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CAUSES OF DEVIATION OF THE BALL INDENTATION TEST RESULTS AND ITS CORRECTIVE MEASURES

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ABSTRACT

Indented area in ball indentation technique is calculated from depth of indentation, which are measured by LVDT. But LVDT measured depth can not able to estimate actual indented depth due to pile-up/sink-in surrounding the indentation profile. To establish a relationship between the pile-up/sink-in and the deviation of actual indentation diameters, a suitable and practical parameter, yield ratio (YR), is considered. It is found that for higher pile-up/sink-in corresponding diameters and the value of YR is higher. The flow curves and flow properties of various materials, calculated by using appropriate correction factor, are verified with conventional test results and found close agreement.

Keywords: LVDT, Pile-up/sink-in, Ball indentation test, Yield ratio, Work hardening

1. INTRODUCTION

When a hard spherical ball indents a metal surface, the materials beneath the indentation will be in a high stress state. As a result there will be a flow of metals that produces unevenness of metal surface surrounding the indentation up to a certain extent. This is termed as pile-up or sink-in of the materials and this behaviour is observed in many materials depending upon the strain hardening characteristics of the particular material. The pile-up/sink-in surrounding the indentation will change the effective indented area and correspondingly the mechanical properties that are determined on the basis of area of the indentation.
Many groups [1-5] worked on indentation technique for evaluating mechanical properties of materials but very few had reported the influence of pile-up/sink-in of materials on the measurement of indentation diameters (both total and plastic) that ultimately deviate the actual results. In 1928, A.L. Norbury and T. Samuel [6] did extensive work on Brinell impression and observed the presence of piling-up and sinking-in surrounding the impressions. The extension and height of the accumulation of materials was found to be independent of the size of impression. Tabor [7] also put some highlights on it and gave a picture about the indentation profile. According to him the displacement of metal from the region beneath the indenter results an appreciable amount of deformation of metal surrounding the indentation. He noticed that pile-up/sink-in is dependent on the work hardening characteristic of the materials.

Meyers and Chawla [8] worked on pile-up/sink-in behaviour of materials using a conical indenter. According to the nature and extent of deformation surrounding the indentation, they divided the materials into three categories (a) non-work-hardening metal, (b) work-hardening metal and (c) work-softening metal [Fig.1]. In case of work hardening materialds, elastic stresses below the indenter are not easily accommodated for the materials, which exhibit a high work hardening rate. So a large plastic deformation region is generated under the indenter. On the other hand, in case of non-work hardening materials the resistance to plastic deformation does not increase in the plastically deformed region resulting much more localised plastic zone. So, in case of non-work hardening materials the extension and height of bulging (pile-up) is more compared to work hardened materials. It was found (2) that extent of plastic deformation region along the surface was six times the diameter of the indenter [8].

Except one Korean group [9], the effect of pile-up/sink-in of materials surrounding the indentation, while determining the indention diameters from the corresponding depths, had little consideration of the investigators. The bulging, surrounding the indentation, deviates the indented area from the actual and consequently the true stress and true strain. Therefore, pile-up/sink-in behaviour should be considered for evaluating d_p and d_t in the course of determining the mechanical properties.

To find a relationship between the amount of pile-up/sink-in and correction value for LVDT determined diameters, a practical parameter is considered for the classification of the materials. This is called yield ratio (YR) parameter, which is defined as the ratio of yield strength to tensile strength. The materials used in the engineering structures are usually specified by YS and UTS. For any material or degraded component, YR can be determined by considering the specified YS and UTS of that particular material.

The work aims to find a relationship among the pile-up/sink-in, strain hardening exponent, work hardening rate and yield ratio parameter for few engineering materials. It also aims to make a suitable classification of the materials according to the amount and extent of pile-up/sink-in and in accordance, to select suitable correction factor to the diameter determined from LVDT measured depth.

