Diminutive Specimen Test Techniques for Predicting Mechanical Behavior of Metals-A Review

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ABSTRACT

The paper presents a literature review of various diminutive specimen test techniques for evaluating a large number of in-situ mechanical and fracture properties of materials under severely stressed conditions, such as: yield strength, ultimate strength, ductility (fracture strain), fracture appearance transition temperature (FATT), fracture toughness (K_{IC} and J_{IC}) etc., The important developments in techniques for analysis of mechanical behavior of metallic alloys during degradation due to temperature, irradiation effect and other environmental effects on in-service structures are presented. The numerous empirical equations proposed by various investigators for prediction of these mechanical and fracture properties are presented and discussed. The numerical simulation using finite element method of such small punch test specimen by various researchers is also discussed. From this review, it is apparent that the Diminutive specimen test is the only existing method which at present is capable of providing experimental determination of various mechanical characteristics of service exposed materials or components. The paper also presents the use of some numerical methods (FEM) along with Neural Network techniques used for predicting and comparing the experimental results.

Keywords: Diminutive Test Specimen, Mechanical Properties, Finite Element Technique, Neural Networks, Degradation of Material Properties, Irradiation and Temperature Effect

1. INTRODUCTION

Mechanical properties characterization is needed in many industrial applications which requires sufficient amount of material for fabricating standard-sized testing specimens. Acquiring standard size specimens from these structures requires long shut down of the plant as well as damaging of the component itself. Thus, the Diminutive specimen test method has been evolved to meet the challenge, for assessing the damage of in-service engineering components, evaluating integrity of long service components and plant life prediction, scheduling, repairing and replacing welds and old components, determining cost of component deterioration, cost of normal service, peak service, plant cycling, and safe periods of plant life extensions and eliminating the cost of expensive full-size specimen testing. In a Diminutive test, a small disk shape specimen is taken out by a shaped penetrator at slow rate.

Foulds and Viswanathan (1996) **[1]** designed and developed a commercial surface miniature sample removal device. The system has specialized 50.8 mm diameter hemispherical head cutter plated with cubic boron nitride grit. The height of the cutter above the component surface is adjustable to produce a maximum sample thickness of 2.54 mm and a maximum diameter of 25.4 mm. The maximum depth of depression left behind is less than 3.3 mm, equal to the sample thickness plus the cut kerf width of 0.66-0.76 mm.

Lucas (1990) **[2]** and Cheon et al. (1996) **[3]** described various diminutive test techniques: tensile, micro hardness, bulge, shear punch (ball, shear, and hemispherical head), bend, and fracture test.

Further, based on geometries of indenter, the test techniques have been described as “Ball Punch Test” or “Bulge Test” or “Shear Punch Test” etc. Ghosh and Hecker (1975)**[4]** employed the criteria of diffuse and localized necking in punch stretching of sheet metals from experimentally measured strain histories. The purpose of such a criterion is to provide understanding of the failure process in punch stretching and predict the strain levels of the forming limit diagram, which help in solving sheet-stamping problems. The test blanks 200mm x 200mm were clamped firmly between die plates and were stretched by an about 100mm diameter hemispherical steel punch, moving at a speed of 25mm/min.

Liaw et al. (1993)**[5]** gave an alternate method of material property determination by non-destructive tests such as x-ray diffraction, ultrasonic, eddy current and magnetic techniques. Foulds and Viswanathan (1994)[**6]** described the determination of material toughness of low alloy steel components in service by small punch test. Foulds et al. (1995)[**7]** in their investigation estimated the material fracture appearance transition temperature (FATT) of components in fossil power plant and carried out fracture toughness evaluation by using small punch test.

2. PUNCH TEST

Punch tests have been developed to predict the mechanical properties (tensile property and fracture toughness *etc.*) from disk type specimens. In this technique, a supported disk or coupon is loaded with a penetrator of particular geometry until the failure occurs. The output of the test is load-displacement curve and it is analyzed for getting the mechanical properties. The test carried out with the spherical indenter is called “ball punch test” and with the cylindrical indenter it is called “shear punch test”.

Manahan *et al.* (1981, 1986) **[8,9]**designed a ball punch test in which they investigated a disk of 3 mm diameter and 0.25 mm thickness which was simply supported over a 2.46 mm diameter hole and displaced axially by a hemispherical punch of 1 mm diameter. Ball punch test is further grouped as: “disk bend test”(disc specimen simply supported) and “bulge test”(specimen clamped in between two dies using a fixed number of screws)

Huang *et al.* (1982)**[10]** assessed the ductility of a set of irradiated steels. They used TEM disks of 3 mm diameter, which were simply supported at the circumference. These disks were displaced by a spherical tipped indenter of 1.588 mm diameter. The resulting load - displacement curve was recorded. He used the load line displacement at failure for estimating the effective failure strain.

Baik *et al.* (1986)[11] used penetrators with different tip geometries to punch the small coupon type ferritic steel over a range of temperature for evaluating fracture and impact data from small punch test. They identified the optimum tip geometry as 2.4 mm diameter ball. In the same way Misawa *et al.* (1987)[12] investigated the steels which undergo a transition from ductile to cleavage fracture.

Misawa (1987)[13] *et al.* used recrystallization technique and small punch test to evaluate the fracture toughness of miniature specimen of ferritic steel. They also studied the effect of proton irradiation and/or hydrogen charging on the fracture behavior of HT-9 steel.

