received and 40% CR steel were observed under optical microscope and shown in the same figure (Fig. 1). The microstructure of the as-received material is single-phased twinned crystal of austenite. Whereas, the 40% cold rolled steel is consisting of heavily elongated austenitic grains. An in-house developed $S/W$ has been used to convert the $P–\delta$ data into true stress–true strain curves ($\sigma–\varepsilon_t$). The $\sigma–\varepsilon_t$ curves from BI tests are shown in Fig. 2 for as-received. In the same Fig. 2, the conventionally obtained true stress–true strain data have also been drawn through dots. It is found that the data obtained through conventional mechanical test are matching well with those of the BIT obtained results. The $\sigma–\varepsilon_t$ curves for other cold rolled materials were determined through BIT and shown in the Fig. 3 along with the as-received material for comparison. It is seen from the Fig. 3 that with increasing CR, the flow stress increases sharply. Up to 24% of CR the increase of flow stress is very much prominent. Further increase of CR has less effect on flow properties. The above results show that the BIT is a very sensitive technique that can be used to measure changes in materials properties due to cold rolling.

The UTS and YS have also been determined through BI experimentation for as-received and cold rolled materials. It is found that UTS and YS both have increased with the percentage of cold rolling shown in Fig. 4. From this curve, it is noticed that the increment in the value of YS is more than for UTS and found that change in YS from as-received to 40% cold rolled material is almost 3.3 times whereas the similar change in UTS is only 1.8 times. In literature [21], it is mentioned that cold working leads to higher increase in YS value compared to UTS.

The UTS values determined from BI tests were compared with those obtained from conventional test results and shown in Fig. 5. It is found that the BI results are very close with those obtained conventional test results and variation is within 5%.

The strain hardening exponent and strength coefficients have been determined using BI test. It is found that with the increasing amount of cold rolling, the strain hardening exponent decreases while the strength coefficient increases and similar result is also observed from conventional test. It is noticed that the decrement of strain hardening exponent is not linear, shown in Fig. 6. Initially the $n$ value decreases rapidly with cold rolling. With further increment of cold rolling the value of $'n'$ becomes almost constant. On the other hand, the increment of strength coefficient is almost linear with cold rolling (Fig. 7). Since the work hardening exponent is a measure of the uniform elongation of the tested sample 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 stretchability decrease.

5. Conclusions

1. Through BIT it is found that with increasing the percentage of cold rolling of SS316L steel, UTS and YS both were increased. But the increment rate of YS is much higher than the increment rate of UTS.
2. After a certain percentage of cold rolling, the increments of flow properties are less.
3. The value of strain hardening exponent 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.

4. 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.

Acknowledgements

The authors would like to thank Shri P. K. Dey for his help and discussions. They are also thankful to the Council of Scientific and Industrial Research (CSIR), India for providing fellowship to one of the authors to carry out this work. They are also grateful to Prof. S. P. Mehrotra, Director, National Metallurgical Laboratory (NML) for encouragement and permission to publish this work.

References