2. EXPERIMENTAL DETAILS

The BI test has been accomplished on a developed laboratory scale set-up. A standard tabletop tensile testing machine of 10 kN capacity with a 5 kN load cell has been converted into BI test set-up. A PC is attached with the set-up. In conjunction with in-house developed software on BASIC, it regulates test and procures test data. The software has provision to input the diameter of the indentation ball fitted with the loading arm and cross-head displacement. The indenter ball (1-2 mm diameter) is made of tungsten carbide and is chosen for experiments depending on the type and thickness of the materials to be tested. The selected ball is brazed into spherical groove, machined at the bottom of the loading arm. The displacement rate, extent of unloading, the number of cycles and the maximum total indentation depth are provided as user input. A Linear Variable Displacement Transducer (LVDT) is affixed with the loading arm and the specimen surface. A pair of spring loaded clamps hold the test specimen on the test bed. Both the plastic depth (h_p) as well as the total depth (h_t) i.e. elastic plus plastic depth of the indentation profile is measured by the LVDT. Occasionally plastic diameters (d_p) are measured directly using optical microscope. For this purpose, various indentations are created for a few specific loads at several locations on the test surface. FORTRAN based programme has been developed for various calculations based on iteration and regression analysis, which described at length in the chapter 4.

The test samples are cut into from 5x5x2 mm^3 to 10x10x6 mm^3. The surfaces are polished up to 1000-grade emery paper to avoid hindrances due to presence of any foreign particle. The tests are carried out at room temperature with pre-set indenter velocity 0.5 to 1.0 mm/min depending on the nature (strain rate sensible) of the material. Applied load and corresponding depths are stored in PC. Multi load-depth curve constitutes raw data in this experimentation. For each cycle, the total (h_t) and plastic indentation depths (h_p) and corresponding maximum applied indentation load are obtained from load-deflection curve generated from digitally stored load-deflection data. The raw data are analysed for obtaining the flow properties and flow curve []. The analytically determined diameter from the depth is validated with the diameters of the indentation profile measured through optical microscope.

For the study of the pile-up /sink-in of the indentation profile, samples are indented on a polished surface up to some specified depth. Then the samples are coated with electroless coating of nickel. After Ni coating, samples were sectioned transversely at a distance slightly away from the indentation profile and then ground up to maximum indented diameter and polished. After etching the polished surface, samples were observed under optical microscope and scanning electron microscope (SEM).

3. RESULTS AND DISCUSSIONS

To study the morphology of pile-up/sink-in, the views of the transverse section of the indentation profile of various materials are observed under optical microscope and SEM. It is found that morphologies of pile-up/sink-in differ from material to material. Broadly three categories of pile-up/sink-in have been observed. Different nature of pile-up/sink-in of materials surrounding the indentation are shown in Figs.2, 3 & 4 and they have categorised as prominent, moderate and less or negligibly small.

According to the J. I. Jang et al. [9], correction factor due to changes in the effective area of the indentation profile can be determined from load-depth curves itself. A schematic of a single cycle of loading-unloading P-δ curve is shown in Fig.5. The unloaded part is extrapolated and can find the value of h_i, the intercept indentation depth. The contact depth (h_c) at maximum indentation load can be evaluated by analysing the unloading curve with the concept of indenter geometry and elastic deflection as [8]

$$\mathbf{h_c = h_{max} - w(h_{max} - h_i) \ldots\ldots\ldots(1)}$$

Where, w = indenter shape parameter and its value can be taken as 0.75 for the spherical indenter. The value of h_{max} can be determined from the P-δ plots (Fig.5). It is the total maximum depth corresponding to maximum indentation load. The material pile-up around the indentation produces the actual contact radius larger than expected. The extent of this pile-up can be determined as:

$$\mathbf{c^2 = \frac{a^2}{a^{*2}} = \frac{5(2-n)}{2(4+n)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)}$$