Mao and Takahashi (1987) **[14]** Mao *et al.* (1987) **[15]** investigated the deformation behavior of small punch test. They also used recrystallization-etch technique and semi analytical method to find equivalent fracture strain. They related the biaxial equivalent fracture strain linearly to fracture toughness and the result was consistent with Bayoumi and Bassim (1983) **[16]**

Mao and Takahashi (1987) **[14]** proposed an empirical correlation for yield strength (σ_y) and the load at breakaway (P_y) as follows,

$$\sigma_y = 0.36 \frac{P_y}{t_0^2} \qquad (1.1)$$

where σ_y represents yield strength in MPa and P_y is the load at breakaway in N and t_0 is the original thickness of small specimen in mm.

Lucas *et al.* (1984, 1986) **[17, 18]** used a shear punch test on 3 mm diameter TEM disk to obtain strength and ductility properties. Okada *et al.* (1986) **[19]** investigated a way to determine strength and ductility information from the load-displacement curve obtained from the ball punch test on a 3 mm diameter TEM disk with a hemispherical/ball indenter.

Misawa *et al.* (1989) **[20]** used small punch test on cryogenic austenitic steels at 77 K and 293 K to evaluate fracture toughness in a fusion material program. They established a universal relationship between the valid fracture toughness J_{IC} and equivalent fracture strain ε_{qf} for austenitic steels at various temperatures. They also attempted a statistical analysis to estimate the relative change in fracture toughness due to neutron irradiation using the results of the small punch test conducted above room temperature.

Matsushita *et al.* (1989) **[21]** conducted an extensive study involving a series of 1/2Mo, CrMo and CrMoV low alloy steels. They carried out a multiple regression analysis to assess the influences of such parameters as chemical composition, grain size, microstructure and material hardness upon the small punch transition temperature (T_{SP}) and fracture appearance transition temperature (FATT) relationship. They established that grain size, d, was the only significant parameter and that the Charpy FATT could be predicted by the expression,

$$FATT = 1.35\ T_{sp} - 26.6\ (d)^{-0.5} + 326 \qquad (1.2)$$

Where the FATT and the T_{sp} are in Kelvin and d is measured in millimeters.

Mao *et al.* (1991a and 1992a) **[22,23]** used a super small punch test to extract fracture strain information from the TEM disk specimen of 3 mm diameter and 0.25 mm thickness clamped between dies. The results of fracture strain obtained from specimens of 3 mm in diameter have been related almost linearly to the fracture toughness J_{Ic} for elastic and plastic behavior. Mao *et al.* (1991b) **[24]** used small punch test to estimate fracture toughness of ductile and brittle materials.

Lyu *et al.* (1991) **[25]** demonstrated the use of small punch test on welds. The fracture strengths of different micro structures in any localized region of interest on the heat affected zone (HAZ), weld metal and the parent material were evaluated using Ductile-brittle transition temperature (DBTT) approach.

Foulds *et al.* (1991, 1992, and 2001) [**26,27,28]** found the feasibility of extending the small punch test to characterize the fracture toughness of low alloy steels used in fossil and nuclear power plants. Results of their study on CrMoV rotor and bolt steels show that the small punch transition temperature T_{sp} is linearly correlated with FATT, so that the measurement of T_{sp} permits estimation of the standard Charpy FATT through the use of empirical correlation given below,

$$FATT\ (°C) = 3.15\ (T_{sp}) + 500 \qquad (1.3)$$

This reasonably portrayed the data over the temperature range of 100–300°C.

Mao *et al.* (1992) **[29]** used small punch test to determine the yield and ultimate strength on irradiated specimens of size 10 mm x 10 mm x 0.5 mm. They also used sub-sized compact tension (CT) specimens to measure the fracture toughness.

Suzuki *et al.* (1993 and 1992) **[30,31]** employed small punch test on neutron irradiated TEM disks to obtain the fracture related properties (i.e. DBTT and J_{IC}) of ferritic steel using 3mm diameter disks. They found the TEM disk to be very useful in J_{IC} evaluation and DBTT determination.

Eto *et al.* (1993) **[32**] examined the effectiveness of the small punch test for evaluating strength and toughness of irradiated ferritic steels. They have shown that the yield stress and ultimate tensile strength at room temperature can be correlated well with the P_y/t_0^2 and P_{max}/t_0^2 respectively where the terms P_y, P_{max} and t_0.are the load at breakaway point, the maximum load and the original thickness of the specimen. Also, the fracture toughness (J_{IC}) was evaluated using the equivalent fracture strain ε_{qf} and the DBTT was measured from the results of temperature dependence of SP energy which was determined from the area under the load - deflection curve using a statistical analysis based on a Weibull distribution.

Bulloch and Hickery (1994) **[33]** used the miniature specimen test technique to assess the degree of in-service toughness degradation of power plant components. They carried out small punch test on small discs of size 9 mm in diameter and 0.5 mm in thickness. They compared the fracture energy transition temperature from the small punch test with the FATT value obtained from full size Charpy V notch impact specimens.

Bulloch and Hickey (1994) **[33]** and Bulloch and Fairman (1995) **[34]** have suggested that the data from the same material could be better described by a non-linear relationship,

$$FATT\ (°C) = 1.92 \times 10^6 / (T_{sp})^2 \qquad (1.4)$$

This gave a fairly adequate description of the data trend over the total test temperature range.

Foulds and Viswanathan (1994)[6] used small punch test in structural integrity assessment of critical components made of low alloy ferritic steels by measuring the extent of degradation and current level of toughness (fracture toughness related properties such as DBTT and J_{IC}).

