INTERPRETATION OF STRESS-STRAIN CURVE IN PIPELINE RESEARCH

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Abstract

For the design of on-shore pipelines installed in areas that are susceptible to ground movements and off-shore pipelines, axial stresses above yield must be considered. In such so-called strain-based design, knowledge of the stress-strain behaviour of the pipeline steel and girth welds is highly important. These behaviours are influenced by many factors, including: welding parameters, operation temperature, tensile test specimen geometry and orientation, and microstructure of the steel. This paper focuses on the influence of the tensile test specimen geometry and orientation, for the case of UOE formed pipes. As regards the geometry, it is concluded that the stress-strain diagram is most representative for a flat full-thickness test specimen. As regards the orientation, the yield stress is higher for transversal test specimens, as compared to longitudinally oriented test specimens.

Keywords pipeline steels, strain-based design, stress-strain curve, UOE, microstructure, anisotropy

1 INTRODUCTION

The mechanical properties of pipeline steels change during plate production and subsequent pipe forming. First, the rolling process is a source of anisotropy, producing differences in stress-strain behaviour between the directions parallel and perpendicular to the rolling direction. Second, pipes can be produced from flat plates in different ways. This paper focuses on the UOE process, illustrated in Figure 1. It is performed by three press processes (edge crimping press, U-ing press, O-ing press), followed by seam welding and a circumferential expansion [1]. Obviously, this cold forming process produces changes in the mechanical properties of the used steel.

Fig. 1: Schematic illustration of production of UOE pipe.

The stress-strain behaviour of a steel is generally characterized by a tensile test. This paper discusses, for the specific case of UOE-formed pipes, the influence of test specimen geometry and orientation on the measured stress-strain behaviour.

2 GEOMETRY OF THE TENSILE TEST SPECIMEN

As regards common geometries of tensile test specimens in the pipeline industry, a distinction can be made between a round bar and a flat strap (full thickness) specimen.

Looking at a round bar specimen, the measured yield stress (YS) depends on the specimen diameter. This diameter is usually much smaller than the plate thickness, and thereby merely produces a measurement of local properties. This effect is pronounced for round bar specimens of girth welds, since these welds show a large degree of heterogeneity. Indeed, a weldment mostly consists of several weld runs, producing a mixture of coarse and fine microstructures. This results in heterogeneity in the thickness direction (Figure 2, above, [2]) and in the circumferential (‘o’ clock) direction (Figure 2, below, [3]). In the base metal, the microstructure also varies in the thickness direction. This phenomenon is due to the inhomogeneous cooling during plate production after rolling.
Considering the abovementioned, round bar specimens may produce stress-strain curves with limited representativeness in terms of the global structural behaviour. Therefore, to obtain an average value of strength properties throughout the entire thickness of the pipe, flat strap specimens of full pipe thickness are advised. This conclusion should, however, be nuanced for transversally oriented test specimens, since full thickness specimens have to be flattened in that case (see section 3.1).

3 ORIENTATION OF THE TENSILE TEST SPECIMEN

Several investigations reveal that the mechanical properties of pipeline steels are highly dependent on the orientation of the tensile test specimens, relative to the pipe axis. A distinction can be made between transversally (perpendicular to the pipe axis) and longitudinally (parallel to the pipe axis) oriented specimens. This observed heterogeneity is due to the steel rolling process, as well as the UOE pipe forming process. Asahi et al. [4] found that both yield stress and ultimate tensile stress in transversal and longitudinal direction are higher than their respective values of the original flat plate (Fig. 3). Differences between the transversally and the longitudinally oriented specimens are further discussed below.

3.1 Transversally oriented specimen specimen

For the determination of the tensile properties of pipeline steels in the transversal direction, three methods can be applied: round bar specimens, flat strip specimens, and the ring expansion method. The flat strip specimen is in this case flattened, since a pipe is curved in the transversal direction. In the ring expansion method, a ring is taken from the pipeline and subjected to a radial expansion.

Several studies have shown that the flat strip specimens produce lower yield strengths than the round bar and ring expansion specimens [5-11] (Fig. 4 [10]). This effect can be assigned to the Bauschinger effect that occurs during the flattening of the strip specimen, as explained below.
During the cold forming of steel plate to its pipe configuration, the mechanical properties change at every point, due to a location-specific deformation cycle. A part of the plate undergoes a tensile load (A $\rightarrow$ B in Fig. 5). Then, in case of a flattened strip specimen, a second deformation cycle is imposed due to flattening. The material that saw a tensile cycle during pipe forming, is now subjected to a compression (B $\rightarrow$ D). If, eventually, the test specimen is subjected to a tensile test (D $\rightarrow$ C'), it can be seen that the yield strength has decreased from A (original plate) to A' (flattened strip specimen). [12-15].

Fig. 4: A comparison of round bar, flat strip (strap) and ring expansion tensile test results [10].

Fig. 5: Illustration of the Bauschinger effect.

Fig. 4 indicates that the yield stresses of a round bar test are similar to those of a ring expansion test. These values are, for transversally oriented specimens, considered the most representative. Preference is given to the round bar specimen, since this method imposes less practical issues than the ring expansion method.

3.2 Longitudinally oriented specimen

In order to determine the strength-properties in the longitudinal direction, two specimens are commonly used: the round-bar specimen and rectangular bar covering the full wall thickness. From Fig. 6 [10] it can be noted that the kind of test specimen has an influence on the measured yield and tensile strength. This variation originates from the microstructure tested. Using a rectangular bar, the testing is performed on a section containing both the coarse and fine grained microstructure which is found in the through thickness direction. On the other hand, the use of a round-bar specimen results in the testing of a section less than the wall thickness. This means it is susceptible to the local properties, depending on the position of the round bar specimen, another microstructure will be tested. Testing a fine grained section will unambiguous result in a higher measured yield and tensile strength, whilst a coarse microstructure will lead to a deterioration of the measured properties [6,8,9,11,16].

Therefore it is recommended to use a rectangular test specimen covering the full wall thickness. This will result in more representative measured data compared to the full pipe behavior. Besides, the preparation of a round-bar specimen requires a higher work load than the preparation of a rectangular bar.
The presence of anisotropy is also worth mentioning. From Fig. 7 a clear difference can be seen between the measured yield strength of a longitudinal and transversal round bar specimen. On the other hand, the tensile strength is comparable for both directions. This difference has most probably originated from the different amount of cold work in these two directions. Due to the pipe forming process, the yield strength of the material might increase [4, 16-30]. Another sort of anisotropy is noted in the right part of Fig. 7. From the elliptical shape of the fractured area it can be seen that the post-yield behavior in the thickness direction differs from the behavior in the testing direction.

4 CONCLUSIONS

Defining the mechanical properties of pipeline steels is not straight forward. An overall picture cannot easily be provided since many factors affect the final tensile properties of pipeline steels. Therefore the testing conditions may never be neglected when the results are discussed. From the literature review, it can be concluded that the use of a full thickness test specimen is more representative and less susceptible to scatter than a round-bar specimen, which only covers part of the wall thickness. Furthermore, the test specimen should not be subjected to any unnecessary plastic deformation during the testing phase, in order to keep the measured strength properties as close as possible to the full pipe behavior.
5 NOMENCLATURE

YS  yield strength

UTS  Ultimate Tensile Strength

YT  Yield to Tensile ratio

WM  Weld Material

BM  Base Material

6 REFERENCES


