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MEASUREMENT OF MECHANICAL PROPERTIES**

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GOVERNMENT OF INDIA
ATOMIC ENERGY COMMISSION

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आवांश

टेंसाइल स्पेशिमेन को सब-साईज स्पेशिमेन से अधिक छोटा करने पर बहुत तरह की चुनौतियाँ आती हैं ; जैसे स्टैण्डर्ड के अनुसार स्पेशिमेन की स्वीकार्यता, एस्पेक्ट रेशियो, गेज सेक्शन में निम्नतम ग्रेन की संख्या, निर्मित रूप में माप एकसमानता आदि। इनके अलावा विकृति की माप के लिए अत्यन्त कम जगह का होना एक व्यावहारिक चुनौती है। इन सभी चुनौतियों के बावजूद विश्व में अति लघु माप के मिनिएचर स्पेशिमेन का परीक्षण की संख्या में निरंतर वृद्धि हो रही है। मिनिएचर स्पेशिमेन का परीक्षण की संख्या में निरंतर वृद्धि होने के मुख्य कारण नए धातू का विकास एवं कार्यरत घटक की उपयुक्तता का आश्वासन प्रदान करने का यह एक बड़ा माध्यम है। हालांकि मिनिएचर टेंसाइल स्पेशिमेन द्वारा मेकैनिकल गुणों का मूल्यांकन अन्य उपलब्ध मिनिएचर नॉवेल परीक्षण विधियों; जैसे स्मॉल पंच परीक्षण, एबीआई, मिनिएचर श्रांति परीक्षण, मिनिएचर संघट्ट परीक्षण आदि से ज्यादा विश्वसनीय है क्योंकि इसमें मेकैनिकल गुण प्रत्यक्ष रूप से प्राप्त किए जाते हैं। यह रिपोर्ट मिनिएचर टेंसाइल स्पेशिमेन के परीक्षण विधि के चिविध पहलुओं; जैसे 3 से 5 मिमी गेज लंबाई के स्पेशिमेन का ज्यामितीय अभिकल्पन, उनका निर्माण, स्पेशल फिक्सचर का विकास और विकृति के मापन हेतु प्रकाशीय विधि का इस्तेमाल का व्योरा देता है। स्पेशिमेन का ज्यामितीय अभिकल्पन एवं प्रतिबल के कारण इसके व्यवहार को एफ ई एम विश्लेषण द्वारा स्थापित किया गया है। परंपरागत टेंसाइल टेस्ट स्पेशिमेन एवं मिनिएचर टेंसाइल टेस्ट स्पेशिमेन के परिणामों के बीच अच्छी तालमेल मिनिएचर टेंसाइल टेस्ट स्पेशिमेन की क्षमता का द्योतक है।

Abstract

Miniaturisation of the tensile test specimen below the sub-size level poses various challenges, such as conformity of specimen to various acceptance criteria as per standard test specimen, aspect ratio, minimum number of grains required in a gauge cross-section, fabrication for uniformity in metrological values, etc. Apart from these, measurement of strain over a very limited available space on the test specimen is another practical challenge. Despite these limitations, miniature specimen testing is increasingly being used worldwide these days. The driving forces behind increasing use of miniature test techniques are new material development, assuring fitness of component after in-service-inspection, low dose of radiation exposure due to smaller dimensions of test specimens etc. However, the evaluation of mechanical properties from a miniature tensile test has a greater advantage over the other miniature novel test techniques, such as small punch test, ABI, miniature fatigue and impact tests etc., as it is a direct method of measurement of mechanical properties. This report covers various aspects of miniature tensile test methodologies, which include geometrical design of specimen having gauge length of 3-5mm, fabrication, development of special fixtures for gripping the test specimens, and use of optical method for strain measurement. The geometrical design of the specimen and its behaviour over application of tensile load has been established using FEM analysis. A good agreement between conventional and miniature test results exemplifies the potential of the miniature tensile test technique.

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Use of Miniature Tensile Specimen and Video Extensometer for measurement of Mechanical Properties

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1. INTRODUCTION

Evaluation of mechanical properties from small or miniature specimen has been a subject of interest among researchers for quite long time. The main driving forces for development of various sizes of miniature test specimens are development of new material and property evaluation of any in-service component. The limited material available due to scooped out volume from any in-service component restricts the shape and size of the test specimens. The basic philosophy adopted in various test standards for conventional tensile test specimens specify dimensions and their ratios; however for miniature specimens such standardisation is not available. This has resulted in large and different designs of the miniature specimens [1-4]. The miniaturisation of specimen cause the so-called ‘scaling effect’, which leads to different material behaviour in the microscale compared to the macroscale [5]. In mechanics, this effect is limited to the strength dependence on cross-sectional area, however in general it is much wider and may relate not only to specimen size and geometry, but also, to other factors, such as micro-structural constraints, viz grain size in the cross-section, micro-structural an-isotropy, micro-structural inhomogeneity etc., surface effect and residual stress. Non-uniform stress distribution during tests provides an additional length parameter that affects the size effect. Papers describe the strength and ductility characteristics dependence on cross-sectional area of test specimen, specimen fabrication methods, surface conditions, gauge length etc.