Where, c is a constant, n is the work hardening exponent of the material, ‘a’ is the actual contact radius and ‘a^*’ is the radius without pile-up. Using the above geometrical relationship of the spherical indenter, the real contact radius is expressed in terms of h_c and indenter radius R as:

$$\mathbf{a^2 = c^2(2Rh_c - h_c^2) \ldots\ldots\ldots\ldots\ldots(3)}$$

In the present chapter it is also tried to find out a suitable and acceptable (for various materials) correction factor in a different approach. For a particular material, plastic diameters at different loads are determined from LVDT measured depth and directly by optical microscopy. Then both the diameters for each load are fitted by Polynomial equation of degree 2. The differences between the two lines give the required corrections for the diameters at that particular load (Fig.6). It is found that the value of correction factor is dependent on the load to produce that particular diameter along with the materials characteristic. It is also found that with the increasing load the amount of the value of the correction also increased along with pile-up/sink-in. After studying the pile-up/sink-in behaviour of various materials it is found that similar type of correction factor can be used for other materials in a particular group.

An attempt has been made to classify the pile-up/sink-in behaviour of various materials on the basis of YR and have been listed in the Table 1. The d_p values of various materials at a particular load have been determined both through approach of Jang et al. [8] and the proposed approach in the present case, are shown in the Table 1. It is seen from the Table that the d_p values from both approach at a particular load for various materials are very close to each other. It is also observed from that Table that the materials, having YR values 90% and above show prominent pile-up. When the values of YR are below 90% but above 40%, a moderate pile-up/sink-in has been observed. Whereas, very small or negligible pile-up has been noticed when the materials are having less than 40% YR values. After incorporating the correction factors, the flow properties of all the investigated materials are determined through BIT and validated with that of the corresponding conventional test results. It is found that for majority of the cases the deviations of mechanical properties are within 5%.

In Table 1 it is observed that the materials having less ‘n’ values (less than 0.1) show prominent pile-up/sink-in surrounding the indentation. Therefore, the materials with high yield ratio i.e. from 90% to 100% and low strain hardening exponent (<0.1) show very prominent pile-up. The materials of this type show low work-hardening rate. Here, the correction factors for determining the indentation diameter is also higher for highest allowable load (i.e. the maximum load up to that the load-deflection curve would remain linear) which is in the range of 0.1mm. This value is also matching with the correction factor ‘C’ used in equation (3). The materials with medium YR parameter i.e. in the range of 50% to 90% with medium strain hardening exponent ($0.1 < n < 0.3$) show moderate pile-up. Again this type of materials possess medium work hardening rate. Correction factors in these cases are about 0.05mm and which is also agreeing with calculated value using the equation of J. I. Jang and et al. [9]. The materials with low yield ratio parameter (< 50%) and high strain-hardening exponent (n>0.3) show very less or almost negligible pile-up. And d_p for these materials are identical when evaluated through direct measurement and derived. Work hardening rate of this type of materials is comparatively higher. Hence no correction factor requires to be applied.

4. CONCLUSIONS

- It is necessary to add correction factors if the LVDT measurements are to be used in the determination of d_p. However, direct measurement of indentation using microscope needs no correction factors.
- For the determination of indentation diameters for a particular group of materials, correction factors are similar.
- A comparatively new materials parameter YR has been introduced to classify the investigated materials on the basis of formation of pile-up/sink-in of materials surrounding the indentation.
- Based on the YR parameters, ‘n’ values and pile-up/sink-in of the material surrounding the indentation, suitable (or require) correction factors can be introduced for determining the mechanical properties of the materials.
- Correction factors determined through the proposed approach are in agreement well with those obtained from the reported approach by J. I. Jang et al. [ ].
- Emergence of three distinct groups of materials on the basis of pile-up/sink-in, which can be correlated with YR parameter, strain ha5dening exponent, work hardening parameter etc. is the out come of the present studies.

