THE LIMIT STATE OF PLASTIC DEFORMATION OF AUSTENITIC PIPES
Františka PEŠLOVÁ, Evgeniy ANISIMOV, Jan RYBNÍČEK

Abstract
The work deals with the limit state of deformation of austenitic steel compensators of piping systems where undesirable plastic deformation has a character of material ripple. Plastic deformation - ripple - appears at random places outside of the pipe and in some areas reaches the limit state of failure (thinning of the thickness, which leads to tearing and rupture). The pipes are made of austenitic steel with the structure of non-homogeneously distributed deformation bands in the whole volume. Furthermore, the material, which was welded in the longitudinal direction of the pipe, was influenced by stress-strain state originating from thermo-mechanical loading resulting from the production technology of welding and subsequent bending. Texture and inhomogeneties observed in microstructure confirm this hypothesis.

Key words: welding, pipe, austenitic microstructure, stress-strain state, fracture, limit state

1. INTRODUCTION
Compensators are flexible metal elements used as a part of axial expansion joints built into the pipe system. These elements have to carry the load, compensate deformation and resist to chemical and electrochemical corrosion. Moreover, there are additional external effects that can influence durability of the whole pipe system and these structural elements, for example: (1) stress due to permanent loading – e.g. pressure in the pipeline and its own weight; (2) stress from permanent, occasional or exceptional weather and seismic loads; (3) stress amplitude due to thermal expansion or contraction and any alternate loading, e.g. due to earthquake; (4) creep of the material at high operating temperatures; (5) incidental loading of the pipe support

As a result, it is important that computational modeling includes the following allowable stresses: (1) stress at the maximum temperature and load; (2) stress amplitude and (3) creep stress.

One of the most effective procedures to achieve a significant reduction of the static stress in the piping system is to control its dilatation behavior. Pipe dilatation elements are arranged to withstand a substantial part of the total thermal strain and to significantly reduce the static stress in the piping system. One of the possible ways is to preload the heat pipe. This method is successfully used especially by steam laid in the ground. Another way is to create locations in the system where piping is in the L, Z or U shape in order to transform the tensile or compression stress into the bending stress. The biggest advantage of the shaped arrangement is compensation of stresses as well as strains.

The material selection of compensators, its connecting parts and the welding material must meet the requirement that the chemical composition, microstructure and mechanical properties do not diverge. The principle is that temperature and corrosion resistance of the compensating system must be the same as that of the basic piping material. It must be borne in mind that the compensator absorbs the major part of the dilatations in the form of deformation, and because of the fact that the relationship between true stress and strain is in a direct correlation, the compensator is exposed to a substantially higher stresses than the piping. To conclude, the selected materials must be capable to work in a wide range of testing and operating conditions.
The steel pipes before and after cold bending were delivered for the assessment. Received samples included the fractured parts after bending (Fig. 1.1) and the pipes with observable limit state plastic deformation - ripples - located in the vicinity of the bent (Fig. 1.2).

The aim of this study is to carry out material and structural assessment of the compensator in respect to the undesired occurrence of fracture and excessive plastic deformation after bending.

2. EXPERIMENT

The light and electron microscopy of metallographic samples from the selected transversal and longitudinal sections was carried out with the help of the high resolution scanning electron microscope JSM 7600F (JEOL) equipped with the EDS (Oxford) analyser. The line and area composition analysis was performed using polished and stained samples; intermediary phases were analyzed in detail. The hardness was mapped with the help of the nanohardness testing machine (Micromaterials). The metallographic analysis of the welds was also performed. The sample (which fractured during cold bending operation) (Fig. 1.1) was additionally broken and the fracture surface was studied in detail.
2.1 Metallographic evaluation of the structure

The entire cross-section has austenitic microstructure with apparent large deformation bands in the direction of plastic deformation (Fig. 2.1.1). Furthermore, the microstructure contains randomly distributed carbides and oxide particles (Fig. 2.1.1, 2.1.2). At some locations the particles were highly accumulated and thus created zones, which initiated the fracture, when the plastic deformation capacity was exhausted.

[Welds and their surroundings were also examined (Fig. 2.1.4). It can be stated that the observed welds were made free of imperfections and significant transient heat affected area. The welds were also free of intermediate particles as well as the base material (Fig. 2.1.5). The weld slightly exceeded the pipe surface, but this did not affect crack initiation during bending (Fig. 2.1.6, a, b), as documented by the weld structure in bent areas.]

Fig 2.1.1 Austenitic structure of supplied samples

Fig 2.1.2 Detail from the initial structure

Fig 2.1.4 The weld-base material interface

Fig 2.1.5 The weld-base material interface detail
The microstructure of the reference pipe material before bending shows oriented austenite grains with the deformation bands in the middle of the section. The slip planes which were not removed by annealing can be identified below the pipe surface.