This report gives methodology for evaluation of mechanical properties of under service pressure vessels, by way of scooping out small volumes of material using a scooping device, Fig. 1 [6]. The scooped out volume of material is boat shaped and has dimensions of 42mmx30mmx3mm. The geometries of various test specimens, viz. miniature tensile, fatigue, Charpy and small punch test, which can be made out from the boat sample are shown in Fig. 2 [7]. This report is limited to the evaluation of mechanical properties using the miniature tensile test specimen.



Fig. 1: Scooping device, scooped region and scooped sample

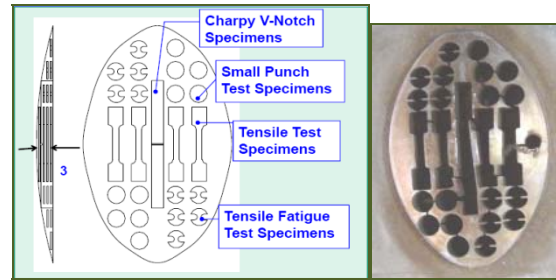


Fig. 2: Test Specimen layout in scooped sample

In order to ensure the usefulness of miniature test techniques, it is important to have comparable results of miniature tests and conventional tests with respect to the mechanical properties, viz. Ultimate tensile strength (UTS), yield strength (YS) and elongation. Two different types of tensile test specimens; namely Type-I (conventional round) specimen, Type-II (sub-size flat) specimen have been tested and compared with the results of Type-III (miniature specimen), Fig. 3. The geometry of the miniature tensile test specimen has also been evaluated using finite element analysis to get results comparable with those from conventional tests.

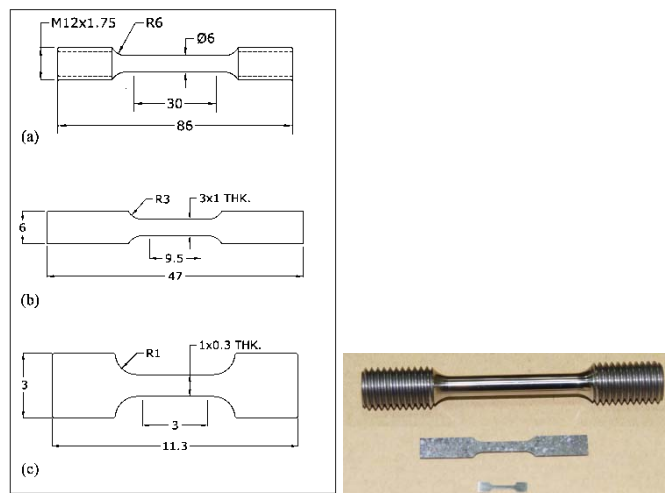


Fig. 3: Dimensional details of (a) Conventional (Type-I), (b) Sub-size (Type-II) and (c) Miniature Tensile (Type-III) Test Specimens and their photographs

2. ISSUES RELATED TO MINIATURE TENSILE TESTS:

Micro-scale uniaxial tests are not yet standardized except for the specific requirements for testing foil materials given in ASTM E345-93 but have the potential to provide uniaxial stress strain data that is representative of macro behaviour. There are many metrological issues, such as specimen geometry, specimen preparation methods, microstructural changes, alignment, ductility, resolution of load cells and strain-measuring devices etc. that can influence the test

results. The various issues with respect to development of Miniature Test techniques can be listed as follows [8]:

- The requirement to have sufficient representative volume in gauge section: The test specimen may not represent the bulk material due to various methods applied on it for its fabrication, such as EDM, grinding, polishing etc. The damage caused due to specimen preparation methods may be significant to affect the results. Specimen geometry, preparation and surface finish are important parameters to be precisely standardized.
- The necessity to ensure the effects of constraint features, such as notches, edges, corners etc. needs to be addressed:
- Micro-structural features, such as grain shape, phase, orientation, texture, precipitate distribution, and their size relative to the dimensions of the test specimen can have significant effect on the flow stress.
- The increased likelihood of probabilistic events from small heterogeneities impinging on the gross mechanical behaviour
- The possibility of surface residual stresses influencing measured gross mechanical behaviour
- The lack of standardization supported by international round robins to validate micro-scale test procedures. Even in case of conventional test specimens, the ductility varies due to change in shape and sizes of test specimens. In order to have comparable ductility, the test specimens must be geometrically similar, like L/D ratio for round specimens and L/\sqrt{A} ratio for flat specimens [9]. It is likely that similar relation will be required for miniature test specimens as well. There is a need for a coherent international effort for standardizing miniature test specimen and technique and adopt these as standard techniques for the mechanical property evaluation of the operating pressure vessels and similar components.
- The challenge of accurate strain measurement: The miniature-size of test specimen does not allow the use of standard extensometers for strain measurement data. The displacement data obtained from crosshead travel of the machine may give large scatter in data. These days different techniques are being employed for measurement of displacement in miniature testing. LVDT, electrical resistance based transducer, capacitance gauges, line scan cameras, laser interferometry, digital speckle pattern interferometry, Digital Image Correlation (DIC), photoelastic stress analysis and thermoelastic stress analysis are such techniques having their own advantages and disadvantages [8].
- The utility of mechanical modeling to optimize test piece geometries: Finite element methods are being effectively utilised for optimization of test specimen geometries and the results are also being validated.
- The need to assess the statistical variation in data: There is a need to address the scattering in data by addressing the proper methods for specimen preparation and limiting the variation in various metrological and metallurgical parameters of the test specimens.