5. ACKNOWLEDGEMENTS

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FIGURES

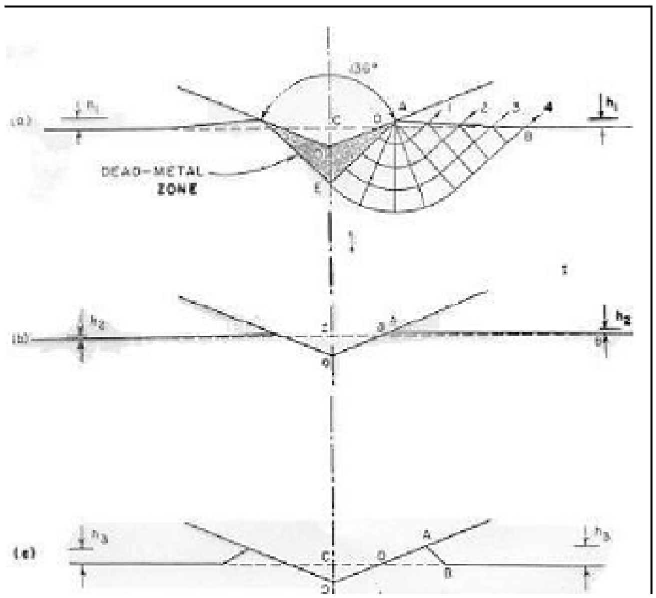
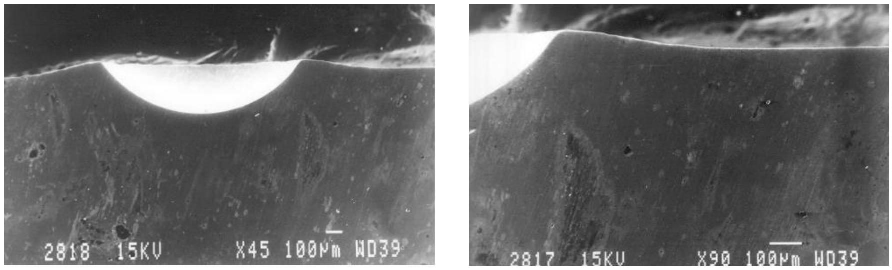
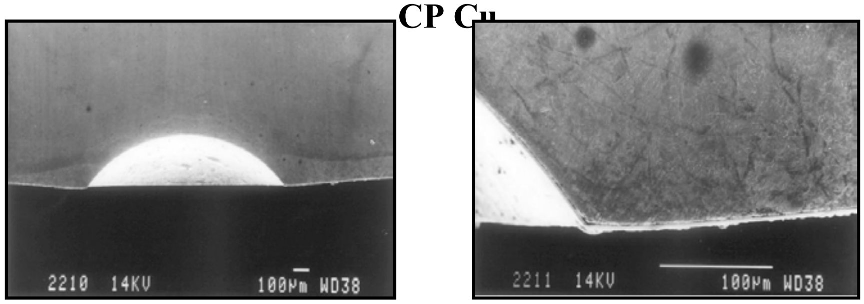


Figure 1 Showing the extent of pile-up when indented by a conical indenter for (a) non-work-hardening metal, (b) work-hardening metal and (c) work-softening metal

