Detection of imperfections on internal surface of super-duplex stainless steel tubes designated for oil and gas exploration by means of eddy current method

Marie BOHACOVA

INDETEC ndt, Chomutov, Czech Republic
Phone: +420 474 651820, Fax: +420 474 651820; e-mail: info@indetec.cz

Abstract
The wide use of steel alloys for tubes requires careful inspection during manufacture and service. Tubes for different applications may be made of specific steel alloys. The Sandvik SAF 2507 tubes are made from a super-duplex (austenitic-ferritic) stainless steel. Sandvik Chomutov tubes are used for oil and gas exploration and production as high pressure hydraulic fluid tubes in umbilicals. To ensure high quality and cost reduction during the manufacture, it is important to find imperfections on internal surface of input material (hot finished tubes) prior releasing for final processing (cold pilgering). The imperfections to be searched are especially dents, impressions, cracks, tears and non-metallic inclusions (residuals of glass after hot process). Eddy current method is an essential part of non-destructive testing and one of the main methods used for tube inspection. To ensure the detection of these imperfections, it was necessary to develop a special eddy current probe which is capable of detecting shallow discontinuities in a magnetic material.

Keywords: Non-destructive testing, eddy current, tube, stainless steel, imperfection

1. Introduction

Duplex stainless steel is a dual-phase steel, whose phases are made of austenite and ferrite (see Figure 1). Generally, it is known that the favourable properties of the steel can be achieved for phase balances in the range of 30 to 70% ferrite and austenite. More often, there are duplex steels with approximately equal amounts of the two phases. While in commercial use is more favoured austenite. The main alloying elements include chromium, molybdenum, nickel and nitrogen. To achieve an optimal and stable structure it is necessary to obtain the correct level of these elements, by affecting the resulting mechanical, physical and corrosion properties of duplex steels. The chromium content in duplex stainless steel ensures resistance to corrosion. The corrosion resistance increases with increasing chromium content. It is a ferrite former and there is at least 20% of chromium in duplex stainless steel. However, higher chromium content means more nickel for the formation of austenitic or duplex structure. Higher chromium also ensures formation of intermetallic phases and oxidation resistance at elevated temperature. By adding molybdenum to the duplex steels resistance to pitting and crevice corrosion increases in chloride-containing environments. It is also a ferrite former and its amount usually does not exceed 4%. Nitrogen as molybdenum increases the resistance to pitting and crevice corrosion. It is added to the duplex stainless steels that contain high chromium and molybdenum contents to avoid the formation sigma phase. Nitrogen is a strong austenite former and it is added to achieve the desired phase balance in the duplex steels. The alloying element nickel is an austenite former, called a stabilizer. It enables change of the crystal structure from body-centered cubic (ferritic) to face-centered cubic (austenitic). The amount of nickel is in the range of 1.5 to 7% in duplex stainless steel and increases its toughness [1].