3. MATERIALS AND EXPERIMENTAL PROCEDURES:

Three different materials, listed in Table-1, were used for carrying out the specimen preparation and testing. Same block and heat of material were used for fabrication of all types of test specimens. The tests have been carried out in different test laboratories to minimise any result-bias for any particular machine. The testing machines used were Instron and Tinius Olesen.

Table-1: Chemical Composition of materials used for experiments

Material	Cr	Mo	V	C	Ni	S	P	Co	Fe
20MnNiMo55	0.17	0.5	--	0.2	0.6	0.005	--	--	96.97
CrMoV	2.81	0.62	0.26	0.16	0.8	0.005	0.008	0.015	94.3
304LN	18.34	0.37	0.07	0.02	8.32	0.0196	0.03	0.13	70.71

3.1 Testing Fixtures:

The miniature specimen having very limited size and grip section, required development of special testing fixture, Fig. 4. Two types of test fixtures were developed for pinned specimen and shoulder supported specimens.



Fig. 4: Test Fixtures for Miniature Tensile Test Specimen

3.2 Ductility measurement for different-sized specimens:

In tensile tests, apart from UTS and YS elongation is also an important parameter which needs to be correlated with the conventional test specimen results. As the size of miniature specimen, having a gauge length 3-5mm did not allow mounting of any mechanical extensometer, earlier extension measurements were done using the cross-head travel. The measurement of elongation using the cross-head travel gives lower value of extensometer, Fig. 5, due to the effective smaller length of necking region. In order to minimise the difference in the elongation properties of different gauge length specimen, it is important that they are geometrically similar.

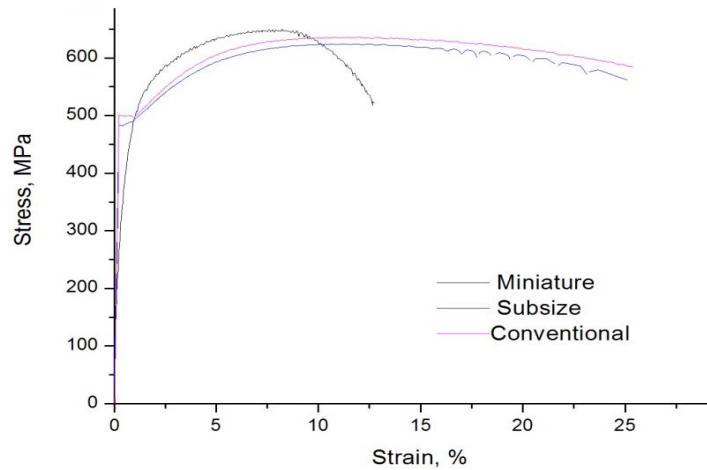


Fig. 5: Elongation properties dependence on the gauge length

The ductility measurement consists of two components, the uniform extension up to necking and the localised extension once necking begins. The extent of uniform extension depends upon the metallurgical condition of material and the effects of specimen size and shape on the development of the neck. Fig. 6 shows the variation of local elongation with gauge length of a prominently necked tensile specimen [9].

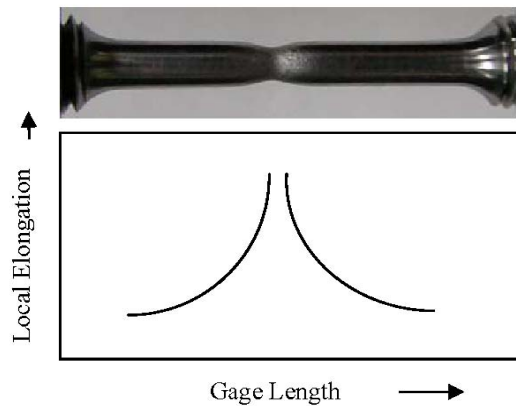


Fig. 6: Ductility results dependence on Gauge length

It is seen that shorter the gauge length the greater the influence of localised deformation at the neck on the total elongation of the gauge length. The total extension is given as,

$$\text{Final Length} - \text{Initial Length} = \text{uniform extension} + \text{local extension at necking}$$

$$\text{i.e. } L_f - L_0 = e_u L_0 + \alpha \text{-----(1)}$$

The tensile elongation is given as

$$e_f = (L_f - L_0) / L_0 = e_u + \alpha / L_0 \text{-----(2)}$$

where, L_0 = initial gauge length, L_f =final gauge length, e_u =uniform strain, e_f =total strain and α = local extension at necking