Xu and Zhao (1995) [35] described the apparatus and the experimental procedure for the modified miniature specimen test. They obtained the mechanical properties by converting the experimental data obtained and by analyzing elastic-plastic bulge deformation behavior of a thick circular plate loaded at the centre and fixed at the circumference. They gave the following empirical relation for the determination of yield strength.

$$\sigma_y = 0.477 \frac{P_y}{t_0^2} \tag{1.5}$$

Foulds *et al.* (1995) [7] used small punch test to empirically estimate the fracture toughness of the components in the fossil power plants. They used the hemispherical punch having tip diameter of 0.5 mm on small punch disc specimen of size 6.4 mm in diameter and 0.50 mm thickness.

Foulds and Viswanathan (1996) [1] described a non-disruptive miniature material sample removal technique and a test approach that was being applied for in-service integrity assessment to a range of operating electric power plants and petrochemical plants. They used small punch test to estimate the material tensile properties and the fracture toughness value.

Kameda *et al.* (1997) [36] used small punch test on disk specimens of 6 mm diameter and 0.50 mm thickness with the hemispherical punch having tip diameter of 2.4 mm. This was used to examine the in-service environmental attack influence on the microstructure/composition and mechanical properties of CoNiCrAlY coating over nickel base super alloy substrates in land-based gas turbine blades.

Kasi Viswanathan *et al.* (1998)[37]described the use of acoustic emission monitoring during the shear punch tests to reduce the error involved in the estimation of yield strength and strain hardening exponent. Karthik *et al.* (2002) [38] employed the shear punch test to determine the mechanical properties of HAZ formed in 2.25Cr-1Mo weldments. They established a linear correlation between the tensile properties from the standard tests and the corresponding properties obtained from the shear punch test.

Fong and Fraser (1998) [39] developed a small ellipsoidal shape punch to evaluate the mechanical properties of anisotropic Zircaloy-2 tube material. The properties from small specimens were used for correlation with the burst properties of the tube. They obtained a consistent correlation for the punch load and displacement with the burst strength and ductility of the tubes.

Foulds *et al.* (1998)[40] used the miniature disk bend test to estimate the conventional tensile and fracture properties of reactor pressure vessel of A533B type steel. They used the disk shaped specimen of size 6.35 mm in diameter and 0.5 mm thickness. They found good agreement between the results of miniature disk bend test and the standard specimen test.

Bulloch (1998)[41] explained the usage of miniature disc specimens to ascertain the loss of toughness in certain critical engineering components which operate at elevated temperatures. Essentially he demonstrated a non-linear expression between small punch transition temperature (T_{SP}) and the Fracture Appearance Transition Temperature (FATT).

Geary and Dutton (1998)[42]used small punch test on 3 mm diameter discs of three structural steels. They explored the relationship between the data obtained from the punch test load - displacement curve and those obtained from the uniaxial tensile test, fracture toughness test and Charpy test. Lee *et al.* (1998**)[43]** developed a small punch test on rectangular specimens. They determined the energy for fracture from the punch load - displacement curve.

Ule *et al.* (1999) [44] compared the results of the conventional creep tests with those of small punch test specimens of two steels i.e. miniaturized disk bending tests performed on 14 MoV 63 and X20 CrMoV 121 steels. Yu *et al.* (1999**)[45]** established a new test method for evaluating stress corrosion cracking susceptibility of high-strength steels using a small punch (SP) test and acoustic emission (AE) technique. They used miniaturized specimens of size 10 x 10 x 0.5 mm for testing at various loading rates and for various orientations of the specimens. They proved that the small punch test method combined with the AE measurements constituted a useful method to evaluate the stress corrosion cracking (SCC) susceptibility of high strength steels.

Brookfield *et al.* (1999) [46]employed the punch and bulge test to determine the material properties from the small specimens. They also carried out the finite element analysis of the test and validated the results by comparing it with experimental results. They obtained load - displacement curves, Von-Mises stress and equivalent plastic strain from the FEM. They also used the finite element model to establish a relationship between the specimen yield stress and the punch force (F) for elastic-perfectly plastic specimens as,

$$\sigma_y = \frac{F + 49.20}{2.35 \times 10^{-6}} \qquad (1.6)$$

where σ_y is the yield strength in MPa and F is in N.

Song *et al.* (2000)[47] used small punch test and subsize Charpy test to estimate the temper embrittlement of neutron irradiated 2.25Cr-1Mo steel. For the small punch test the specimen size used was of 3 mm diameter, 0.5 mm thickness and for subsize Charpy test it was of size 3 mm x 4 mm x 27 mm. Cheon and Kim (2000)[48] employed small punch test to characterize thermal aging embrittlement of CF8 dublex stainless steel aged at 370 and 400°C.

Zidan and Brookfield (2003)[49] determined the post yield material properties from small punch test results i.e. from the load - displacement curve. They determined the material properties by comparing the experimental curve with a large set of previously determined finite element curves for different post yield properties expressed in terms of Ramberg-Osgood parameters.