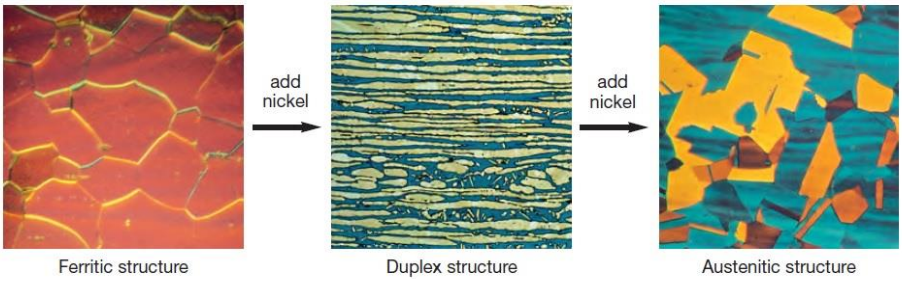
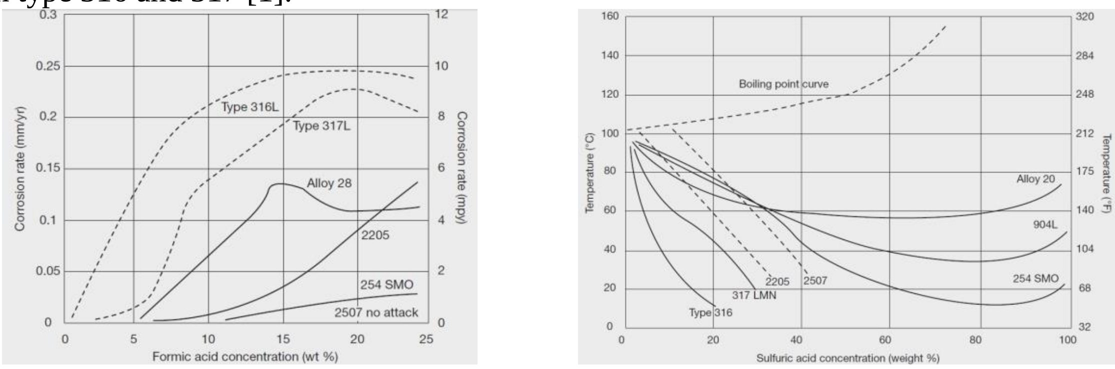


Figure 1 Change of microstructure by increasing the nickel content in stainless steel [1]

The greatest advantage of duplex stainless steels is their resistance to various types of corrosion in different environments. Resistance to organic and inorganic acids (see Figure 2) may be comparable to, or even better than the highly alloyed austenitic stainless steel in certain concentration ranges. Figure 2a) demonstrates that the duplex stainless steel 2507 does not show any deterioration in the steel structure. From Figure 2b), it is apparent that the duplex stainless steel 2507 clearly overcomes the resistance of austenitic steels with high nickel content against to solutions containing up to 15% acid, and also has better resistance than type 316 and 317 [1].



a) b)

Figure 2 Corrosion curves of duplex and austenitic stainless steels a) in boiling mixtures of 50% acetic acid, b) in non-aerated sulfuric acid, 0.1 mm/yr [1]

The high chromium content and the presence of ferrite ensure caustic resistance. The pitting and crevice corrosion resistance is primarily determined by chromium, molybdenum and nitrogen. A parameter of resistance to pitting is the PRE (Pitting Resistance Equivalent). For duplex stainless steels the value of the PRE is dependent on both ferrite and austenite phases. Figure 3 shows a minimum value of PRE for duplex stainless steels.

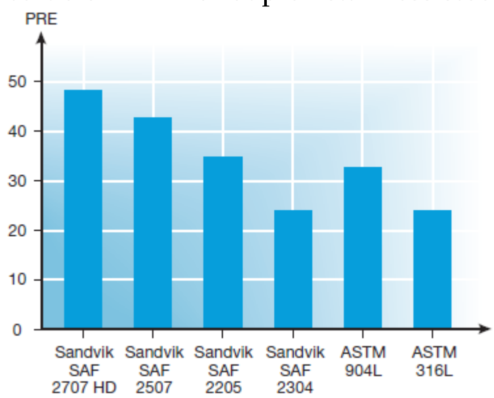
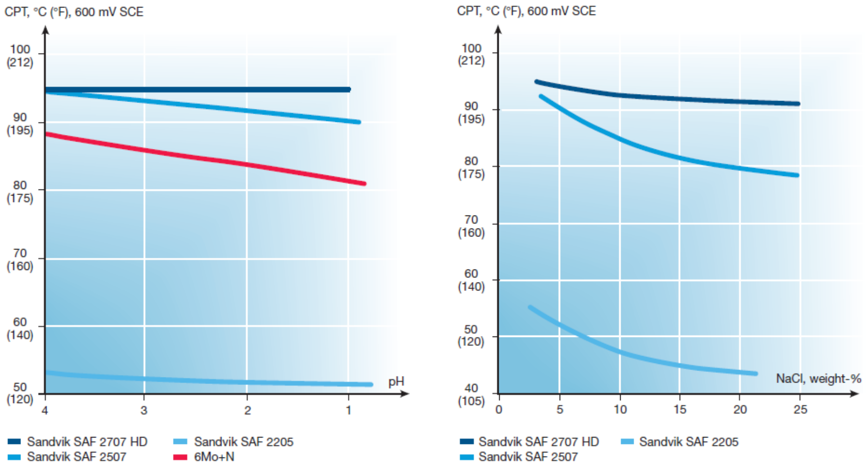


