NON-DESTRUCTIVE EVALUATION OF MECHANICAL AND FRACTURE PROPERTIES BY BALL INDENTATION TECHNIQUE

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ABSTRACT

Mechanical and fracture properties of several materials are being determined non-destructively using the Ball Indentation Test (BIT) method. This technique is based on the strain controlled multiple indentations at the same location on a given material surface by a small and hard spherical indenter. The technique permits the evaluation of tensile deformation parameters such as yield strength, ultimate tensile strength, strength coefficient and strain hardening exponent, and a fracture energy parameter called indentation energy to fracture (IEF). BIT is a relatively simple, rapid and non-destructive technique that requires only a small amount of material with very little specimen preparation, and can be adopted for in-situ testing on real structures. It is non-destructive since no material is removed from the specimen. A smooth hollow spherical indentation, less than 0.3 mm deep is left at the end of the test. This spherical indentation is harmless to the tested structure since it has no sharp edges and so it does not introduce any stress concentration site. As BIT is a miniature sample testing technique, it provides the advantage of testing highly radioactive samples with a low man-rem exposure.

The current paper brings out the methodology that was developed in-house for the evaluation of various components of nuclear interest. The materials used for the study were : 1) ASTM A106 Grade B steel (used as feeder pipe), (2) SA333 Gr.6 carbon steel (used as PHT piping), (3) AISI 304 (used as calandria vessel), (4) AISI 403 steel (used as end fitting material), (5) 17-4 PH steel (used as stud for the yoke assembly), (6) Spring steel washer and hexagonal nut of AISI 410 used for adjusting the axial elongation of the pressure tube during operation in the reactor (7) Zr-2.5%Nb pressure tube (PT) and (8) ASTM A335 P22 (used as high temperature header in the power plants operated by National Thermal Power Corporation). All the materials except the last one belonged to Pressurized Heavy Water Reactors (PHWRs) some of which already had served their intended purpose in the reactor.

Two of the above materials, namely SA333 Gr.6 carbon steel and AISI 304 were subjected to different degrees of cold work and then evaluated using BIT methodology. Both of them were evaluated through conventional tension tests also. Further, Zr-2.5%Nb material was subjected to various heat treatment cycles in order to vary the tensile properties as well as its fracture toughness. These were evaluated through conventional tension tests and also J tests in order to assess the effectiveness of BIT in providing reliable data on mechanical properties and fracture toughness.

This paper would discuss the principles of BIT, the method involved in the calculation of fracture toughness using IEF approach, its applicability in the study of the above components of the reactor.

1.INTRODUCTION

The assessment of mechanical and fracture properties of components in operation if done through a non-destructive technique would be of immense utility especially when the question of extending their life is under consideration. Ball Indentation Test (BIT) method is one such technique that has the potential of being employed for such purposes as the test is basically non- intrusive and at the same time reliable.

The BIT technique is a methodology that is gaining more and more acceptance in the modern day mechanical testing parlance due to its vast advantages over other forms of test techniques including the conventional ones. In this, a test piece of a given metallic material is subjected to a series of loading and partial unloading cycles with the help of a spherical indenter of high hardness such that it can furnish the tensile and fracture toughness values of the material being studied. It has been commercialized and named as “Automated Ball Indentation or ABI” by Haggag [1-3] who was originally instrumental in developing it to such an extent so as to make it quite acceptable like any other conventional methodology for the evaluation of components made of steel. The fascinating feature of this approach is that it can furnish most of the relevant data which can be directly utilized for many applications like integrity evaluation of structural components, embrittlement estimation of heat treated components, failure investigation of components etc. This test is indeed akin to an NDT method of evaluating any structural component. Hence, this methodology comes very much handy for being adapted for on-line assessment of the health of many operating components as well since it does not leave any harmful damaged zone due to the testing procedure. It is this aspect of it that specifically enables it to score over other test methodologies in order to make it quite suitable for evaluating components which are inaccessible especially in the case of irradiated materials. However, this approach needs to be initially calibrated against conventional methods so that the data furnished by it would become fully reliable for any intended application.

The paper will present the work done on various types of steels (ferritic, martensitic, austenitic and precipitation hardenable) and also one zirconium alloy tube material. It is to be noted that the work carried out on three of the materials, namely SA333 steel, AISI 304 steel and Zr-2.5%Nb were indeed done as blind problems in which a second laboratory independently performed the conventional data generation.