Recently Husain (2003) [50] employed small punch test on different materials having varieties of strength to establish a general relationship between the data obtained from small punch test and the yield strength. They used circular, rectangular and square shaped specimens with three different hemispherical ended punches. The empirical equations proposed for the determination of yield strength are shown in table 1.1

Shape of the Specimen	Yield strength in MPa
Circular	$\sigma_y = 1.50 \frac{P_y}{\pi t_0^2} (1+\upsilon) \left[\ln \frac{R}{r} + \left(\frac{r}{2R} \right)^2 \right]$
Square	$\sigma_y = 1.50 \frac{P_y}{\pi t_0^2} (1+\upsilon) \left[\ln \left(\frac{a}{2r} \right) \right]$
Rectangular	$\sigma_y = 0.75 \frac{P_y l}{b t_0^2}$

Table 1.1 Empirical equations for yield strength for various shapes of the miniature specimen

where,

υ = Poisson's ratio = 0.3, r = 0.80 r_0,

r_0 = tip radius of hemispherical headed punch in mm

r = the contact tip radius of rigid punch up to yielding in mm

R = radius of the miniature disk sample in mm

σ_y = Yield strength of material in MPa

P_y = Load at breakaway in N

a = side of square shape miniature specimen in mm

t_0 = original thickness of the specimen in mm

l = length of rectangular shape miniature specimen in mm

b = width of rectangular specimen in mm

Eskner and Sandstrom (2004)[51] developed a small punch test machine and also investigated the miniature disk specimens of size 5 mm and 3 mm in diameter with the thickness ranging from 50 to 400 µm. They assessed the flow curves of low alloy steels and austenitic steels and compared them with the results obtained from standard tensile tests. They obtained the yield stress from small punch test by analyzing the initial elastic deformation with the use of classical bending theory. Shindo *et al.* (2004)[52] examined the effect of magnetic field on the fracture properties of austenitic stainless steels using small punch test method.

Shin and Cai (2006)[53] employed the small punch test technique to evaluate the fatigue crack propagation behavior of surface crack in a cylindrical rod under tension. They tested rods of various sizes and concluded that as the size of the rod specimen is reduced, the fatigue crack growth rate tends to increase when correlated using the stress intensity factor range. This increase in crack growth rate has been attributed to the decrease in the degree of premature crack closure in the small specimens.

Toshiya at el.(2006)[54]conducted the small punch test on reduced activation ferritic/martensitic steels (RAFs) JLF-1 and F82H at 823-923K.The results revealed that the load at initial localized plastic straining F_y and F_{max} determined by the small punch test were well correlated with the yield strength f_y and the ultimate tensile strength f_b respectively. The empirical linear correlation established are $f_y = 1.5\ F_y + 19$ and $f_b = 0.37\ F_{max} + 86$.

Parthepan (2005) [55] recently studied the dumb bell shaped specimen of 0.5mm thickness for various mechanical properties. The output from miniature test in the form of load elongation diagram was recorded. He also developed new empirical correlation for the estimation of yield strength.

3. PREDICTION OF YIELD STRENGTH

Cheon and Kim (1996) [3] proposed that the deformation of the small punch specimen is governed primarily by elastic bending and the effect of denting formed under the ball is negligible, which can validate the simple bending theory. The load at the breakaway (P_y) from the linearity can be used to estimate the yield strength of the material by calculating the maximum bending stress $\sigma_b^{\max}$ in terms of the following equation,

$$\sigma_b^{\max} = \frac{3P_Y(1+\upsilon)}{2\pi t_0^2}\ln\frac{R}{r'}$$

$$r' = \sqrt{1.6r^2 + t_0^{\,2}} - 0.675t_0 \qquad for \quad r \langle \frac{t_0}{2}$$

$$r' = r \qquad for \quad r \rangle \frac{t_0}{2} \tag{1.7}$$

Where R = the radius of the lower die, r = the radius of the contact area between the ball and the SP specimen, t_0 = the thickness of the specimen and υ = Poisson's ratio. Cheon et al.(1996)[3] measured the value r as 0.15, (though did not describe procedure for its measurement). But later, r was determined from an analytical formulation, proposed by Fleury and Ha [1998][56]

The load P_y can be determined graphically by identifying the point of breakaway through offset method (intersection of the tangent lines by t/10 or t/100 offset line). But the value of $\sigma_b^{\max}$ determined by equation (1.7) is found to be much higher than σ_y. This is because of the effect of local deformation on $P-\delta$ relation, which is not very small compared to the other dimensions [Timoshenko (1985)] **[57]**

Xu and Zhao (1995**)[35]** suggested the empirical relation to determine the yield stress based on the analysis of elasto-plastic bulge deformation behaviour of the thick circular disc loaded at centre. The thickness is about the $1/10^{th}$ of diameter and maximum deflection is less than four times of thickness. The following empirical relation gives the yield strength.

$$\sigma_y = 0.477\frac{P_y}{t_0^2} \tag{1.8}$$

where σ_y is in Mpa, P_y is in N and t_0 is in mm.

Mao and Takahashi (1987) [14]established an empirical correlation between the yield strength σ_y (MPa) and P_y (kN). Further, a correlation between ultimate strength σ_{uts} (MPa) or the fracture stress σ_f (SP) can be developed from the load vs. deflection and maximum load P_{max} (kN) using materials of various strengths and specimen geometries as given below.

$$\sigma_y = 0.36\frac{P_y}{t_0^2} \tag{1.9}$$

$$\sigma_{f(SP)} or \sigma_{uts} = \left[130\frac{P_{\max}}{t_0^2} - 320\right] \quad (1.10)$$

where t_0 is in mm.

Cheon and Kim (1996) **[3]** obtained a normalized relationship expressed as;

$$\sigma_y = \frac{P_y}{t_0^2} \times \frac{1}{proportional coefficient} \quad (1.11)$$

The proportional coefficient is 1.68 and 1.6 for 0.5mm and 0.25mm thick specimens, respectively. Here, the proportional coefficient is depending on the geometry of miniature specimens. Fleury and Ha (1998) **[56]** formulated an appropriate analytical description of the uni-axial stress-strain behavior for modeling the elastic bending, plastic bending and membrane stretching regimes of small punch load-deflection curve. This approach is applied to austentic 12Cr-1Mo steel in the temperature range 25-600^0 C.