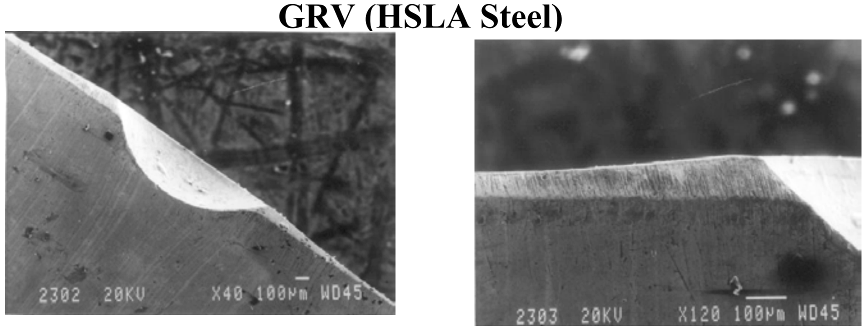
Prominent Pile-Up



CP Cu



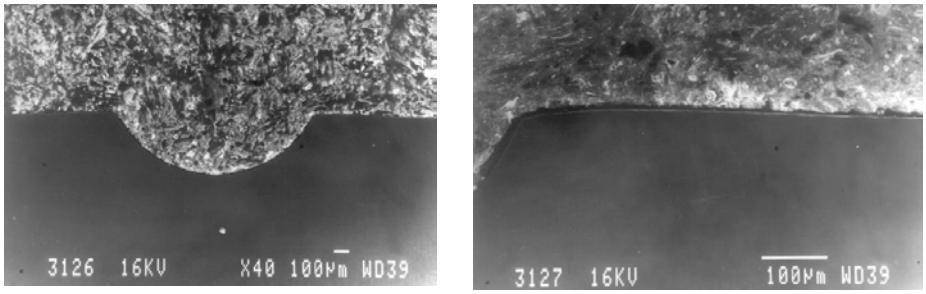
GRV (HSLA Steel)



GPQ (HSLA Steel)

Figure 2. SEM photographs of prominent pile-up surrounding the indentation profile of various materials

Medium Pile-Up



Aluminium

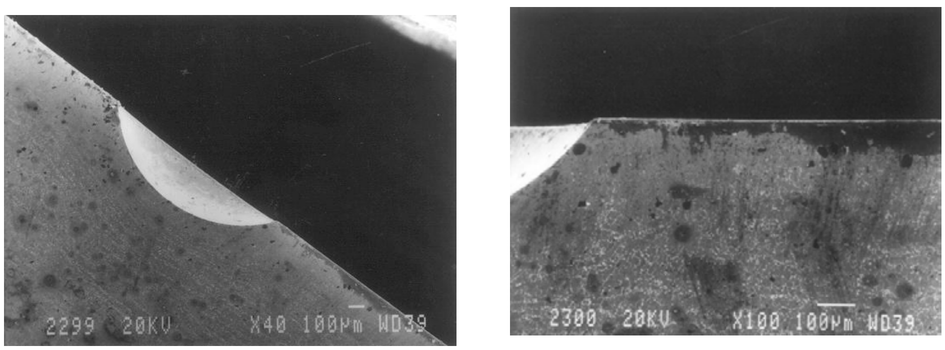


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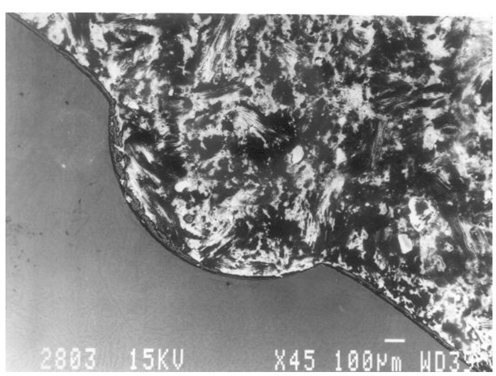
Figure 3. SEM photographs of medium pile-up surrounding the indentation profile of various materials

Negligible Pile-Up



Brass

Figure 4. SEM photograph of very low pile-up surrounding the indentation profile for Brass.

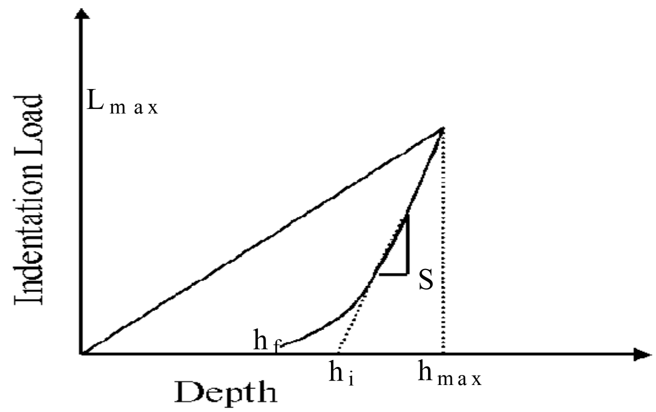


Figure 5. Schematic diagram of load–depth curve showing slope of the unloading line