A number of attempts have been made to rationalise the strain distribution in tensile test and based on which it has been concluded that geometrically similar specimens develop geometrically similar necked region. According to Barba’s law gives, $\alpha=\beta\sqrt{A_0}$, the elongation becomes

$$e_f = e_u + \beta\sqrt{A_0}/L_0 \text{-----(3)}$$

It is generally recognised that in order to compare elongation measurements of different-sized specimens, they must be geometrically similar. The equation (3) shows that for measurement of ductility properties of different-sized specimens the ratio $L_0/\sqrt{A_0}$ for sheet specimen and L_0/D_0 for round specimen must be maintained. Table-2 gives the dimensional relationship followed by different countries vis-a-vis in the present work.

Table-2: Dimensional relationships of tensile specimens used in different countries

Type of Specimen	ASTM A370	ASTM E8M	Great Britain (before 1962)	Great Britain (Current)	Germany	Present report
Round (L ₀ /D ₀)	4.0	5.0	3.54	5.0	10.0	5.0 (Type-I)
Sheet (L ₀ /√A ₀)	2.8-14.1	3.2-14.1	4.0	5.65	11.3	5.5 (Type-II) 5.5 (Type-III)

3.3 Use of Video Extensometer:

As the miniature test specimen size does not permit for mounting any mechanical extensometer on its gauge section, there was a need for using non-contact type extensometer. Various types of such extensometers have been used by many researchers, like laser based, DCM, video extensometer etc. In present case, video extensometer having single camera with fixed focus, Fig. 7, has been used for measurement of gauge section extensions. The technique works on the principle of pattern recognition technique, in which the gauge section is marked with target points, and the strain between them is measured by the camera.

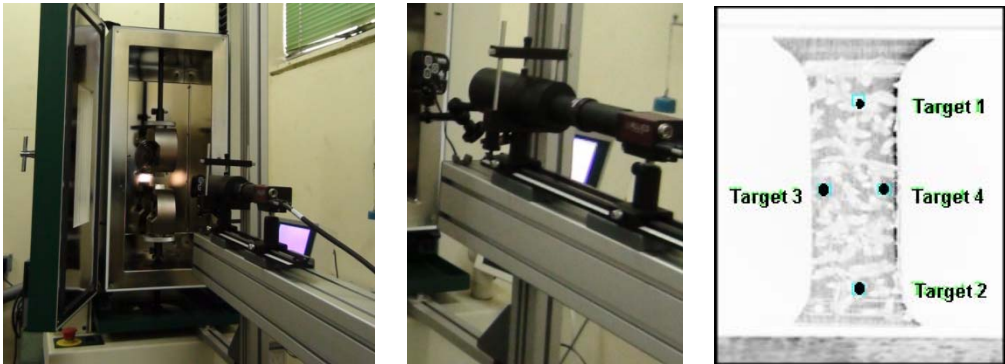


Fig. 7: Video Extensometer

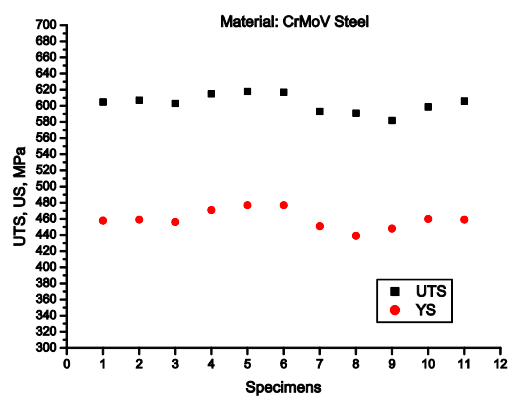
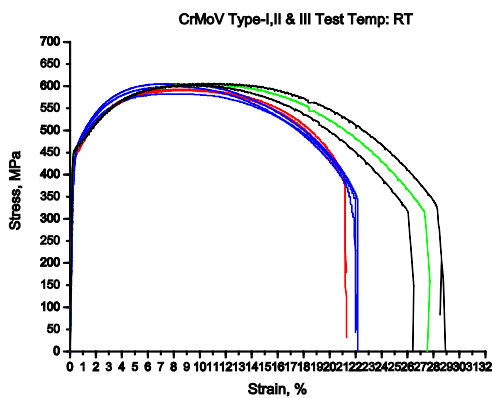
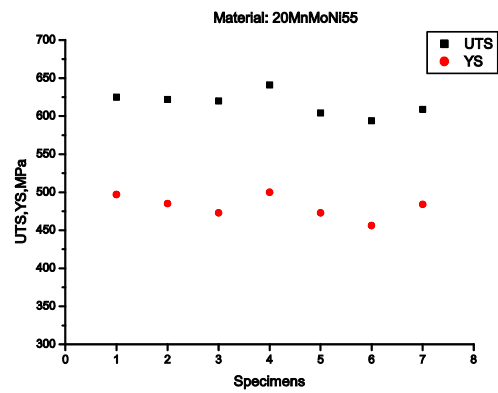
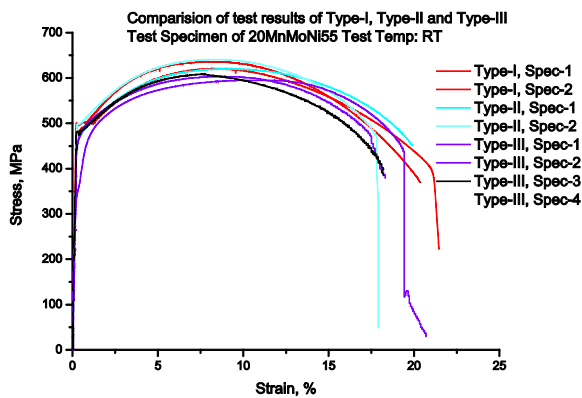
4. RESULTS AND DISCUSSIONS:

Results of tests conducted at room temperature for three materials namely 20MnMoNi55, CrMoV steel and SS304LN at a strain rate of 10^{-3} per sec are summarised in Table-3. Fig 8-10 give the results of the various tests conducted on the specimens. For 20MnMoNi55, the test of conventional (Type-I) specimens, give the minimum UTS and YS values as 622 MPa and 485 MPa respectively. In comparison to these values the UTS values given by miniature test specimens (Type-III) are in the range of 2-4.5% less. The YS values given by Type-III test specimens are in the range of 0.2-6% less in comparison to Type-I specimens. The uniform elongation given by Type-III test specimens are in the range of 7.7-9.8% in comparison to the range of 8.1-8.2% for Type-I specimens. The total elongation of Type-III test specimens are 18.2-20.9% in comparison to 20.3-21.5% of the Type-I specimens. For CrMoV steels there are significant differences in mechanical properties in two perpendicular directions, marked as B1 and C1 as suffixes in the nomenclature in the table-3. Out of total six specimen of Type-I tested, three each from block B1 and block C1, the UTS values are 603-605 MPa for block B1, and 615-618 MPa for block C1. The corresponding YS values for B1 and C1 blocks for Type-I specimens are 456-459 MPa and 471-477 MPa. The elongation values of these specimens are however, in the same range, 26.5-28.9% irrespective of their orientation. Block B1 was used for fabrication of miniature specimens and their test results give UTS values as 582-606MPa and YS values as 448-460MPa, which are comparable to their Type-I values. The uniform elongation values for Type-I and Type-III are in agreement however, the total elongation values (22-23.8%), are less in comparison to Type-I specimens' elongation values (~27%). This may be due to the reason the thickness/width ratio of 0.445 was taken in this case, whereas specified value of 0.3. For the third material SS-304LN, the minimum UTS and YS values for Type-III specimens are 540MPa and 225MPa in comparison with 571MPa and 237MPa for Type-I specimens. The higher YS values may be attributed to any residual stresses in the Type-III specimen during the fabrication and polishing stage. This needs further tests and analysis. The uniform elongation and total elongation of Type-I and Type-III specimens are comparable. Overall it can be concluded that the results obtained by miniature test specimens are comparable with those obtained by conventional test specimens within a certain error band. With the precise control of surface finish of test specimen, dimensional deviations, alignment of test fixtures, better strain measurement, the error band can be minimised and potentiality of miniature test specimen can be enhanced.

Table-3: Test Results

Material	Type of Specimen	Gauge Section, mm	Gauge Length, mm	UTS, MPa	YS, MPa	e_u	e_f	Strain Rate, /s
20MnMoNi55	Type-I	dia 6.05	30	625	497	8.22	20.32	1×10^{-3}
20MnMoNi55	Type-I	dia6.00	30	622	485	8.15	21.45	1×10^{-3}
20MnMoNi55	Type-II	0.990x2.9533	9.5	620	473	8.26	19.88	1×10^{-3}
20MnMoNi55	Type-II	0.9867x2.9833	9.5	641	500	8.9	17.9	1×10^{-3}
20MnMoNi55	Type-III	0.30275x1.022	3	604	473	8.43	18.30	1×10^{-3}
20MnMoNi55	Type-III	0.2978x1.018	3	594	456	9.83	20.91	1×10^{-3}
20MnMoNi55	Type-III	0.3621x0.996	3	609	484	7.73	18.19	1×10^{-3}