2. MATERIALS

a) Ferritic steels:

i) ASTM A106 Grade B steel: It is used as feeder pipe material.

ii) SA333 Gr.6 carbon steel: It is used as PHT piping.

iii) ASTM A335 P22: It is used as high temperature header in the power plants operated by National Thermal Power Corporation.

iv) Spring steel material: It is used as washer and forms a part of axial creep adjustment assembly

b) Martensitic steels:

i) AISI 403 steel: It is used as the end fitting material.

ii) AISI 410 steel: It is used as the material for lock nut in the axial creep adjustment assembly.

c) **Austenitic steel**:

(i)AISI 304: It is used as calandria vessel material.

d) Precipitation hardenable steel:

(i) 17-4 PH steel: It is used as stud for yoke assembly

e) Zr-2.5%Nb material: It is used as pressure tube in PHWRs.

All the materials used in the study belonged to Pressurised Heavy Water Reactors (PHWRs) excepting the high temperature header material used in the power plants operated by National Thermal Power Corporation (NTPC).

Some of them namely, the feeder pipe, stud, spring steel washer and lock nut had been received for post irradiation examination after their operation in certain nuclear reactors. They were required to be evaluated for their performance in the reactor. The remaining materials were in unirradiated condition.

Out of the materials in unirradiated condition, three materials were chosen for additional experimentation. They were SA333 steel, AISI 304 steel and Zr-2.5%Nb materials. The first two were subjected to varying degrees of cold work and the third one was subjected to varying heat treatment conditions. The basic intention was to explore how far the BIT methodology would be effective in determining not only their correct mechanical properties but also the change in these properties consequent upon varying degrees of cold work or heat treatment as the case may be. As the feasibility of BIT in providing reliable mechanical property data on anisotropic material like Zr-2.5%Nb had already been established by the authors else where [4-5], it was felt prudent to extend the study further to verify whether it could be utilized for evaluating when the material is subjected to heat treatment cycle also.

3. **EXPERIMENTAL PROCEDURE:**

3.1. Feeder pipe (ASTM A 106 grade B material): The feeder pipes which were used in Rajasthan Atomic Power Station-2 (RAPS-2), had been made out of ASTM A-106 Grade-B material. They were seamless and cold drawn but in the process annealed condition. They had welded joints between the Grayloc hub and the elbow region. One of them had failed after 30 years of operation. This pipe, B12(S) of RAPS-2 was received post irradiation examination study. The experiment was conducted at three locations of the pipe corresponding to the base, bend and weld so as to ascertain their mechanical properties as indicated in the attached figure.

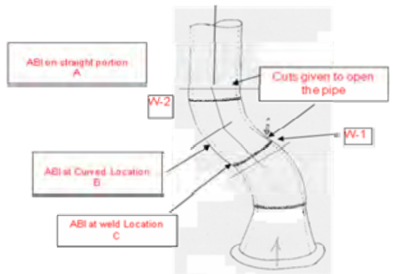

Fig.1. Elbow portion of the feeder pipe taken for BIT

3.2. SA-333 Gr.6 carbon steel (PHT piping) The material was selected for detailed study wherein it was subjected to varying degrees of cold work namely 10%, 20 % and 30 % to find out the effectiveness of BIT in providing the mechanical properties.

3.3. High temperature header material (P22): It is steel containing chromium and molybdenum **(**Cr- 2.2, Mo-1.04 and C-0.14). The component made out of htis material was discharged from the power plants after several years of operation. Their mechanical properties were to be found out.

3.4. **AISI 403 end fitting material:** Specimens prepared out of this material were subjected to BIT experiment at room temperature.

3.5. Axial creep adjustment assembly: It consisted of 17-4-PH steel stud, spring steel washer and hexagonal nut of AISI 410**.** Such a yoke assembly which had failed in PHWR, was received at PIED for evaluating the cause of failure experienced in each one of them **[6].** The samples were prepared from the stud and washer and tested by BIT.

3.6. SS-304: It is used as the cladding in the reactor pressure vessel steel and as the PHT piping in the Boiling water reactors (BWRs). For studying the effect of cold rolling on the mechanical and fracture properties, it was cold rolled to 10% and 20 % so that the material could be studied using BIT method for comparision with the conventionally tested results.