Figure 3 Minimum PRE values for the duplex stainless steel and some other alloys [2]

PRE values can be used to predict the behavior of the alloy in chloride environment. Next parameter is the critical pitting temperature CPT. The critical temperature can be determined by electromagnetic methods. These temperatures were determined in solutions of sodium chloride with the potential fixed at 600 mV relative to the saturated calomel electrode (SCE). This is a very high value comparable to the value occurring in chlorinated sea water. Figure 4 shows the critical pitting temperature CPT for each duplex and super-duplex stainless steel [2].



a) b)

Figure 4 Critical pitting temperature CPT for Sandvik SAF 2707 HD, SAF 2507 and SAF 2205 a) in 3% NaCl solution with varying pH at +600 mV SCE, b) in various concentrations of NaCl at +600 mV SCE, neutral pH [2]

Resistance to stress corrosion cracking (SCC) is one of the corrosion resistances. Duplex stainless steels are more resistant in chloride solutions than austenitic steel ASTM 304L and 316 at temperatures above 60°C. This can be seen in Figure 5.

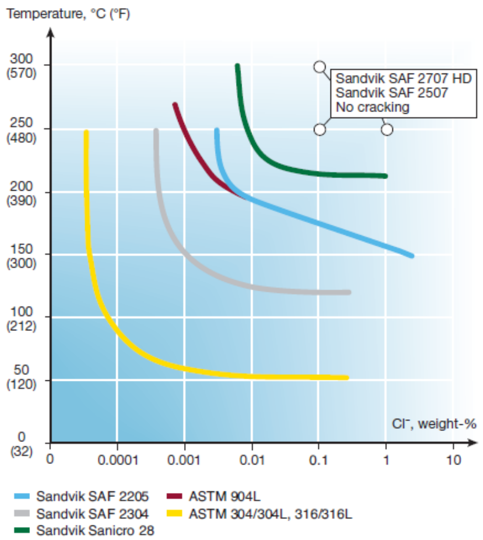


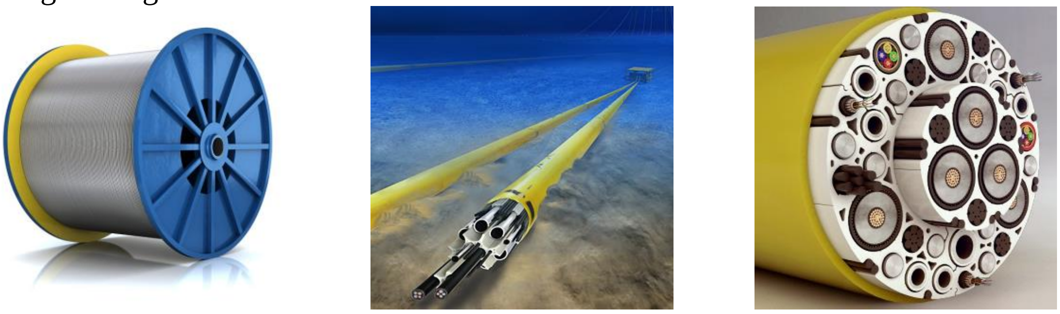
Figure 5 Stress corrosion cracking SCC resistance for Sandvik SAF 2707 HD, SAF 2507, SAF 2205 and SAF 2304 in oxygen-bearing neutral chloride solutions [2]

Tubes made of super-duplex stainless steel Sandvik SAF 2507 are characterized by excellent resistance to stress corrosion cracking (SCC) in chloride-bearing environments and to pitting, crevice and fatigue corrosion. They are characterized by high mechanical strength, physical properties that offer design advantages and good weldability. Chemical composition of SAF 2507 is described in the following Table 1.

