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EFFECT OF COLD WORK ON MECHANICAL PROPERTIES OF EXPANDABLE TUBULARS

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ABSTRACT

Some of the challenges being faced by the petroleum development industry worldwide are low-cost and more efficient well completion, water-shutoff, other types of zonal isolation, etc. Successfully addressing these issues, solid expandable tubulars (SETs) are finding increasing use for enhanced oil recovery from difficult or damaged wells. All SET applications revolve around cold expansion of the tubular in a casing or in an open hole, by hydraulically pushing a cone through the tubular, or by mechanically pulling it. Issues such as maximum expansion ratio, post-expansion pipe integrity, etc are directly linked with material properties of the tubular before and after expansion. An SET expansion test rig has been designed, fabricated, and commissioned at the Engineering Research Lab, Sultan Qaboos University (SQU) in collaboration with Petroleum Development Oman (PDO). Various types of material testing and characterization equipment augment this facility. The current paper presents some results from an ongoing study about comparison of pre and post-expansion mechanical properties of the tubular material subjected to different expansion ratios. Material properties specifically addressed here are elastic modulus, yield strength, tensile strength, fracture stress, fracture strain, and ductility.

Keywords: Solid expandable tubular (SET), expansion test rig, mechanical properties, tensile testing

1. INTRODUCTION

Solid expandable tubular (SET) technology is being used as an answer to challenges such as unconventional gas formations, re-entry wells, and low-producing wells. SET-based solutions have been utilized during both completion and production stages. SETs can help to increase fracturing rates, thereby increasing the production significantly [1]. For more than a decade, expandable technology has proved its value as an alternative to conventional zonal isolation techniques. Incorporating swelling elastomer seals, SETs can effectively isolate different zones without cementing, thus overcoming many problems faced in production from mature/brown fields, deep and ultra-deep wells, and other highly complex reservoirs [2]. SETs also play an important role in workover operations such as correction of production profiles, fixing of cementation problems, repair of corroded casings, and perforating of new zones. SET systems also find applications in smart completions, multifracturing solutions, and other unconventional enhanced oil recovery (EOR) methods [3].

SET technology involves the cold expansion of a tubular by hydraulically or mechanically forcing a conical mandrel through it; Fig-1. The permanent plastic deformation is achieved by cold-working the solid tubular beyond its elastic limit [4]. SET applications suitable for specific drilling problems and field conditions cannot be designed and implemented without a good understanding of the changes in material behavior of the tubular due to the expansion process (to be able to assess structural integrity of the tubular after expansion). Before doing any post-expansion material characterization, a huge experimental setup is needed for cold expansion of actual petroleum tubulars to different final diameters.

2. EXPANSION SETUP

Perhaps the second-largest facility of its kind, an SET Test Rig has been designed, fabricated, and commissioned [5] at the Sultan Qaboos University (Muscat, Oman) for full-scale expansion tests of solid tubulars (of different tube sizes, materials, and end conditions); Fig-2. Expansion ratio (ER) is defined as the ratio of the final and initial cross-sectional areas of the expandable tubular. Different conical mandrels have been designed and manufactured for different tubular sizes [6] and ERs (8% to 30%). Tubes of up to 10m length and 10-300 cm diameter can be expanded hydraulically or mechanically under different boundary conditions. A carefully designed aligner (one for each mandrel size) is attached to the downstream side of the cone for proper alignment of the expansion process. Tubes of up to 2m length can be expanded mechanically, using a 4000-kN Dartec universal testing machine in compression mode. For hydraulic expansion of 3-10m length tubes, a 2000-bar pump is used to push the mandrel with a flow rate of 11 liters/min. LVDTs, ultrasonic gauges, and a data-logging system are used to record real-time test data such as strain, displacement, expansion force, tube thickness and length, and mandrel speed and location. This tubular expansion is a complex procedure, and requires detailed and careful test preparation and post-test activities.