CrMoV-B1	Type-I	dia 6mm	30	605	458	9.54	27.7	1x10 ⁻³
CrMoV-B1	Type-I	dia 6mm	30	607	459	11.10	28.93	1x10 ⁻³
CrMoV-B1	Type-I	dia 6mm	30	603	456	8.97	26.48	1x10 ⁻³
CrMoV-C1	Type-I	dia 6mm	30	615	471	9.89	27.93	1x10 ⁻³
CrMoV-C1	Type-I	dia 6mm	30	618	477	10.55	28.86	1x10 ⁻³
CrMoV-C1	Type-I	dia 6mm	30	617	477	9.32	27.80	1x10 ⁻³
CrMoV-B1	Type-II	0.971x3.0224	9.5	593	451	9.43	21.4	1x10 ⁻³
CrMoV-B1	Type-II	0.9725x3.0285	9.5	591	439	8.72	21.3	1x10 ⁻³
CrMoV-B1	Type-III	0.4462x1.0	3	582	448	9.54173	21.99	1x10 ⁻³
CrMoV-B1	Type-III	0.47x1.0	3	599	460	8.73	23.8	1x10 ⁻³
CrMoV-B1	Type-III	0.443x1.0	3	606	459	7.57	22.17	1x10 ⁻³
SS304LN	Type-I	dia 6mm	30	565	228	68.75	76.04	1x10 ⁻³
SS304LN	Type-I	dia 6mm	30	573	237	66.36	72.66	1x10 ⁻³
SS304LN	Type-II	0.9949x3.055	9.5	571	256	65.28	76.08	1x10 ⁻³
SS304LN	Type-II	1.007x3.058	9.5	581	251	68.24	75.68	1x10 ⁻³
SS304LN	Type-III	0.3145x1.03	3	559	244	69.50	75.2	1x10 ⁻³
SS304LN	Type-III	0.2993x1.06	3	540	244	65.60	69.4	1x10 ⁻³
SS304LN	Type-III	0.3223x1.05	3	549	225	61.60%	69.4	1x10 ⁻³
SS304LN	Type-III	0.299625x1.08	3	547	257	67.39238	72.59	1x10 ⁻³