Han et al.(2006)[58]developed the micro tensile test to predict the mechanical properties of AU thin film for application in microelectromechanical systems (MEMS).Stess strain curve, elastic modulus and ultimate tensile strength of Au thin film was obtained.

Charpy V-Notch (CVN) testing is the most commonly used method to evaluate the ductile-to-brittle transition in steels through the fracture appearance transition temperature (FATT). The FATT is the temperature at which fracture transition from an apparently brittle to a ductile mode occurs in the standard Charpy impact specimen. The test method for determination of FATT is empirical and based on obtaining a correlation between the standard Charpy FATT and the small punch transition temperature, $T_{SP,}$ measured in a series of SP punch tests. The T_{SP} is defined as the temperature at which the fracture energy is equal to the mean of the upper and lower shelf SP energy. The small punch specimen test energy is obtained from the area surrounded under load vs. displacement curve.

Baik et al. (1983) [59]developed an empirical correlation between the transition temperature on the CVN tests, T_{CVN}, and that on the small punch tests, T_{SP},as follows

$$T_{CVN} = \alpha T_{SP} + \beta \quad (1.12)$$

Where α a mechanical correlation is factor and β is the offset transition temperature. The mechanical correlation factor is directly related to the combined effects of strain rate and stress state. The dynamic loading and triaxial stress state in CVN tests facilitate brittle behaviour over a wider temperature range than the static loading and biaxial stress state in the small punch tests. The offset transition temperature (β), depends on the type of materials and its segregated impurities.

Takahashi et al.(1988) [60] have developed the small punch test technique for the purpose of evaluating material mechanical properties. Mercaldi (1989) [61]developed its application in case of high–pressure (HP), intermediate pressure (IP) turbine and generator rotor bores, and low–pressure turbine disks were noted. Foulds and Jawett (1991)[26] developed the small punch test for determination of both fracture properties and FATT. Foulds et al. (1994)[6] determined material fracture properties from miniature sample of 6.4mm diameter by 0.5mm thick disks, using small punch test. Shektar et al. (1999)[62] derived fracture toughness correlation for an improved assessment of structural integrity and remaining life of low alloy steel pressure equipment.

Wakai et al.(2006)[63] developed the new bend test machine to obtain the fracture behaviors of F82H steel for very small end specimens of pre-cracked t/2- 1/3 CVN (charpy V-notch) with 20mm length and deformation and fracture mini bend specimen (DFMB) with 9mm length and disk compact tension of 0.18 DCT type. Further, the effect of specimen size on ductile brittle transition temperature (DBTT) of F82H steel was examined by using 1/2t-CVN, 1/3 CVN, and t/2 -1/3 CVN.It was concluded that DBTT of /2-1/3 CVN and 1/3 CVN is lower than that of t/2-CVN.

4. EVALUATION OF FRACTURE TOUGHNESS

Existing approaches to using the small punch test for measuring fracture toughness are based either on the measurement or the estimation of equivalent fracture strain ε_{qf} and its correlation with fracture toughness, J_{IC}, for ductile case, or the estimation of "Small Punch" fracture stress, $\sigma_{f(SP)}$, and its correlation with fracture toughness K_{IC} for the brittle case. The fracture toughness can be determined by finding out the equivalent fracture strain (ε_{qf}) by developing a theoretical model, Bayoumi and Bassim (1983)[16] concluded that the variation of J_{IC} with ε_{qf} is linear in elastic– plastic region, but the coefficients of linearity were determined empirically.

5. THEORETICAL DETERMINATION OF ε_{qf}

Chakraborty (1970)[64] proposed that the fracture in small punch (SP) test specimen occurs after membrane stretching, and the ε_{qf} can be calculated by using membrane theory proposed by The radial and circumferential strain components, $\varepsilon_r and \varepsilon_\theta$ respectively, are assumed equal and strain in the thickness direction is given by

$$\varepsilon_t = \ln\left(\frac{t_0}{t^*}\right), \qquad (1.13)$$

where t* is the minimum thickness at fracture.

Considering the incompressible plastic deformation, this is expressed as

$$\varepsilon_r + \varepsilon_\theta + \varepsilon_t = 0 \qquad (1.14)$$

The equivalent strain is $\varepsilon_{qf} = \sqrt{2/3}\left(\varepsilon_r^2 + \varepsilon_\theta^2 + \varepsilon_t^2\right)^{0.5}$

(1.15)

Substituting Eqs 1.13 and 1.14 into Eqs 1.15, the equivalent fracture strain is obtained in the form

$$\varepsilon_{qf} = \ln\left(\frac{t_0}{t^*}\right) \qquad (1.16)$$

5.1 Empirical relations for determination of ε_{qf}

Kameda [1994][65] suggested the biaxial fracture strain can be estimated from the empirical relation using small punch test, given as follows;.

$$\varepsilon_{qf} = 0.12\left(\frac{\delta^*}{t_0}\right)^{1.72} \qquad (1.17)$$

where δ^* is max. deflection

Similarly, another empirical relationship proposed by Mao, Shoji and Takahasi (1987)[15] is as follows

$$\varepsilon_{qf} = 0.15\left(\frac{\delta^*}{t_0}\right)^{1.5} \qquad (1.18)$$

5.2 Empirical relation for determination of J_{IC} and K_{IC}

Bayoumi and Bassim (1983)[16] proposed an empirical relation that establishes a correlation between biaxial fracture strain and fracture toughness, J_{IC}, for engineering purposes. However, the relation between fracture toughness and the biaxial fracture strain also contains the yield stress and work hardening coefficient. For the fracture toughness relationship with the fracture strain of ductile materials,

$$J_{IC} = S\rho^*\varepsilon_{qf}\, f\left(E, K, n, \varepsilon_y\right) + 2\sigma_f^2 \pi L_e^* \frac{(1-\upsilon)}{E}$$

(1.19)

Here *S* is the shape factor characterizing the geometry of plastic zone, which is approximated to be 1.0 and ρ^* is the Neuber's micro support effect constant, which is approximated to be 0.025mm. L_e^* is a characteristic distance which depends on the microstructure of the material, $f(E, K, n, \varepsilon_y)$ is a function determined from material stress vs. strain relationship.

