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# Effect of microstructure on mechanical properties and corrosion resistance of 2205 duplex stainless steel

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ABSTRACT

*This paper presents results of the research on impact of microstructure of austenitic-ferritic steel of duplex type on its mechanical properties and susceptibility to stress corrosion cracking. As showed, improper processing technologies more and more often used in shipbuilding industry for plates and other half-finished products made of duplex steel may cause significant lowering their properties, which frequently makes their replacing necessary. Results of the tests on stress corrosion under tension with low strain rate (SSRT) conducted in an inert and corrosion (boiling magnesium chloride) environment , are presented. It was proved that even minor structural transformations taking place in 500°C ageing temperature lower corrosion resistance of the steel. Structural transformations occurring in 700°C temperature to a smaller extent influence susceptibility to stress corrosion of the steel, however they cause drastic drop in its plasticity.*

**Keywords:** duplex stainless steel; stress corrosion cracking; microstructure, ageing

## Introduction

Many branches of industry have recognized the benefits of using duplex (of austenitic-ferritic structure) stainless steel. In marine industry tanks and pipelines on chemical carriers are made of stainless steels of various grades. The austenitic stainless steel is that most commonly used. Such steels have a good corrosion resistance are easy to form and weld. However, today the trend towards the use of duplex stainless steels instead of austenitic one is evident. An evaluation to establish the relative benefits of the two steel types has been carried out with taking into account cost, corrosion resistance, and weldability. Use of duplex stainless steels for hull structures, especially in chemical tankers, has many advantages over conventional austenitic steels. Duplex steels provide higher pitting corrosion resistance, and enhance stress corrosion cracking resistance. In addition, the cargo tanks form an integral part of the hull structure and the high yield strength of duplex steels, over 450 MPa, enables the plate thickness of the tanks to be considerably reduced and in consequence to lower ship structure mass [1]. An unfavourable feature of duplex steel is its susceptibility to high temperature effects causing structural transformations. Depending on their chemical composition, austenitic – ferritic steels are less or more susceptible to precipitation processes. Their ageing in a temperature higher than 500°C initiates precipitation processes. The intermetallic phases ($\sigma$, R, $\chi$), carbides and nitrides appearing in microstructure cause embrittlement of such steel and makes its corrosion resistance lower. Its ageing in a temperature lower than 500°C also leads to worsening its mechanical properties, especially plasticity, but structural transformations are less distinct. The so called "embrittlement 475°C" appears in the steels in question after their ageing in the temperature range from 300 to 500 °C, and is associated with steel hardening due to building $\alpha$' - phase rich of Cr, resulting from spinoidal disintegration of ferrite [2-6].

Intensification of precipitation processes in microstructure depends on duration time of keeping the steel in an elevated temperature. In industrial practice it may happen that an occasional heating of the steel occurs or that it results from the nature of technological process itself. In such case one should be aware of hazards resulting from the lowering of mechanical properties of steel, especially its corrosion resistance.

In the work [7] results are presented of tests on influence of microstructure of duplex steel on its impact toughness. The present research has been aimed at determination of effects of structural changes which occur during ageing the steel in temperature of 500 and 700 °C on its mechanical properties determined by tensile tests, as well as its susceptibility to stress corrosion cracking.

## Testing method

12 mm plate made of AVESTA 2205 (UNS-S31803) duplex steel was used for the tests. The plate was delivered after solution heat treatment in 1050°C temperature. Its chemical composition according to cast analysis is given in Tab. 1

Tab. 1. Chemical composition of 2205 duplex stainless steel, ( wt %)

| C | Si | Mn | P | S | Cr | Ni | Mo | N |
|---|---|---|---|---|---|---|---|---|
| 0.017 | 0.4 | 1.550 | 0.024 | 0.005 | 21.9 | 5.7 | 3.0 | 0.17 |

From the plate some sections were cut to prepare specimens for stress corrosion resistance testing by using the Slow Strain Rate Test (SSRT) at low velocity acc. PN-EN-ISO 7539-7 [8]. Tensile specimens of the working length l = 20 mm and the diameter d = 5 mm were used. Their axes were parallel to plate milling direction.

The specimens were aged in 500 and 700 °C temperature for 6, 60 and 600 min. The heat treatment was conducted in a vacuum furnace with the following cooling in water.

Metallographic examinations which were aimed at revealing microstructural changes taking place in the steel after ageing, were carried out by using a light microscope.