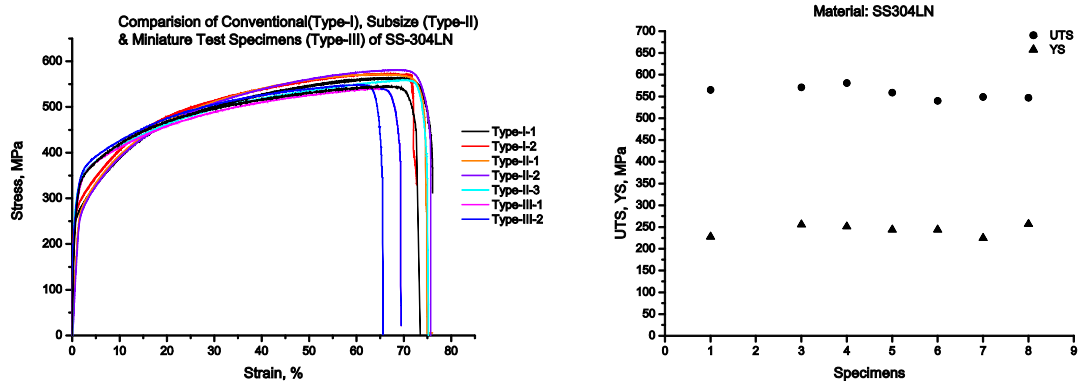


Fig. 8: Tensile Properties Results

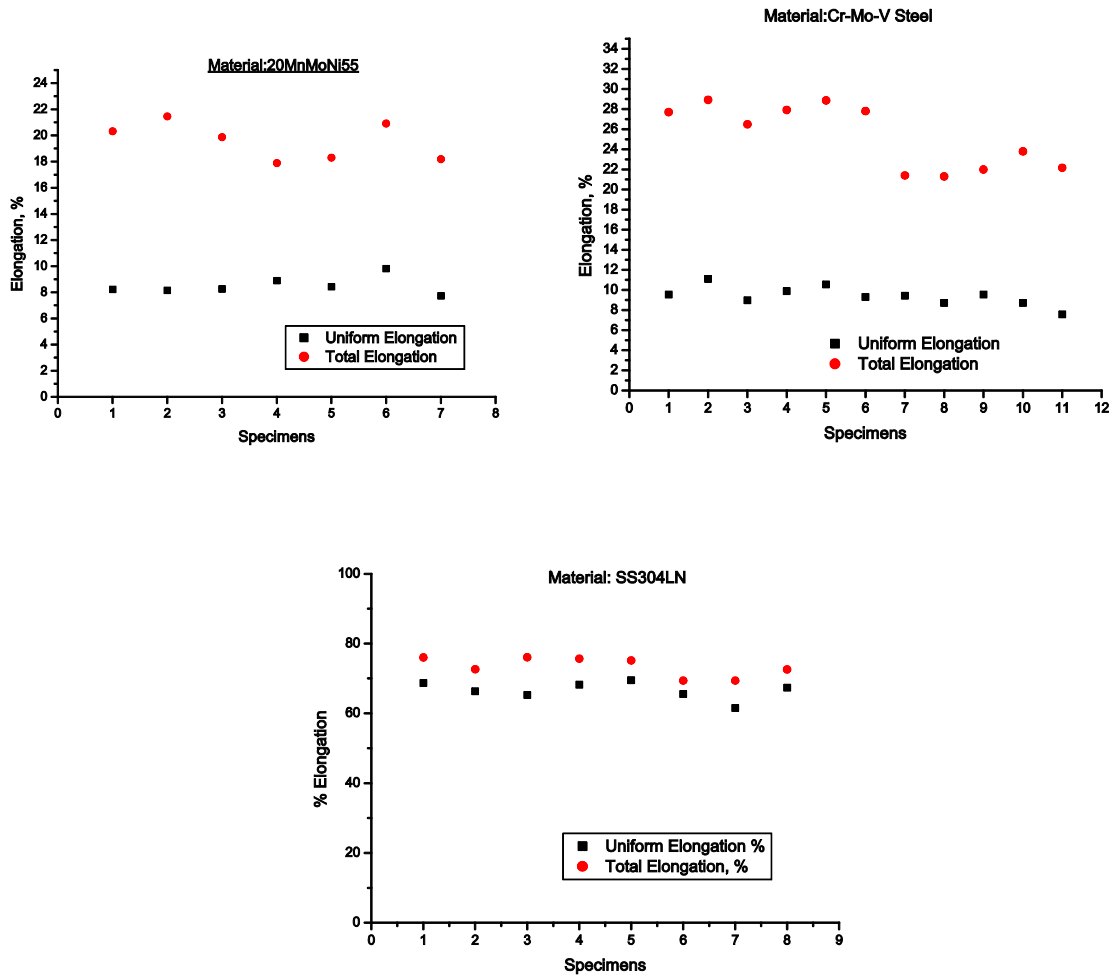


Fig. 9: Elongation and Tensile Properties Results

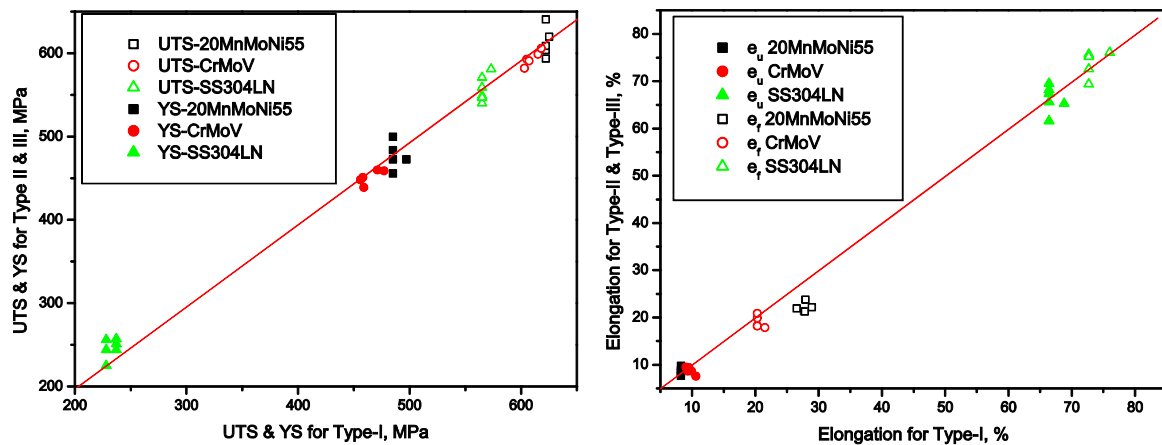


Fig. 10: Scatter in Elongation and Tensile Properties

5. FINITE ELEMENT MODELING (FEM)

5.1 Geometrical modelling

Finite element modelling computations were conducted using the commercial finite element software. The 2-dimensional finite element model of quarter shape of the miniature test specimen was used due to geometric symmetry, as shown in Fig. 11. The test specimen is modelled with four noded quadrilateral plane stress elements because the thickness of the body or domain is small relative to its lateral (in-plane) dimensions. The stresses are functions of planar coordinates alone, and the out-of-plane normal and shear stresses are zero. The meshing area was divided in three zones; first the gauge zone, the gripping shoulder zone and the top part of the specimen, which is broader than the gauge section. Mapped meshing was adopted for the gauge length while other sections were free meshed with emphasis given to the number of elements in the gauge section and shoulder sections of the specimen. The model consists of 17586 nodes and 17210 quadrilateral plane stress elements (of unit thickness) after mesh independency analysis. Geometric nonlinearity was also modeled on top of material non linearity. In order to represent the experimental setup, the loading pin was simulated for providing load to the specimen. The loading pin was treated as 2-D rigid body with a low friction coefficient of zero. Due to symmetry only one pin is modelled and the motion in X-direction was arrested. However, it was allowed to experience displacement in the Y direction as in the experimental situation. Contact elements were defined between the loading pin and the shoulder contact line of the specimen model. A concentrated force was applied to the reference point of the pin in the Y direction. The load is applied through the amplitude field in a linear fashion i.e. at time zero, the load value is zero and at time $t=1$ the load is maximum. All these prescribed conditions are applied in the respective reference node of load pins.