Takahashi et al. (1980)[66] proposed a linear correlation between equivalent fracture strain and fracture toughness (J_{IC}), based on the single specimen technique, as follows;

$$J_{IC} = 280\varepsilon_{qf} - 50 \qquad (for \quad \varepsilon_{qf} \rangle 0.2)$$

Where J_{IC} is in $\left(kJ/m^2\right)$ (1.20)

Similarly another empirical relationship suggested by Mao and Takahashi (1987)[14] is

$$J_{IC} = 345\varepsilon_{qf} - 113 \qquad (for \quad \varepsilon_{qf} \rangle 0.4)$$

Where J_{IC} is in $\left(kJ/m^2\right)$ (1.21)

(1.16)

In both the cases (Eqs 1.19 and Eqs 1.20) the correlation coefficient were determined by plotting $J_{IC} and \varepsilon_{qf}$ at different temperatures, and for different materials, and it was observed to be valid for the ductile fracture phenomena.

In the brittle or predominantly elastic case, K_{IC}, is proposed to be related to the small punch fracture stress, $\sigma_{f(SP)}$, by Mao, Saito and Takahashi (1991)[67]

$$K_{IC} = 0.07\sigma_{f(SP)} \qquad (1.22)$$

where K_{IC} is in MPa√m and σ_f in Mpa

Lucas et al.(1990)[2] and Mao et al. (1991)[67] proposes another standard relation for K_{IC}, has been approximated from the reported and predicted J_{IC} values under plain strain condition

$$K_{IC} = [EJ_{IC}/(1-\upsilon^2)]^{1/2} \qquad (1.23)$$

Ha and Fleury (1998)[68] developed the correlation between small punch test and Charpy impact tests to evaluate the FATT. Two distinct approaches based on the fracture stress and fracture energy were used to estimate the fracture toughness in the upper-shelf and lower-shelf regimes in low alloy steel.

Kasada .et al. (2005) [69] studied the master curve (MC) methodology to evaluate the change in fracture toughness in the cleavage regime of a reduced –activation ferritic (RAF) steel before and after a thermal embrittlement treatment was applied by using the sub-sized compact tension (CT) specimens. It was found that the shift of the reference temperature obtained by the MC methodology was larger than that f the ductile–brittle transition temperature shift obtained by charpy impact tests.

6. NUMERICAL TECHNIQUES

6.1 Finite Element Method (FEM)

Application of finite element methods for the analysis of Diminutive specimen is very promising for obtaining the material properties. There are two methods namely forward or direct approach and reverse or inverse approach. The forward approach is to model the miniature specimen using the known material properties and getting the results like load - displacement curve, stress - strain diagram *etc.* whereas the inverse method is applied to extract material properties using the data obtained from miniature test results.

In an indirect method also known as inverse finite element method, the experimental output is divided into a number of linear parts. Results from a series of finite element simulations are compared to the experimental output. And the most closely

(1.21)

fitted data sets of assumed values become the properties of the unknown material specimen.

Manahan (1983)[70]performed finite element analysis to convert miniature disk bend test experimental load - deflection curve into useful stress-strain curve and for obtaining information on ductility using ABAQUS. The miniature disk bend test contains material, geometric and boundary non-linearity. Out of these, the boundary non-linearity had not

(1.22)

been adequately addressed in general purpose finite element code at that time. He proposed a new finite element frictional contact boundary condition model to accurately analyze the miniature disk bend test using FEM.

Foulds *et al.* (1995)[**7**] used large deformation finite element analysis of small punch test to measure the critical strain energy density. They carried out finite element analysis of small punch test using commercially available Lawrence Livermore National Laboratory NIKE2D code. The absorbed strain energy density at the observed crack initiation location was computed. In order to account for the change of contact between the punch head and the small specimen's top surface, a sliding interface was used.

Cheon and Kim (1996) **[3]**used small punch test to estimate the yield stress from the initial deformation behaviour of heat treated SA508 Cl.3 nuclear pressure vessel steel and 12Cr turbine rotor steel. They used t/100 offset method to find out the load at breakaway point. They also carried out FEM of small punch test using the commercially available ABAQUS code. The load-displacement curve obtained by FEM simulation of small punch specimen was used to find the yield stress.

Eck and Ardell (1998)[**71]** used the controlled-flaw method in conjunction with the miniature disk bend test (MDBT) to measure the fracture toughness of the inter-metallic alloy Ti-46.5Al-2.1Cr-3.0Nb-0.2W, heat-treated to produce a duplex microstructure. This method requires knowledge of the fracture stress which cannot be calculated analytically for disk-shaped specimens that deform plastically prior to failure. The fracture stresses were therefore determined using the finite element program NIKE2D, along with the elastic constants of TiAl, the measured yield stresses and the published tensile stress-strain curve as input information. The fracture toughness was obtained by analyzing the data on fracture stress versus indentation load for specimens for which fracture initiated at the corners of the Vickers indentations.