When one end of the expanding tubular is fixed and the other is free, the test is called *fixed-free*; to maintain volume-constancy, length contraction takes place to balance out the diametral expansion. When both ends are fixed, the test condition is known as *fixed-fixed* (FF); as no length contraction can now occur, the result is a higher thickness reduction and higher expansion force than for the fixed-free case. For this study, expansion tests were carried out for 7⅝-inch outer-diameter tubulars using 8-inch, 8¼-inch and 8½-inch diameter cones under fixed-free condition, and under fixed-fixed condition (using an 8-inch cone). For test nomenclature, U represents unexpanded sample; M and H stand for mechanical and hydraulic expansion respectively; numbers 1, 2, and 3 denote 8, 8¼, and 8½-inch cone sizes; and FF refers to the fixed-fixed end condition. For instance, H3 is the label for test samples cut from tubes hydraulically expanded using 8½-inch expansion cone.

3. MECHANICAL TESTING

To prepare samples for mechanical testing, sections from the tubulars are first cut (before and after expansion) using a band saw. Tensile testing specimens (in line with ASTM/DIN standards) are then cut from these sections using milling, turning, and grinding operations. Because of the curvature involved, special jigs and fixtures are required to hold the samples during machining. A Dartec universal testing machine of 600 kN capacity (equipped with a data-logging system) was used to determine pre and post-expansion tensile properties of the tubular material; Fig-3.

4. MICROSCOPY AND FRACTOGRAPHY

To understand the effect of cold work on mechanical behavior of the tubular material, optical microscopy was performed on unexpanded and expanded samples to record changes in the crystal structure. For failure analysis, fractography of samples fractured during tensile tests was carried out using a scanning electron microscope (SEM).

5. RESULTS AND DISCUSSION

Tensile results for each sample are plotted as stress-strain graphs, and mechanical properties are extracted from these graphs, including modulus of elasticity, yield strength, ultimate tensile strength, fracture stress, fracture strain, and ductility (% elongation). All reported values are average of results from three different samples; a 3-sample graph for one case is shown in Fig-4. Results are summarized in Table-1.

Elastic Modulus

Compared to an elastic modulus of around 200 GPa for typical mild steels, the *E*-value for this steel is in the 70-78 GPa range. One reason for this discrepancy is the very special nature of SET steel. This is a unique steel specially developed for in-situ cold expansion during petroleum drilling operations. Not much is known about the material development of SET tubulars, owing to reasons of confidentiality. However, these steels most probably belong to the specialty class known as transformation induced plasticity (TRIP) or twinning induced plasticity (TWIP) steels, having a peculiar ultra-fine grain microstructure; Fig-5. As to the slight variation in *E*-values for different expansion ratios, it is also against normal behavior of regular steels, which are expected to have the same slope for different amounts of cold work or heat treatment. However, TRIP-type steels exhibit the unique behavior of dependence of elastic modulus with plastic strain, explaining this discrepancy [7].

Yield Strength: Except for the 8-in cone, yield strength consistently increases for larger size of expansion cone (higher amount of cold work). This is in line with the standard behavior of ferrous metals which exhibit strain hardening with cold work. Lower σ_Y value for 8-in expansion compared to unexpanded samples may be due to some experimental error. The significantly high yield strength for fix-fix expansion (8-in cone) should be especially noted. As mentioned above, when the tubular is fixed at both ends, normal length contraction cannot take place, resulting in higher amount of thickness reduction, which translates into more-than-usual cold work and significantly higher expansion forces and stresses.

Slightly higher value of yield strength during hydraulic expansion as compared to mechanical expansion is consistently observed for all three cone sizes. Various effects need to be considered to explain this trend. Speed of cone travel is different in mechanical and hydraulic expansions, and the effect of tool speed on resulting stress in metalforming operations has been consistently documented [8]. Heat of deformation during mechanical expansion is affected by air-cooling provided by atmospheric air, while the material being deformed is water-cooled during hydraulic expansion; water quenching generally increases strength compared to air-cooling. Mechanical expansion is done in several steps (due to maximum travel limit of machine head in one step) while hydraulic expansion is done in a continuous single step. In mechanical expansion, tubular material is free to spring-back as soon as the cone passes a certain point. In hydraulic expansion the material is under high hydraulic pressure even after the cone has passed a given location; this longer exposure to stresses obviously generates higher amount of work hardening. Mechanical expansion has free-fixed boundary conditions while hydraulic expansion is fixed-free.

