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Microstructure evolution of ultra-fine grain low-carbon steel tubular undergoing radial expansion process

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ABSTRACT

Tubular expansion is a cold metal forming process where diameteral change is achieved by propagating a conical mandrel through the tubular either by mechanical pull or hydraulic push. Cold metal forming alters post-expansion mechanical and microstructural properties of tubular material, which may lead to premature failure during operation. In order to prevent tubular from failure, its post-expansion material and mechanical properties must be investigated thoroughly. Initial grains morphology, distribution of phases, and subsequent variation in material and mechanical properties due to expansion process of low-carbon LSX-80 steel tubular are investigated in the current study. The observed microstructure is typical of high strength steels with a mixture of carbon-poor and carbon-rich regions. A noticeable volume fraction of martensite phase was also observed. Presence of smaller grains in the material is a clear indication of the application of grain refinement mechanism to improve strength and toughness. Microhardness and Charpy impact tests were done on unexpanded and expanded sections of tubular in order to determine their mechanical properties. In addition, fractographic analysis was accomplished and obtained results showed that the morphology of the fractured surface was nearly alike at the macroscopic scale throughout the range of expansion ratios considered in this study. However, at the fine microscopic scale, the fractured surface was mostly ductile at low expansion ratio, while it was mainly brittle at large expansion ratio. Hence, an expansion ratio in the vicinity of 15% is highly recommended for the current tubular material in order to have adequate safe margin for down-hole application. An alternative material has to be selected and/or developed in order to realize the goal of achieving higher expansion ratio ($\geq 30\%$) while preserving the tubular structural integrity after expansion.

1. Introduction

The petroleum industry is facing new and difficult technical challenges for exploration and production of hydrocarbons. Critical issues are related to remote locations such as deep-water and arctic environment drilling, harsh conditions such as high-temperature and high-pressure formations, and non-conventional reservoirs such as heavy oil, tight gases, tar sands, etc. dominate the list among others. The progress made to overcome these challenges by researchers, and subsequently by engineers, have resulted in a number of technological innovations to provide effective and efficient solutions. Although these developments provided an imminent solution but have not matured yet. One such innovative technology, which aimed to resolve drilling issues associated with ultra-deep or deep water, is termed as solid expandable tubular (SET) [1]. It is an innovative extension of traditional tube manufacturing process, which has gradually drifted from drilling conventional telescopic wells to slim wells. The use of SET is successful in producing hydrocarbons under extreme exploration and production scenarios. It involves pushing or pulling a lubricated mandrel assembly through a tubular of small inside diameter than the mandrel and expanding it in-situ [2]; Fig. 1. It reduces the tapering effect of conventional wells design resulting in an appropriate conduit size that allows drilling deeper. This is extremely interesting because it simplifies the wells design i.e., just one tubular size all the way until the target depth, rather than starting with a very large diameter at surface to leave a room for telescoping. Hence, one can drill a well with less energy, steel, mud, and cement, ultimately reducing the cost and environmental footprint of the drilled well [3]. Further advantages include; drilling and completions in difficult formations, in-situ repair of wells, etc. [4]. From an economics and performance perspective, it enables significant reduction in non-productive drilling and

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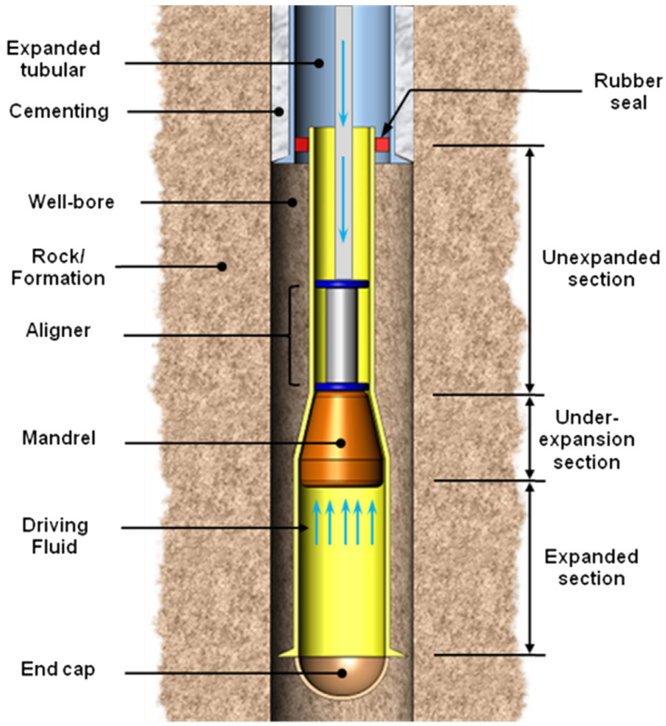

Fig. 1. Schematic representation of mandrel-tubular assembly in down-hole tubular expansion process.