Brookfield *et al.* (1999)**[46**] used the finite element analysis to understand the behaviour of specimens under the punch and the bulge test. The finite element analysis gave punch force-displacement curve, Von-Mises stress, equivalent plastic strain and vertical deflections of the upper and lower surface of the disk specimen. They used FEM to find the relationship between the specimen yield stress and punch force for elastic-perfectly plastic material. They had shown that yield stress is not significantly influenced by experimental uncertainties.

Husain *et al.* (2003)[49] used small punch test and conducted 3D finite element modeling using ABAQUS to find out the effect of punch diameter on the load-displacement diagram. They used three hemispherical headed punches to conduct the small punch test on circular disk specimen having 10 mm diameter and 0.5 mm thickness which was clamped along the circumference.

Partheepan(2006)[**72]** conducted the finite element simulation of miniature test to obtain the mechanical behavior of materials. He has modeled the dum bell shaped miniature specimen geometry along with the loading pins using the commercially available finite element based software "ABAQUS". The simulation is carried out using implicit code. The study also contains the detailed description of steps involved in modeling and analysis of the results. The miniature specimen is modeled in two dimensional spaces as a deformable body and the loading pins are modeled as rigid bodies. The miniature specimen is modeled using quadrilateral plane stress elements. Simulation of miniature test is carried out in such a way that it represents the experimental situation as closely as possible by prescribing the appropriate boundary conditions. The load – elongation diagrams from finite element simulation for different materials are obtained and compared with the experimental results. A wide spectrum of information has been collected from the finite element simulation of miniature specimen test. This includes the deformation behavior of miniature specimen, load – elongation curve, von-Mises stress contour, equivalent plastic strain etc.

6.2 Inverse Finite Element Method

Hainsworth *et al.* (1996)[73] used inverse FE approach to analyze the shapes of the nano-indentation curve and thus quantitatively model the relationship between Young's modulus, indentation hardness, indenter geometry and the resultant maximum displacement for a given load.

Beghini *et al.* (2001) [74] used the numerical approach for the evaluation of the stress-strain curve for metallic materials starting from the results of instrumented spherical indentation test. They modeled spherical indentation process by means of finite element for materials having different σ-ε curves. By means of proper use of these results, they developed an iterative procedure, which allows the σ-ε curve to be obtained with satisfactory accuracy for a large number of materials.

Dao *et al.* (2001)[75] had undertaken a comprehensive computational study to identify the extent to which elasto-plastic properties of ductile materials could be determined from instrumented sharp indentation and to quantify the sensitivity of such extracted properties to variations in the measured indentation data. They also carried out large deformation finite element computations using general purpose commercially available ABAQUS for 76 different combinations of elasto-plastic properties that encompass a wide range of parameters commonly found in pure metals and alloy. In this study, the Young's modulus (E) was varied from 10 to 210 GPa, yield strength (σ_y) from 30 to 3000 MPa, strain hardening exponent (n) from 0 to 0.5 and the Poisson's ratio (ν) was kept fixed at 0.3. They used dimensional analysis to construct a new set of dimensionless functions to characterize instrumented sharp indentations. Forward and reverse analysis algorithms were thus established; the forward algorithms allow for the calculation of a unique indentation response for a given set of elasto-plastic properties, whereas the reverse algorithms enable the extraction of elasto-plastic properties from a given set of indentation data. They noted that the plastic properties of materials extracted from instrumented indentation are very sensitive to even small variations in the indentation load-depth responses.

Extending Dao's approach, Bucaille *et al.* (2003) [76]studied the influence of the included angle of conical indenters and the friction coefficient on the force penetration curves based on finite element analysis on elasto-plastic material. Based on this analysis, they suggested a more general method for determining the plastic properties of metals. They have shown that friction has a significant effect on the normal force measured on tips having included angles lower than or equal to 50°. They also found that in determining strain hardening coefficient, sharper the indenter the better the accuracy of the result.

DiCarlo *et al.* (2003)[77] presented a method for determining the stress-strain relationship of a material from hardness values (H) obtained from the cone indentation tests with various apical angles. The materials studied were assumed to exhibit power-law hardening behaviour. As a result, the important properties are the Young's modulus (E), yield strength (σ_y) and the work-hardening exponent (n). Previous researchers showed that E can be determined from the initial force-displacement data collected while unloading the indenter. They did a parametric study of σ_y/E and n using the finite element method to model material behavior. They used regression analysis to correlate the H/E findings from the simulations to σ_y/E and n. With the a priori knowledge of E, this correlation was used to estimate σ_y and n.

Lee *et al.* (2003)[78] proposed a novel and simple experimental and computational method to extract stress-strain curves based on finite element modeling of nano-indentation. They verified this method using bulk Al by comparing the stress-strain curves extracted as obtained from tensile testing and applied to Al thin films deposited on a Si substrate.

Husain *et al.* (2004)[79] performed an experimental and a computational study of small punch test using circular disk shaped miniature specimen through inverse finite element procedure using ABAQUS computer code for the determination of constitutive tensile behavior of materials. Their proposed inverse technique is based on the small punch experimental load vs. displacement curve. They conducted small punch tests (SPT) on circular disk shaped specimens (10 mm diameter, 0.5 mm thick) made from three different steels. By using the output of experimental small punch test, they traced constitutive stress–strain curves through inverse technique. The computed constitutive stress–strain curves are compared with the curves obtained from a standard conventional tensile test and the results obtained for all the three cases demonstrated the effectiveness of the inverse procedure

7. ARTIFICIAL NEURAL NETWORKS (ANN)

Neural network has the ability to learn directly from test data set or examples of the material by adaptation of the weights it assigns to each data set, extract information from noisy data, and predict the future trends. Neural networks can be trained to solve problems that are difficult for conventional computers or human beings. A neural network constitutes a parallel distribution processor made up of simple processing units or nodes. It has a natural propensity for storing experimental knowledge and making it available for use Haykin (1997)][80].