3.7. Zr-2.5%Nb Pressure tube:

Tension tests and fracture toughness experiments were carried out on this material which had been heat treated to eight different conditions so as to bring about variation in their properties. These individual specimens were subjected to BIT study also in order to find out its ability to reveal the variation in mechanical properties (For specimens namely B, C, D, E and F). The KJ_c from BIT were determined for specimens G, H, I and J whose conventional fracture toughness values were known.

4. RESULTS AND DISCUSSION:

4.1. **Feeder pipe:**

Table 1: Results of BIT on Feeder pipe material

Location	Details of the Material	Region	Mechanical properties		
			Y.S. (MPa)	U.T.S. (MPa)	Hardness (BHN)
A	Base Metal	Straight portion	270	402	118
B	Base Metal	Bent portion	288	430	126
C	Weld	At the weld	414	699	184

The results obtained using BIT methods are shown in Table 1. The test results indicated a clear demarcation in the mechanical property values as we moved from locations A to C. The mechanical properties were found to be the maximum for the weld region C and minimum for the base metal corresponding to the straight portion A. This is as expected since the weld would be stronger than the parent metal. The bent portion B exhibited marginally higher values of mechanical property in comparison with the base material. This could be due to the residual stresses present at that region of the pipe.

4.2. SA-333 Gr.6 carbon steel (PHT piping):

The test results generated through BIT on SA-333 Gr.6 steel with varying amounts of cold work are furnished below. The results indicated that the material exhibited increase in strength properties with increase in cold work. The value of ‘n’ was found to decrease with increase in the amount of cold work. As the strain hardening exponent ‘n’ is an indication of the uniform ductility of the material, the results of the BIT experiments are in conformity with the expected trend with regard to varying amounts of cold work imparted to the material through cold rolling which is shown in the table 2. The true stress-strain graph is shown in the fig.2.

Table 2: Results of BIT on SA-333- material

Material	YS (MPa)	K (MPa)	n	UTS (MPa)	BHN
SA-333-As received	315	748	0.139	494	159
SA-333- 10% CW	374	858	0.134	574	185
SA-333-20% CW	392	851	0.126	578	192

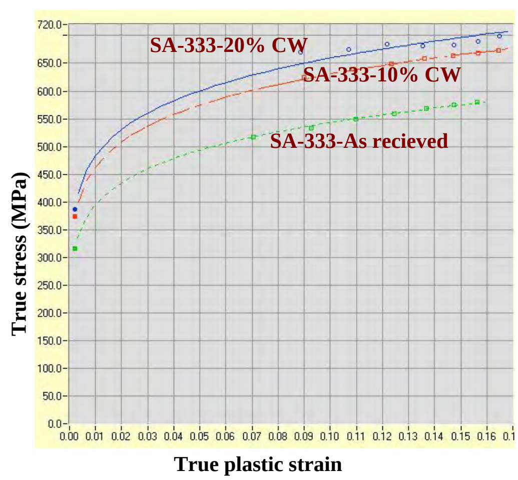

Fig.2. True stress-strain graph for SA-333 material with varying degree of cold-working

4.3. High temperature header material (P22):

Table 3. Mechanical property data through conventional and BIT methods

Method of data extraction	0.2 % Yield strength (MPa)	Ultimate tensile strength (MPa)	Total ductility (%)
Conventional tensile sample	250	450	30
Through BIT	252	447	-

Table 3 depicts the results of conventional tension tests and BIT experiments on P22 material useed in thermal power stations showing a very good match.

4.4. **AISI 403 end fitting material:**

Table 4 depicts the results of conventional tension tests and BIT experiments on a typical unirradiated end fitting material being used in PHWR showing a very good match.

Table 4. Mechanical property data through conventional and BIT methods

Method of data extraction	0.2 % Yield strength (MPa)	Ultimate tensile strength (MPa)	Total ductility (%)
Conventional tensile sample	625	750	30
Through BIT	633	754	-

4.5. **AISI 304 material:**

Table 5. Mechanical property data on AISI 304 through BIT method:

Material type	Yield strength (MPa)	Strength coefficient (MPa)	Strain hardening exponent	UTS (MPa)	BHN	IEF (KJ/m^2)	KJ_c ($MPa*m^{1/2}$)
SS-304 As received condition	252	1137	0.284	599	180	173	298
SS-304 -10% cold worked	445	1180	0.184	718	213	122	253
SS-304 -20% cold worked	518	1263	0.168	791	234	27	135