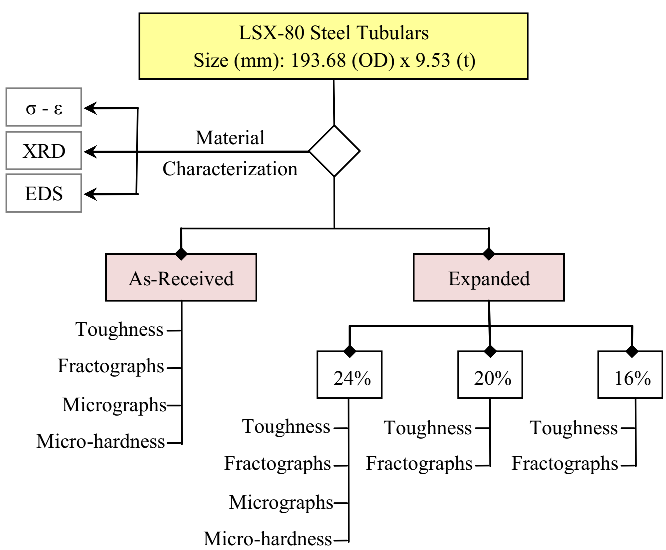

Fig. 2. Flowchart of experimental investigation.

completion time, possibility of using rigs of smaller sizes, less environmental effect, potential savings, etc. [5,6].

A review of pertinent literature on SET shows a significant number of successful trials and case histories that demonstrate the usefulness of the technology in addressing issues that are faced by oil and gas industry [7,8]. However, a closer look on the use of SET in designing the complete well, from surface to the reservoir, showed the successful construction of slim wells and not the mono-diameter wells, as is the target for future. In other words, the adoption of SET technology has not yet achieved the desired level of success to become a primary option for designing complete wells. The industry seems to be reluctant for its full-scale implementation. The major possible reason behind this dogmatic approach is the limited knowledge about the tubular behavior after it undergoes through large magnitudes of plastic deformation in down-hole conditions. Besides, there is a lack of confidence in the performance of tubular during abnormal circumstances. Lack of availability of post-expanded tubular data in down-hole conditions is another limiting factor. In brief, all of these have resulted in limited information available about the tubular performance after expansion, which brings an uncertainty within the community of researchers and application engineers. An in-depth understanding of mechanics, materials and lifetime operational performance is needed for its full-scale adoption [9].

Numerous other factors may affect the properties of tubular material. A number of application based studies have been carried out by oilfield operators and service providers to investigate the effect of the expansion process on mechanical properties [10,11], geometrical variations [12], burst and collapse pressures [13,14], and corrosion resistance [15]. It was found that tubular strength increases due to strain hardening effect while its total elongation, and burst and collapse pressures rating tend to decrease. To maintain volume-constancy, it was also found that the tubular length shortens and its wall-thickness reduces to balance out the increase in diameter [16]. However, no attempts can be found in literature on investigating the microstructural variations induced by the expansion process and its influence on the macro-level properties of the tubular. It is an established fact that the final mechanical and structural properties of any material are intimately connected to its micro-level characteristics including chemical composition, initial manufacturing and further deformation process, and resulting microstructure including the amount and distribution of primary phases, grains sizes and morphology, and grains orientation, to name a few. Considering API (American Petroleum Institute) 5L pipeline steels used for oil and gas transportation as an example, significant research work has been done on the relationship between microstructure and mechanical properties. Sung et al. [17] investigated the effect of ferrite on Charpy impact properties of API-X80 pipeline steels. Having a ferrite volume fraction of 20% and above, resulted in a dominant ductile fracture, which was much higher than that of the conventional X80 steel. Joo et al. [18,19] investigated the anisotropy of fracture toughness and the role of delamination and crystallographic texture on the anisotropy. It was found that toughness at certain orientations is worse because a large density of cleavage planes is placed parallel to the fracture plane of the Charpy specimen. Another critical issue in design of these steels is the low carbon content intended for good field weldability [20]. The compensation in strength loss is attained through additions of micro-alloying elements such as niobium, titanium and molybdenum [21]. These additions contribute to the enhancement of strength and toughness both directly, through solid solution strengthening, precipitation hardening and microstructural refinement, as well as indirectly, through improved hardenability and related modification of the produced transformation microstructures [22,23]. Another technique, typically used, to achieve desired mechanical properties is to control the tubular microstructure through properly designed thermo-mechanical processing schedules [24,25]. Rosado et al. [26] presented the recent developments in mechanical properties and metallurgical features of high strength pipeline steels.

All of these studies have greatly helped in advancement of API pipeline steels up to API X80 and beyond. However, very little or no information is available on the relationship between mechanical properties and microstructural features of high strength tubulars used for oil and gas wells production lines and casings. It was mainly focused on conventional API 5CT grades including K-55, N-80, L-80, S-95 and P-110 [27,28]. No published data is available in literature, which address the mechanical and microstructure properties variation of the new LSX-80 steel grade developed