5.2 Material modeling

In the elastic analysis of simulation, the material properties of the columns were defined by elastic modulus and Poisson's ratio. In the nonlinear analysis stage, material nonlinearity or plasticity was included in the FEM using a mathematical model known as the associated

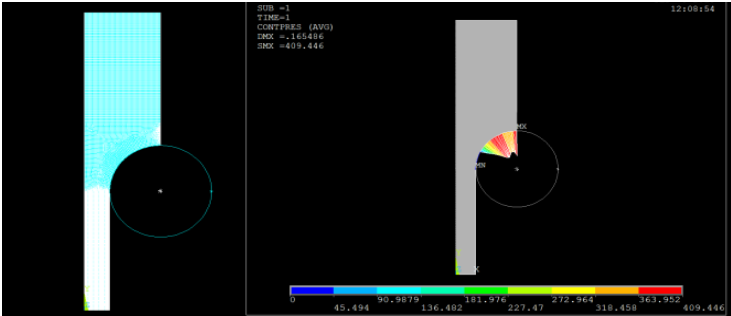
plasticity flow rule with von Mises yield criterion. In the finite element simulation of miniature specimen, the plastic properties are defined together with the isotropic hardening rule. It means that the yield surface size changes uniformly in all directions such that the yield stress increases in all stress directions as plastic straining occurs. In the incremental plasticity model true stresses (t) and true plastic strains (tp) of a conventional test specimen were specified. This is because, during the tensile test, the cross-section area of the sample decreases due to elongation, while each subsequent increase of sample length takes place over an already elongated sample length. The true stress-true strain defines the flow curve appropriately as they represent the basic flow characteristics of the material. The incremental plasticity model requires the true stress-strain curve from the point corresponding to the last value of the linear range of the engineering stress-strain curve to the ultimate point of the stress-strain curve. The material properties used for the finite element simulation were determined through standard uniaxial tensile test and are shown in Table-4.

Table-4: Material Properties used in FE Simulation
 Material: 20MnMoNi55
 Young’s modulus (GPa) : 194
 Poisson’s ratio 0.29

True stress(MPa)	True plastic strain
401	0.00206
455	0.00272
479	0.00438
503	0.009719
534	0.01772
583	0.0322
620	0.04759

5.3 Finite Element Results:

A concentrated load of 300 N (for two pins load would be 600N) is applied on the reference node of the pin in a linearly varying manner i.e. at time $t=0$, the load was zero and at time $t=1$, the load applied is (300N) with the use of amplitude option in FEM software. For each time step both the load taken by the specimen and the corresponding elongation in the specimen is stored in the software. Fig. 12 shows the load-time diagram obtained by the FE simulation of specimen and experimental results, which are in good agreement.



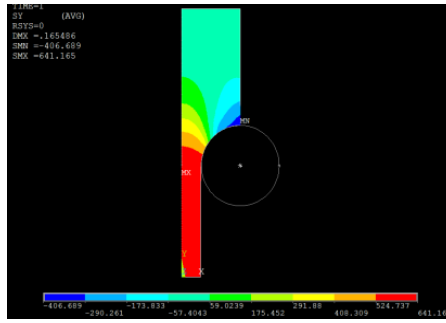


Fig. 11: Geometrical Modelling and Results of FE analysis

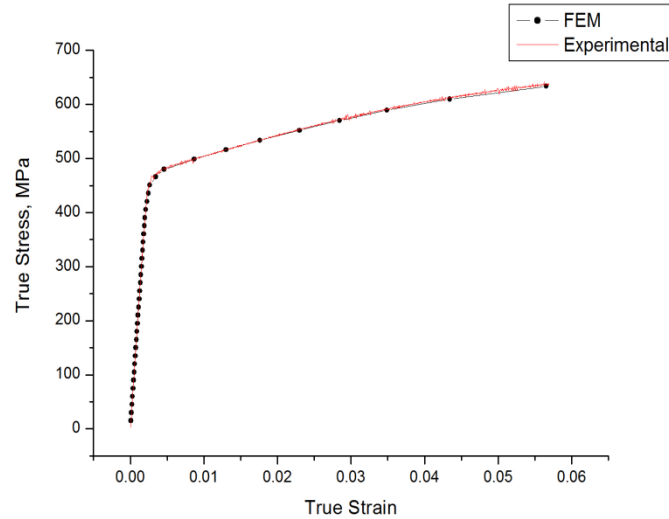


Fig. 12: Comparison of Experimental Results and FE analysis

6. CONCLUSION:

Miniature tensile specimen test techniques have been found to be very good for evaluation of mechanical properties of service-aged components when conventional destructive tests to obtain these data are not possible. These test techniques are being increasingly employed to characterize mechanical properties, such as yield strength, tensile strength, and fracture toughness, of structural materials. For tapping the vast potential of these miniature test techniques, there is a need for a coherent international effort for standardizing the techniques to have proper co-relation with the conventional test specimens and to adopt these as standard practices for the mechanical property evaluation of operating pressure vessels and similar components. This needs a standardization and adaptation of the following:

1. Shape and size of miniature test specimen
2. Method for fabrication of test specimen
3. Test procedure
4. Acceptability criteria for the test results.

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