Table 1 Chemical composition (nominal) in % [3]

C	Si	Mn	P	S	Cr	Ni	Mo	N
≤ 0.030	≤ 0.8	≤ 1.2	≤ 0.035	≤ 0.015	25	7	4	0.3

From this super-duplex stainless steel can be produced not only seamless and welded tubes and pipes, but also fittings, flanges, wire and covered electrodes, plates, sheets, bar steel, forgings and castings. Typical application of these tubes includes oil and gas exploration in chloride-containing environments. This is especially sea water, where the tubes are used for subsea oil and gas extraction as high pressure hydraulic fluid tubes in umbilicals (see Figure 6). Other applications of super-duplex stainless steel are cooling systems using seawater and salt evaporation, various desalination plants and geothermal wells, oil refining, petrochemical processing, pulp and paper production, chemical processing and mechanical components that require high strength.



a) b) c)

Figure 6 a) Umbilical tubes [4], b) pipelines in the seabed [5], c) pipeline cross-section [6]

2. Task

The main task was to find imperfections on internal surface of input material (hot finished tubes) prior releasing for final processing (cold pilgering). Defects to be detected are dents, impressions, cracks, tears and non-metallic inclusions (residuals of glass). Thirteen tubes of Ø73 x 8 mm and Ø73 x 9 mm were subjected to visual and ultrasonic inspection. Several imperfections especially hollow and linear defects were indicated by visual inspection (see Figure 7 and Figure 8). There were registered indications only in four specimens by ultrasonic inspection. These four specimens were submitted to eddy current inspection. To ensure the detection of these defects, it was necessary to develop a special eddy current probe, which is able to detect very shallow imperfections.

Specimen 1 – hollow Specimen 2 – corrugation

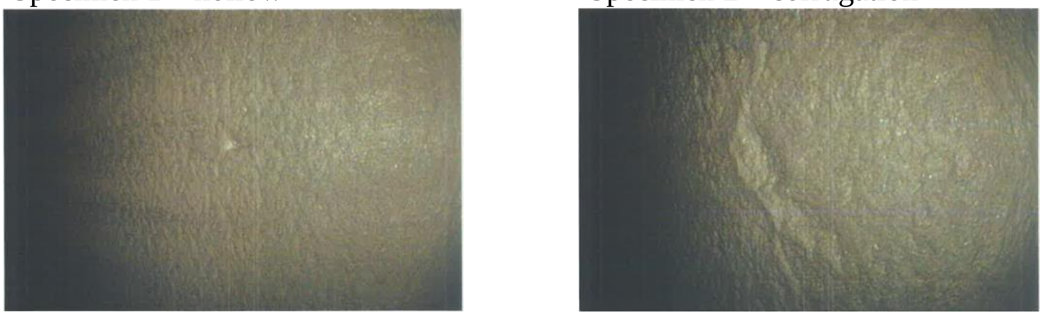


Figure 7 Indications detected by visual inspection using videoscope – specimen 1 and 2 [7]

Specimen 3 – hollow Specimen 4 – glass

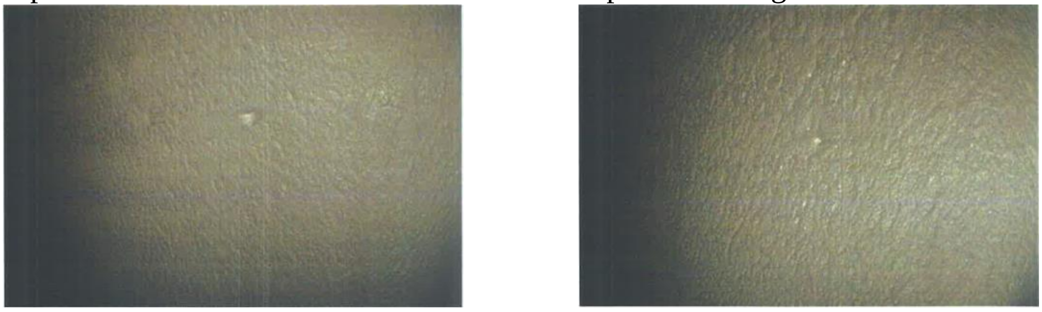


Figure 8 Indications detected by visual inspection using videoscope – specimen 3 and 4 [7]