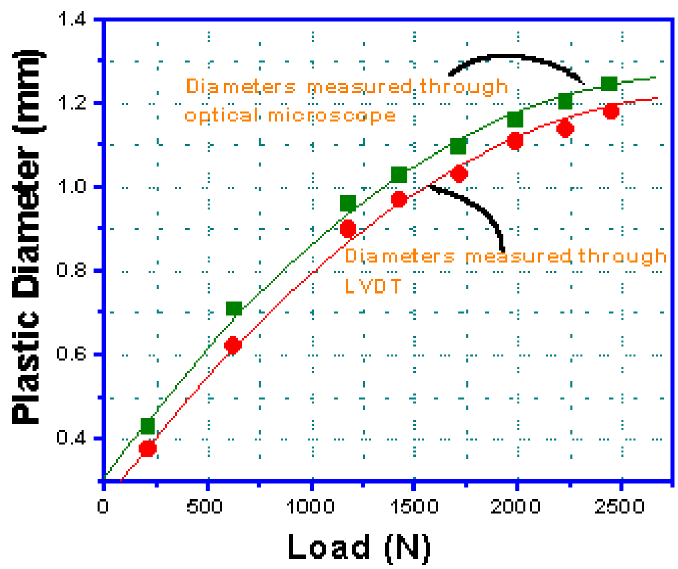


Figure 6. Comparison of plastic diameters of indentation measured directly through optical microscope and through LVDT

Table 1. Comparative study of correction factor using equation and from deviation diameters curves at various loads for different materials.

Material	$c^2 = \frac{5(2-n)}{2(4+n)}$	d_p in mm Using C & h_c	d_p in mm using correction from deviation of curves	Load (N) at which d_p is calculated	Error of overall results from in-house Accepted International BI system
Cp Cu	1.214	1.22	1.2	1005	3 %
HSLA steel (GRV)	1.177	1.153	1.15	2956	3.5 %
HSLA steel (GPQ)	1.147	1.2	1.25	2608	2%
A517	1.166	1.12	1.09	2466	5 %
16Cr-Mo 44 steel	1.107	1.33	1.32	3041	9 %
9Cr-Mo steel	1.11	1.26	1.27	3260	9 %
En A	1.096	1.26	1.26	2908	1.5 %
En B	1.138	1.24	1.24	3306	2 %
En C	1.145	1.128	1.07	2842	4 %
Mild steel	1.004	1.36	1.42	2922	5 %
SA333	1.026	1.29	1.32	2344	5 %
SS316L	0.988	1.476	1.477	3941	4 %
Brass	0.949	1.35	1.38	2396	5 %
Al	1.04	1.159	1.16	597	8 %
Ni	0.899	1.33	1.4	1522	5 %

Table 2. Relations among the material's pile-up, strain hardening exponent, nature of pile-up/sink-in and the Yield Ratio parameter.

Material	'n' value	Correction factor $C = \{5(2-n)/2(4+n)\}^{1/2}$	Nature of the surrounding of the indentation	Yield Ratio =(YS/UTS)X100
CP Cu	0.039	1.102	Prominent Pile-up	98.46 %
HSLA Steel				
GRV	0.08	1.085		95 %
ASTM A517 Gr.F	0.09	1.08		92 %
16Cr-Mo44 steel	0.159	1.052	Medium Pile-up	75 %
9Cr-Mo steel	0.152	1.054		75.7 %
En steel (A)	0.17	1.047		62.5 %
En steel (B)	0.123	1.067		62.2 %
En steel (C)	0.11	1.07		77 %
Micro alloyed steel				
RIM	0.24	1.02		64.5 %
EDD	0.23	1.023		61 %
DISC	0.162	1.05		73.4 %
DAQE	0.267	1.008		58.6 %
SA333	0.254	1.012		72 %
Aluminium	0.234	1.02		47.43 %
Mild Steel	0.28	1.002		62.4 %
SS316L	0.3	1.00		47.8 %
Wheel Materials				
FMRA	0.29	0.998		59 %
FMR	0.16	1.05		55.3%
FWRA	0.336	0.98		51 %
FWR	0.316	0.99		52.7 %
Brass	0.34	0.974	Negligible Pile-up	38.35 %
Ni based super alloys	0.45	0.948		50 %