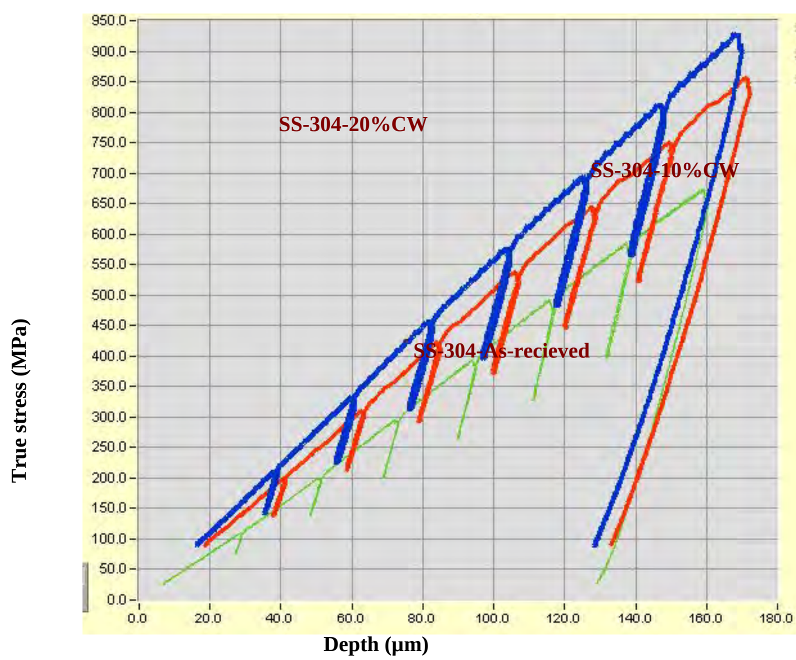

Fig.3. Load-depth graph for SS-304 material with varying degree of cold-working

AISI 304 material exhibited substantial variation in tensile properties in the cold worked conditions in comparison with that in the as-received condition as shown in the table 5. The trend of increase exhibited in the case of strength values was evident in the case of BHN also. The strain hardening exponent registered drop with increasing cold work level. The study thus showed that the BIT methodology would be able to indicate the change arising from varying degrees of cold work. The graph of load-depth profile for SS-304 material with varying degree of cold working is shown in the fig.3.

4.6. Axial creep adjustment assembly:

Table 6: Mechanical properties determined through BIT on 17-4 PH stud, SS-410 nut and spring steel washer

Material	YS (Mpa)	UTS(Mpa)	BHN
17-4-PH stud	761 762	1013 1034	273 278
SS 410 nut	428 428	690 714	211 215
Spring Steel Washer	--	--	359

The mechanical property data were estimated using BIT at room temperature. The results obtained on components of axial creep adjustment assembly are depicted in Table 6. It is evident from Table 6 that the spring steel washer possessed maximum hardness value of about 359 BHN while the nut had the least hardness of about 210 BHN with the stud having in between values of 278 BHN.

The failure at the threading of the 17-4 PH stud seems to suggest that the threading had given way due to overloading. This is a distinct possibility as the hardness value of the stud was only 278 BHN (as revealed by BIT experiments).

The stud material was 17-4 PH and it was supposed to be in H 1100 condition. As per ASTM specification-A564, the material if heat treated to H1100 condition should have certain minimum mechanical properties: 795 MPa for yield strength (YS), 965 MPa for ultimate tensile strength (UTS) and hardness of 302 BHN. However, the results obtained from BIT showed that the maximum value of YS obtained by conducting four experiments was only 769 MPa though the UTS indicated equal to or more than the stipulated value of 965 MPa. Thus the material did not meet even the minimum requirements. This brings out the fact that the material was soft and did not have enough yield strength to withstand the type of loading it experienced during service.

4.7. Zr-2.5%Nb Pressure tube:

The details of the heat treatments carried-out on the samples are given in the table 7.1. Conventional tensile test results on B, C, D, E and F samples are given in the table 7.2. Load-indentation plots for the heat treated materials are shown in the fig. 4. From fig.4 it is clear that BIT can distinguish differences in mechanical properties caused due to different heat treatment methods. The results from BIT are given in the table 7.3. The conventional test results of K_Q and also KJ_c determined by BIT route are given in the table 7.4.