## Results of the tests

Fig. 1 shows pictures of duplex steel microstructure after the heat treatment. Share assessment of phases was conducted by using a computer software intended for quantitative phase analysis. Metallographic samples were etched by means of Berach agent which does not etch austenitic phase, dyes ferrite in red, and makes the phase s visible as white precipitates. Results of measurements of ferrite and s-phase content in 2205 steel microstructure subjected to ageing, are collected in Tab. 2 and 3.

Tab. 2. The ferrite content in 2205 duplex stainless steel structure after ageing,( wt %)

| Ageing temperature, °C | Ageing time, min. | | |
|---|---|---|---|
| | 6 | 60 | 600 |
| 500 | 33.6 | 33.2 | 33.1 |
| 700 | 34.3 | 25.7 | 19.5 |
| As received condition | 33.8 | | |

Tab. 3. The s- phase content in 2205 duplex stainless steel structure after ageing,[wt. %]

| Ageing temperature, °C | Ageing time, min. | | |
|---|---|---|---|
| | 6 | 60 | 600 |
| 500 | 0 | 0 | 0 |
| 700 | 0 | 3.8 | 9.9 |

a)
b)
c)
d)

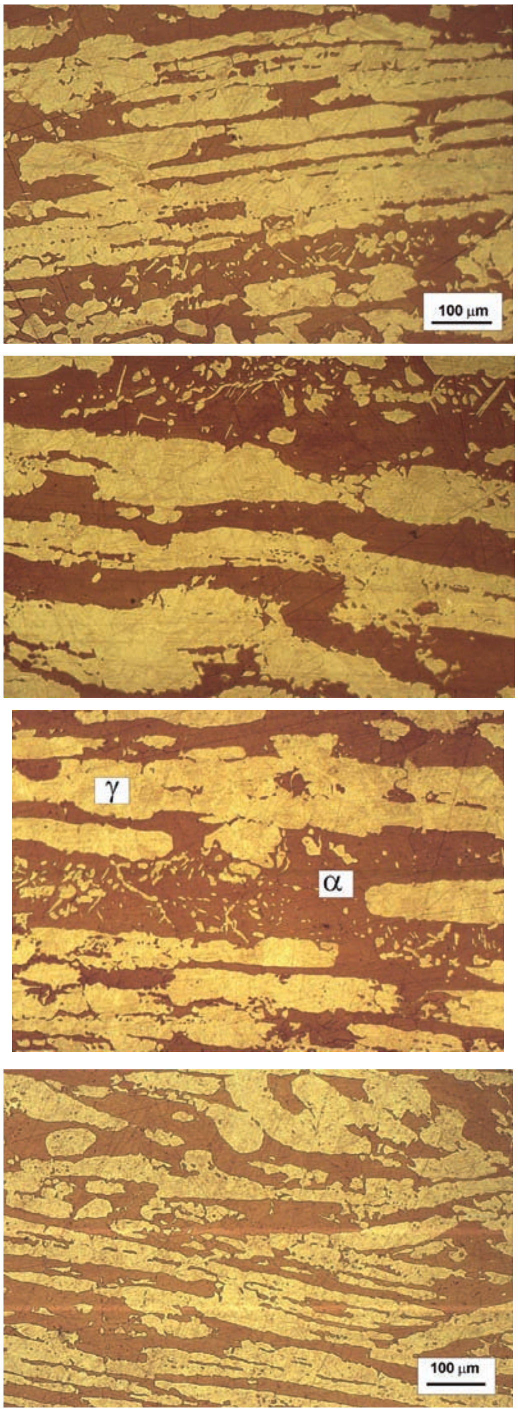
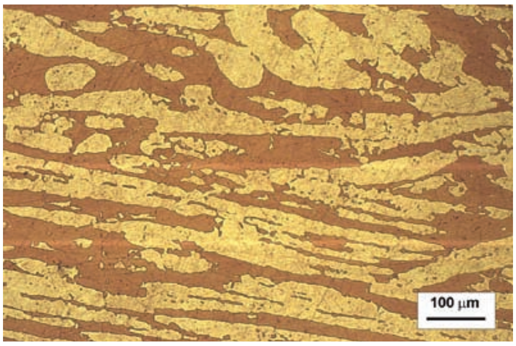



Fig.1. Microstructure of 2205 duplex steel after ageing : in 500°C temperature for a) 6 min., b) 60 min., c) 600 min.; in 700°C temperature for d) 6 min.