Huber and Tsakmakis (1999)[81] performed spherical indentation test to obtain constitutive properties from the resultant test data using neural network. They obtained a data base for the training and validation of the neural network by carrying out numerous finite element simulations using commercially available ABAQUS code, for various sets of material parameters. The simulation and training of the neural network was performed using the SNNS code (SNNS, 1995). From the different training algorithms supplied by SNNS, the so called 'Rprop' algorithm was chosen. (Rprop stands for 'Resilient back propagation' and is a local adaptive learning scheme, performing supervised batch learning in multilayer neural networks).

Muliana *et al.* (2002)[82] presented 2D axisymmetric and 3D finite element models of nano-indentation tests. They compared the calculated load-displacement curves from the FE models with the load-displacement curves from nano-indentation measurements on annealed copper. They also performed numerical parametric studies to examine the effect of indenter geometry and the material's stress-strain behavior on the load-displacement response. An artificial neural network was used to model the indentation test. In this approach, ANN models are generated to approximate the FE load-displacement curves for a wide range of material and geometric parameters. They examined the ability of ANN models to predict the indentation response of other FE results not used as part of the training data. They showed that the monotonic indentation load-displacement response during loading contains ample information for the ANN model to extract material flow properties of the indented material.

Haque and Sudhakar (2002)[83] used artificial neural network back propagation model to predict the fracture toughness and tensile strength as a function of microstructure. They found that both fracture toughness and tensile strength increase with the increase in martensite content in a dual phase microstructure of a micro-alloy steel. They used the ANN training model to predict the best/optimum toughness properties in terms of interfacial annealing temperature and martensite content.

McBride *et al.* (2004) [84] developed a model for the prediction of correlation between alloy composition and microstructure and its tensile properties of gamma based titanium aluminide alloys through the use of ANN. The input used for the neural network were alloy composition, microstructure type and test temperature. The outputs of the model were ultimate tensile strength, elongation, reduction in area and elastic modulus. The simulation and training of the network was based on feed forward neural network with the data collected from various literatures. They also have shown the use of this model to optimize processing parameters to obtain desirable tensile properties.

Madhusudan (2004)[85] developed a neural network model for predicting the yield stress, and fracture toughness values based on the results from small punch tests and standard tests on different materials.

Sergueeva A. V(2009)[86] and Lord J. D et al(2010)[87] has demonstrated that a sub sized and miniature specimen tests over specific materials can effectively be used to predict the mechanical behavior of metals by correlating the properties through empirical relations.

Lim, W., Kim, H.K(2013)[88] has successfully developed a simple miniature tensile testing machine that can effectively used for laboratory demonstration. Machine is versatile and can be employed for testing various shape miniature specimen.

8. CLOSURE

In this paper, the basic concepts of miniature specimen test techniques are described, along with the review of the application of small punch specimen test method to evaluate the mechanical behaviors of in-service structures/components. The paper gives the comprehensive study of large number of mechanical and fracture properties, such as: yield strength, ultimate strength, ductility (fracture strain), fracture appearance transition temperature (FATT), fracture toughness (K_{IC} and J_{IC}) etc., that have been sought with small punch test technique. The numerous empirical equations proposed by various investigators for prediction of these mechanical and fracture properties have been presented and discussed. The numerical simulation using finite element method of such small punch test specimen by various researchers is also discussed. It is apparent from the review that there is a lack of a general methodology, which could be used for various materials and structures. There is a need for additional research to develop appropriate correlations to accurately predict behavior of standard size specimen or the full size structure based on the testing of miniature samples. In addition, more detailed investigation is required for developing standard experimental set-up and procedure for diminutive specimen tests, which have the potential of overcoming the limitations of material, and testing space etc. The diminutive tests appears to be the only method existing at present which is capable of providing determination of several mechanical properties of service exposed materials and components.

9. NOTATION

σ_f fracture strength

L_e^* distance based on microstructure of the material

σ_{uts} ultimate strength

σ_y yield strength

$f(E, K, n, \varepsilon_y)$ a function determined from material stress vs. strain relationship

ε_θ circumferential strain

ε_{qf} equivalent fracture strain

$\sigma_b^{\max}$ maximum bending stress

δ^*	maximum deflection at fracture
ε_r	radial strain
ρ^*	the Neuber's micro support effect constant
ε_t	thickness direction strain
CVN	Charpy V-Notch test
E	modulus of elasticity
FATT	fracture appearance transition temperature
J_{IC}	fracture toughness for ductile case
K_{IC}	fracture toughness for the brittle case
α	mechanical correlation factor
n	strain hardening coefficient
β	offset transition temperature
P_{max}	maximum load
υ	poisson's ratio
P_y	the load at the breakaway point
r	the radius of the contact area between the ball and the SP specimen
R	the radius of the lower die,
S	the shape factor characterizing the geometry of plastic zone
SP	small punch
t^*	the minimum thickness of SP specimen at fracture point
t_0	the initial thickness of the specimen
T_{CVN}	transition temperature from Charpy V-Notch testing
T_{SP}	small punch transition temperature

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