Table 7.1: Details of heat treatment done on the material:

Specimen ID	Heat treatment Conditions	Specimen ID	Heat treatment Conditions
B	AR+550^{o}C for 6 hour and furnace cooled	G	As recieved
C	AR+700^{o}C for 2 hour and furnace cooled	H	AR+843^{o}C +30 min hold+ He Quenching
D	AR+800^{o}C for 0.5 hour and furnace cooled	I	AR+873^{o}C +30 min hold+ He Quenching
E	AR+850^{o}C for 0.5 hour and furnace cooled	J	AR+903^{o}C +30min hold+ He Quenching
F	AR+900^{o}C for 0.5 hour and furnace cooled		

Table 7.2: Summary of the mean values of properties evaluated from conventional tests

Condition of Material	No. of tests	n	K(MPa)	YS(MPa)	UTS (MPa)	% Elongation
B	3	0.1239	1179	551	780	18.35
C	3	0.1023	888	492	642	23.8
D	3	0.1094	833	456	594	25.76
E	2	0.1223	781	420	540	34.1
F	2	0.1229	754	386	501	35.2

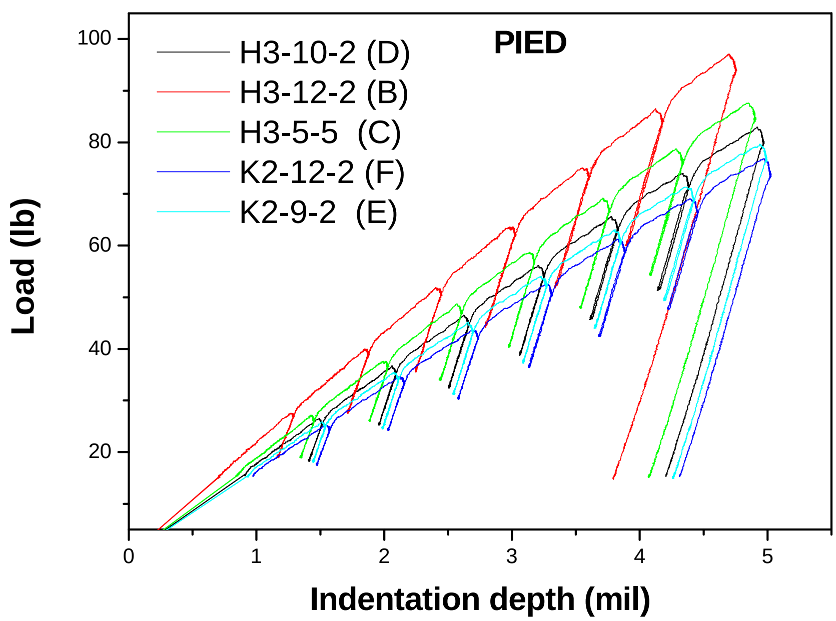

Fig.4. Load-depth graph for Zr-2.5 Nb material with different heat treatments

Table 7.3: Summary of the mean values of properties evaluated through BIT

Condition of Material	No. of tests	n	K (MPa)	YS (MPa)	UTS (MPa)	BHN
B	3	0.1003	1090	584	783	229
C	3	0.097	944	518	684	203
D	3	0.093	867	487	634	189
E	3	0.0925	819	464	599	179
F	3	0.091	783	445	576	172

The fracture toughness calculations were performed according to the method described by Haggag etal [2].
$K_{JC} = (2EW_f)^{0.5}$;
where E = Youngs modulus, W_f = fracture energy per unit area which is the summation of lower shelf fracture energy (W_0) and temperature dependant fracture energy (W_T).
Due to the inability of ascertaining W_0 for zirconium alloys (as it naturally does not exhibit DBTT), the value of W_0 is assumed to be zero for the current study.

Table 7.4: Summary of the mean values of properties evaluated through BIT

Sample name	BIT KJ_c(MPa√m)	Conventional K_Q(MPa√m)
G	38	48
H	41	60
I	68	57
J	65	45

5. CONCLUSIONS:

1. BIT was able to indicate the trend of variation in tensile properties arising from cold work in both SA333 steel and AISI 304 materials.

2. Employing the BIT methodology was helpful in assessing the cause of failure in axial creep adjustment assembly

3. BIT could provide reliable output in the case of Zr-2.5 Nb with respect to both tensile and fracture toughness values. It is necessary to identify the appropriate value of W_0 for this material.

4. There is almost no variation in the KJ_c values taken for the study which is also reflected from the values obtained from the BIT study. So in the future study, samples with large variation in KJ_c values needs to be taken.

5. BIT was able to predict reasonably well the tensile properties of all the 3 different materials taken as blind problems

6. ACKNOWLEDGEMENT:

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