Magn. 200x. dark zones – ferrite, light zones – austenite, white precipitates - σ-phase e)




f)

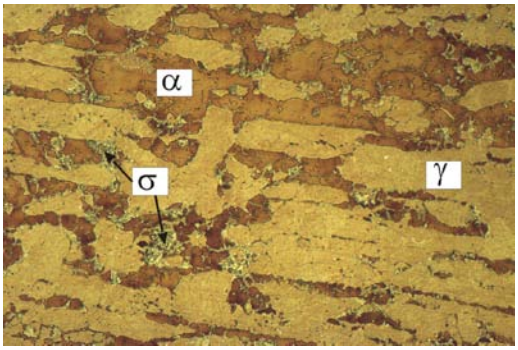



Fig.1. Microstructure of 2205 duplex steel after ageing : in 500°C temperature for e) 60 min., f) 600 min.

Magn. 200x. dark zones – ferrite, light zones – austenite, white precipitates - σ-phase

Hardness measurements were made acc. Vickers method under 98N load. Their results (mean values) are given in Tab. 4.

Tab. 4. Hardness tests results

| No. of specimen | Ageing temperature, $^0$C | Ageing time min. | HV10 Hardness |
|---|---|---|---|
| PM | - | - | 254 |
| 51 | 500 | 6 | 273 |
| 52 | 500 | 60 | 282 |
| 53 | 500 | 600 | 299 |
| 71 | 700 | 6 | 276 |
| 72 | 700 | 60 | 263 |
| 73 | 700 | 600 | 271 |

Results of corrosion tests are presented in Tab. 5. Tests of susceptibility to stress corrosion cracking were carried out by using the method of Slow Strain Rate Test (SSRT) for specimens immersed in boiling 30% $MgCl_2$ solution environment of 117$^0$C temperature. Tensile specimens in inert environment (glycerine) of 117$^0$C temperature were comparative ones. During the tests maximum value of the force ($F_{max}$), fracture energy (En) as well as elongation (E) was measured. After the tests the reduction of area of specimens (RA) was measured in the place of their fracture. The specimens were tensioned with the strain rate equal to 2,2 x $10^{-6}$ 1/s.

Tab.5.The results obtained in the SSR tests in an inert and corrosive environment, respectively

| Specimen | Environment | $F_{max}$ kN | TS MPa | En MJ/m$^3$ | RA % | E % |
|---|---|---|---|---|---|---|
| PM-G | glycerine | 12.3 | 628 | 235 | 78 | 44 |
| PM-M | $MgCl_2$ | 12.4 | 630 | 189 | 56 | 37 |
| | | | | | | |
| 51-G | glycerine | 12.8 | 655 | 221 | 75 | 43 |
| 52-G | glycerine | 12.9 | 660 | 241 | 78 | 43 |
| 53-G | glycerine | 13.2 | 672 | 249 | 79 | 44 |
| 51-M | $MgCl_2$ | 12.1 | 615 | 152 | 40 | 32 |
| 52-M | $MgCl_2$ | 12.0 | 611 | 148 | 40 | 30 |
| 53-M | $MgCl_2$ | 13.3 | 675 | 135 | 29 | 24 |
| | | | | | | |
| 71-G | glycerine | 12.7 | 646 | 242 | 56 | 44 |
| 72-G | glycerine | 12.5 | 639 | 221 | 56 | 40 |
| 73-G | glycerine | 13.0 | 660 | 135 | 24 | 25 |
| 71-M | $MgCl_2$ | 11.0 | 562 | 95 | 48 | 22 |
| 72-M | $MgCl_2$ | 12.5 | 637 | 176 | 34 | 33 |
| 73-M | $MgCl_2$ | 13.7 | 697 | 155 | 21 | 27 |

Susceptibility to stress corrosion cracking can be assessed by comparing results obtained on identical specimens exposed to action of a chemically active environment and inert one. For assessing susceptibility to stress corrosion cracking the relative factor Frel is usually applied [8].

$$F_{rel}(RA_{rel}, En_{rel}, E_{rel}) = \left(1 - \frac{W_{corr}}{W_{inert}}\right) \cdot 100\%$$

where: $W_{corr}$, $W_{inert}$, - a selected property of material (the fracture energy En, elongation E, reduction of area RA) determined in an aggressive environment and inert one, respectively.

Rise in susceptibility to stress corrosion cracking is the greater the more the parameter $F_{rel}$ deviates from 100%.