Ultimate strength: Overall, ultimate strength increases after expansion (cold work), though not by a significant amount. This is as expected during cold working of steels. Also, as expected, σ_U values are slightly higher for hydraulic expansion as compared to mechanical expansion.

Ductility: Compared to unexpanded material, ductility consistently decreases as the amount of cold work increases (larger cone size, higher expansion ratio, more cold work). Effect of cold work on microstructure of steels is an established fact. Cold work results in grain size refinement, giving rise to strain hardening or loss of ductility. This transition from ductile to brittle failure due to cold working can be easily verified through fractography of the failed specimens; Fig-6.

6. REFERENCES

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Table 1. Summary of expansion results; same tubular material, different expansion ratios

Sample #	**Expansion Type**	***E*** (GPa)	σ_Y (MPa)	σ_U (MPa)	**Ductility** (%EL)
U	Unexpanded 7⅝-in tubular	77.797	580.274	657.211	17.99
M1	Mechanically expanded (8-in cone)	69.734	410	716.001	13.68
H1	Hydraulically expanded (8-in cone)	72.931	520	744.368	13.45
FF	Hydraulically expanded fix-fix (8-in cone)	74.105	642.430	741.984	6.98
M2	Mechanically expanded (8¼-in cone)	74.209	589.221	731.156	10.34
H2	Hydraulically expanded (8¼-in cone)	74.739	612.387	776.586	10.01
M3	Mechanically expanded (8½-in cone)	74.027	625.769	773.930	9.76
H3	Hydraulically expanded (8½-in cone)	76.630	645.806	817.164	9.09

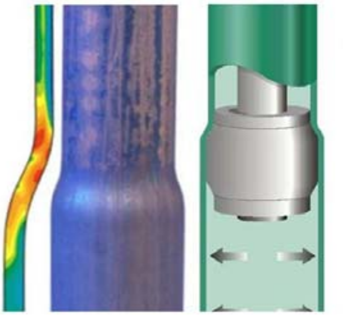

Figure 1. Schematic diagram of tubular expansion

Figure 2. Solid expandable tubular test rig at Sultan Qaboos University, Muscat

Figure 3. Tensile test setup

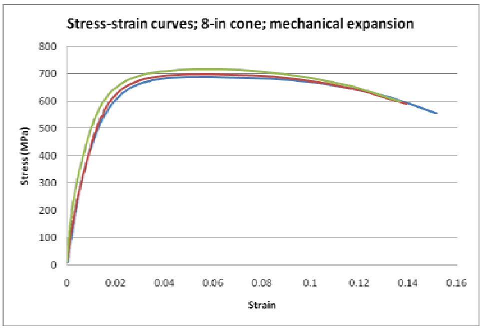

Figure 4. Three-sample stress-strain curves after mechanical expansion using 8-in cone

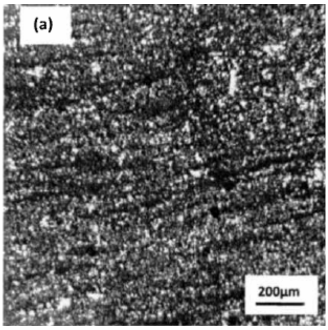

Figure 5. Optical micrograph of fix-fix expanded material showing very fine grain structure and shear bands

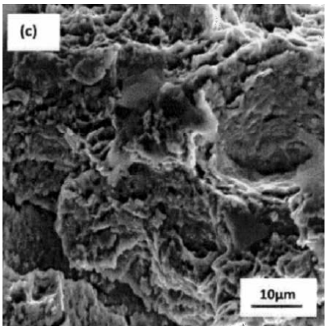

Figure 5. SEM fractograph of expanded sample (8¼-in cone) showing microscopic cracks and voids, and dimples in the region of overload