Austenitic structure was studied in detail. Fracture initiations in austenitic grains are evident in the form of primary cavities at the higher magnification (Fig. 2.1.8 a,b). It means that the structure has fully utilized the capacity of plastic deformation, which initiates subsequent fracture.

Significant macroscopic plastic deformation becomes evident in the microstructure as a result of the dislocations movement in different directions within the austenitic grains (Fig. 2.1.9).
2.2 Fractographic evaluation of the structure

The fractographic assessment of the fracture surface of the broken pipe was carried out, where areas with dropped out intermediate phases, oxides, or carbides can be observed at the magnification of 300 times (Fig. 2.2.1).

The character of the fracture surface is ductile with apparent cavities induced by oxides different in size and morphology (Figure 2.2.2). The cavities were deformed in the direction of plastic deformation induced by bending (Fig. 2.2.2 and Fig. 2.2.3). Furthermore, the oxide particles were found predominantly in the deformation bands (situated in the middle of the wall thickness of the pipe) (Fig. 2.2.4). It was documented by the fracture surface (Figure 2.2.4, a) and also by metallographic section (Fig. 2.2.4, b). Finally, close to the oxide particles occurred a large number of carbide particles of different chemical composition (mentioned bellow).
Fig 2.2.1 Fracture surface with undesirable phases

Fig 2.2.2 Fracture with ductile-hole morphology

Fig 2.2.3 Detail of cavity with oxide particle

Fig 2.2.4 Chain of oxide particles
### 2.3 Chemical analysis

The distribution maps (Fig. 2.3.2) and the point chemical analysis (Fig. 2.3.1, Tab. 2.3.1) of selected areas confirmed the presence of oxides, carbides and their complexes.

![Chemical analysis](image)

**Fig 2.3.1** Oxide and carbide complexes (see Tab. 2.3.1)

**Table 2.3.1** Chemical analysis of oxide and carbide complexes (see Fig. 2.3.1)

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2.4 Nanoindentation

Nanohardness tester with the instrumented recording of the load and indentation depth at the nano to micro scale was used (Fig. 2.4.1). The nanoindentation was carried out at the cross-section of the pipe. Fifty indents were made on the line of 1.5 mm with the step of 30 μm. The Berkovich indentor was loaded to the maximum force $P_{\text{max}}$ of 30 mN and indentation time cycle was set to 30/30/30 seconds (loading/holding/unloading). From the loading/unloading records it was possible to determine the maximum depth $h_{\text{max}}$ and the final depth $h_f$ (Fig. 2.4.2).

Fig 2.4.1 Nano-hardness tester (Micro Materials, UK) with a horizontal indentation system. Force range is 0.1 mN – 500 mN, indentation depth range 0.5 nm – 12 μm.
Fig 2.4.2 Instrumented indenter load/unload record (force versus depth of indent)

The structure showed a vast heterogeneity of indentation depths. The stiff structural regions show the maximum indentation depths of about 500 nm and the soft ones reached the maximum depths of 1500 - 2250 nm (Fig. 2.4.3). The heterogeneity is associated with the strain hardening of deformation bands in the longitudinal direction of the pipe.

Fig 2.4.3 Measured load/unload curves across the wall of the tube

3. CONCLUSION

Based on the evaluation of experiments we can say that:

- The microstructure of the compensator (the wall thickness of 0.6 mm) was formed by austenitic grains with a low occurrence of δ-ferrite (the danger of which lies in the local accumulation in the middle of the wall thickness)
- The austenitic microstructure was significantly oriented in the direction of plastic deformation – resulting in deformation bands throughout the whole structure
- The microstructure of the reference pipe was also formed by austenitic grains with a little occurrence of the highly oriented δ-ferrite. Heterogeneity of grain size was demonstrated - the austenitic grains in the middle of the section were in some cases smaller than those in the outer areas
- The reference material exhibits some differences in structure and grain size (the size of deformed austenitic grains could not be evaluated)
- Oxides are observed throughout the structure and in some cases also the carbides. The strip of oxides had a maximum thickness of 22 micrometers and it is found mostly in the middle of the wall thickness
- Significant slip lines were observed in the austenite grains
• Nanoindentation showed heterogeneity in hardening of the austenitic structure associated with deformation bands.

It is well known that a high degree of plastic deformation leads to a limit stress-strain state in the microstructure initiating the catastrophic fracture. Therefore, we recommend measuring residual stresses at the locations where the macroscopic deformation (in the form of ripple) occurred and to make the stress-strain states calculations along the whole length of the compensator.

Acknowledgment

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LITERATURA

a) Monographic publications