3. Design of eddy current probe

The inspection of ferromagnetic tubes can be performed using various testing techniques. These three techniques are the most used in practice: external encircling probe with additional magnetization, internal magnetic bias encircling probe, called BIAS probe and finally rotary probe. The eddy current inspection of super-duplex steels is difficult due to chemical composition and structure. This is caused by the movement of the probe in the tube creating a noise of the structure. The cause of this noise is ferromagnetic component, which significantly affects the inspection result. This noise can be partially eliminated by magnetizing the tube, but for practical purposes this method is more expensive and time consuming than using the probe without magnetic bias.
The rotary technique was chosen as a basic requirement to develop a probe for reasonable financial cost for development and inspection, and which will be able to detect shallow surface defects on the internal surface. Special rotary probe consists of a multi-differential coil of size Ø1 mm x 3 mm. The probe operates in the frequency range from 250 kHz to 1 MHz. This is a transducer with reduced lift-off. The manual test equipment bearing the transducer is shown in Figure 9.

Figure 9 Manual test equipment with transducer

Setting the inspection parameters for the specimens was performed on a reference standard (see Figure 10) which is made of the same super-duplex stainless steel SAF 2507. The tube dimension is 63.5 x 5.5 mm. The reference standard contains two notches (longitudinal and transversal) of dimension 0.275 x 1.0 x 12.5 mm (D x W x L). The individual eddy current responses to the notches are shown in Figure 10 (right). The second reference standard (tube) of thickness 5.5 mm contains through holes. Setting of parameters was performed on the two holes of Ø1 mm and Ø3 mm. The individual eddy current responses to the holes are shown in Figure 11 (right).
The individual eddy current responses to imperfections occurring in the specimens 1 to 4 are shown in Table 2. Signal to noise ratio of at least 2:1 or even better is almost at all

imperfections. Eddy current response does not expressive at specimen 3. Thus, this size of hollow would probably be overlooked by automatic rotary system.

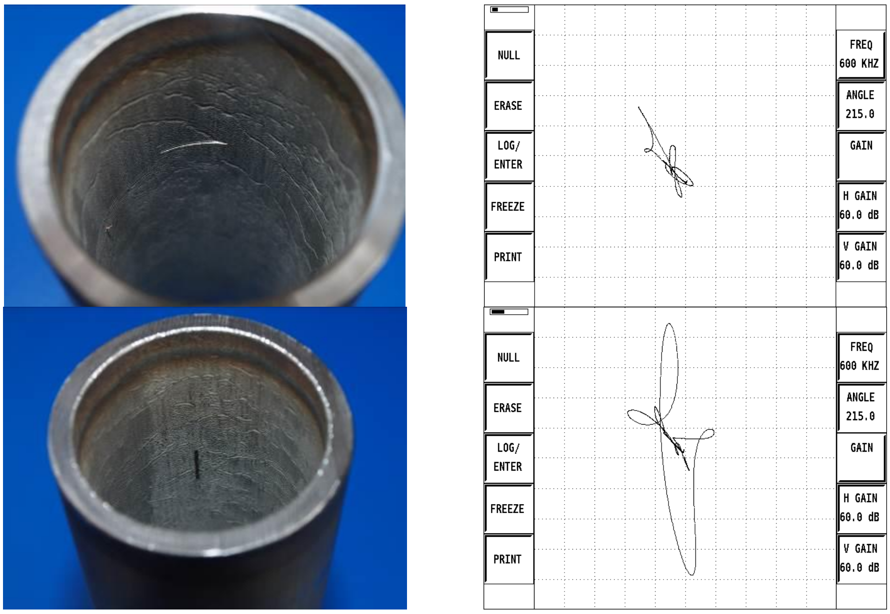


Figure 10 Reference standard with the notches – transversal (above), longitudinal (below)

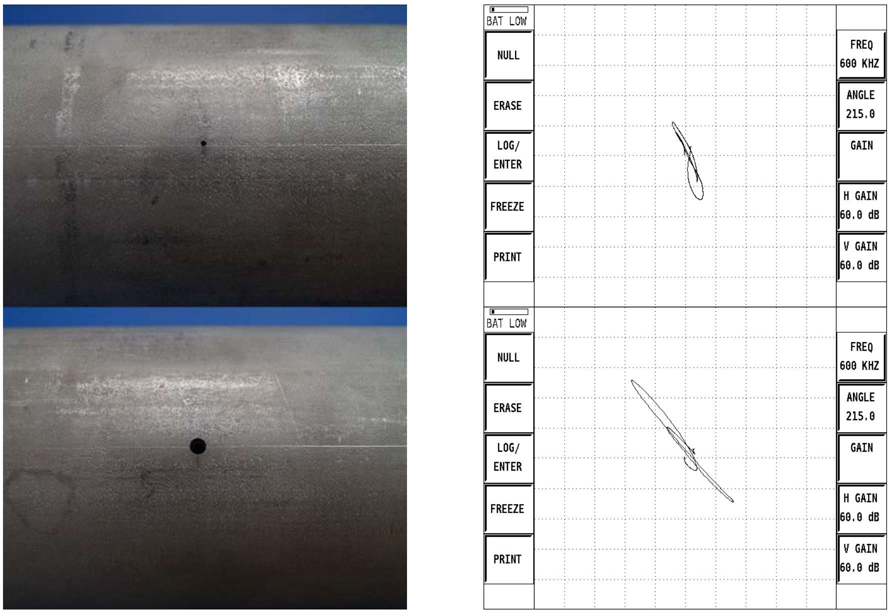
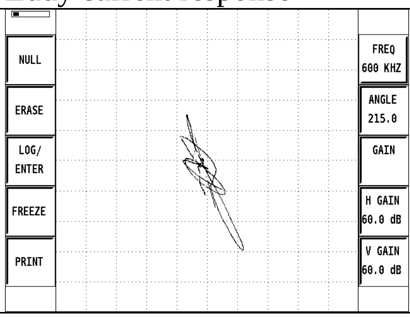
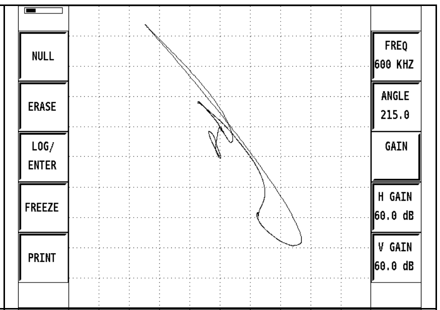
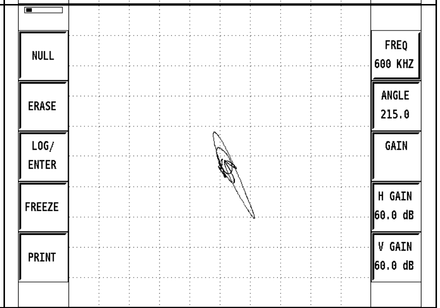
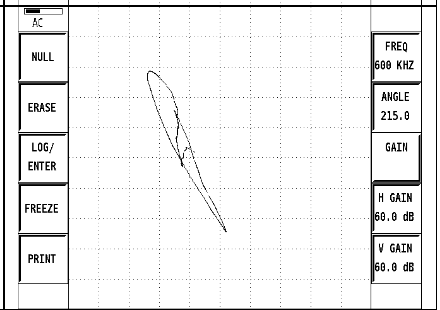
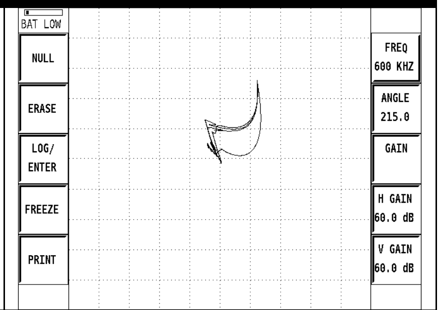
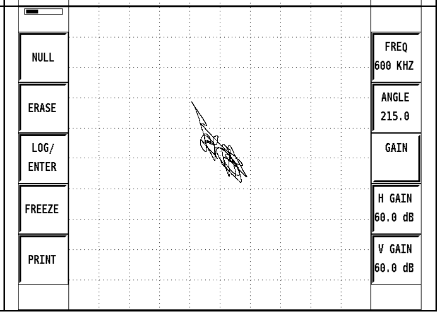


Figure 11 Reference standard with the through holes

Table 2 Eddy current responses to the imperfections in the tubes of super duplex steel SAF 2507

Title	Type of imperfection	Eddy current response
Specimen 1	Hollow	

Specimen 2	Corrugation	
Specimen 3	Hollow	
Specimen 4	Glass	
Lift -off		
Structure noise		

4. Summary

The SAF 2507 tubes made of super-duplex stainless steel have excellent resistance to various types of corrosion (pitting, crevice, fatigue, stress corrosion cracking) in highly corrosive environments containing chlorides such as sea water. These tubes are used for subsea oil and gas extraction as high pressure hydraulic fluid tubes in umbilicals. The aim was to design a reliable inspection system that would be able to detect imperfections in hot finished tubes already in production. The undesirable defects include non-metallic inclusions in the form of glass which is used as a lubricant during pressing. Insufficient removal of glass leads to the formation of hollows which can create long longitudinal defects at final cold processing. The objective has been achieved. It was designed manually rotary probe which is able to reliably detect imperfections on the internal surface of the tube. A good signal to noise ratio (SNR) was achieved at almost all specimens. It can be assumed that the SNR improves by using HP/LP filters to automatic high-speed rotary motion of the probe along the internal surface of the tube. It becomes task for the future.

Reference

[1] STAINLESS], [prepared by TMR. *Practical guidelines for the fabrication of duplex stainless steels*. 2nd ed. London: International Molybdenum Association, 2009. ISBN 978-190-7470-004.

[2] SANDVIK. *Sandvik duplex stainless steels*. 2009, 20 s. Dostupné z: http://www.smt.sandvik.com/Global/Downloads/Products_downloads/tubular-products/S-120-ENG_10.pdf

[3] SANDVIK. *Datasheet: Sandvik SAF 2507*. 2013, 14 s. Dostupné z: http://www.smt.sandvik.com/cz/centrum-material/materialove-listy/tube-and-pipe-seamless/sandvik-saf-2507/

[4] Umbilical tubes. SANDVIK. *Sandvik Materials Technology* [online]. 2014 [cit. 2014-07-15]. Dostupné z: http://www.smt.sandvik.com/en/products/tube-pipe-fittings-and-flanges/tubular-products/umbilical-tubes/

[5] Umbilical contract awarded to Aker Solutions. *Aker Solutions* [online]. 2011 [cit. 2014-07-15]. Dostupné z: http://www.akersolutions.com/en/Global-menu/Media/Press-Releases/All/2011/Umbilical-contract-awarded-to-Aker-Solutions/

[6] Power umbilical and HV subsea cables. *Aker Solutions* [online]. 2014 [cit. 2014-07-15]. Dostupné z: http://www.akersolutions.com/en/Global-menu/Products-and-Services/Subsea-technologies-and-services/Subsea-production-systems-and-technologies/Umbilicals-and-power-cables/Power-umbilicals-and-HV-subsea-cables-/

[7] ŠTEMBERK, Jiří a Tomáš JUHAS. NDT SERVIS. *Protokol o defektoskopické kontrole*. Chomutov, 2014, 4 s.