Relative parameters $E_{rel}$, $RA_{rel}$, $En_{rel}$ were calculated in order to assess decrease in the elongation (E), reduction of area (RA) and fracture energy (En) of tested specimens in relation to results obtained in inert environment.

On this basis the susceptibility to stress corrosion of duplex steel in an as-received state and after various ageing duration times in 500 and 700 $^0$C temperature, was estimated. The obtained results are shown in Fig. 2 ÷ 4.

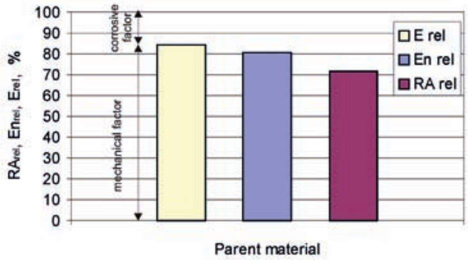



Fig.2. Assessment of susceptibility to stress corrosion cracking of duplex steel in as- received state. Ranges of mechanical and corrosive factor effects in the destruction processes are indicated.

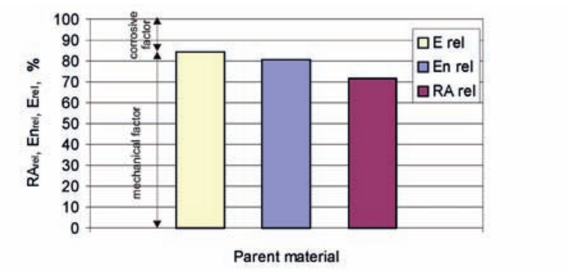



Fig.3. Assessment of susceptibility to stress corrosion cracking of duplex steel after ageing at 500°C temperature

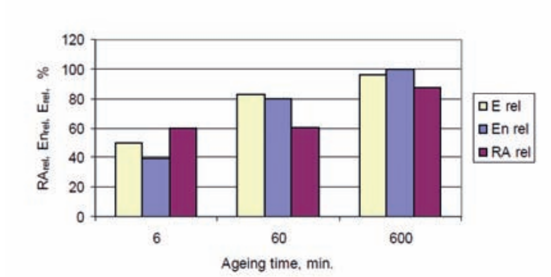



Fig. 4. Assessment of susceptibility to stress corrosion cracking of duplex steel after ageing at 700°C temperature

## Discussion

Metallographic examination of duplex steel in the as-received state revealed its austenitic – ferritic structure. The zones of ferrite and austenite were found extended in compliance with milling direction. In the structure a greater share of austenitic phase (abt. 66%) was observed. Ageing at 500°C for the time up to 600 min did not cause any noticeable changes in steel structure (Fig.1a-c). It was in compliance with expectations as after the ageing at low temperature it was possible to expect occurrence of very tiny releases of phase α', which could not be observed by means of an optical microscope. However, the rise in hardness of the steel along with ageing time extending shows that some transformations took place in its microstructure (Tab. 3) [7].

Ageing at 700°C for 6 min did not cause any noticeable precipitation of secondary phases (Fig.1d). Only after the ageing for 60 min a precipitates of σ phase occurring at α/α and α/γ phase boundaries was observed ( Fig.1e). After the ageing for 600 min σ-phase appeared in the continuous form at the α/α grain boundaries and in the form of tiny spots along the α/γ grain boundaries (Fig.1f). Amount of the precipitated σ-phase was larger and larger along with steel ageing time extending. Also, a decreasing share of ferritic phase was observed. Quantitative assessment of share of phases (Tab. 2 and 3) clearly shows an increase in share of σ-phase by abt. 10% and a decrease in share of ferritic phase. Ferrite in duplex steels in the temperature over 600°C is not stable and easily undergoes transformations. As a result of ageing in temperatures ranging from 600 to 850 °C eutectoidal disintegration of ferrite takes place accompanied with production of the σ-phase rich of molybdenum and chromium, as well as the secondary austenite (γ2). The reaction proceeds as follows : $\alpha \rightarrow \sigma + \gamma_2$. Growth of σ- phase particles causes that chromium and molybdenum is shifted out of the surrounding ferrite making the neighbouring zones less rich in these elementary substances. Changes in ferrite chemical composition cause its transformation into secondary austenite whose chemical content may significantly differ from that of the austenite primarily rising after solution heat treatment of the steel [3,9]. Presence of the secondary phases in steel microstructure results in changes of its mechanical properties.

SSR tests conducted in glycerine environment has proved that ageing at $500^0$C for 600 min does not practically influence duplex steel strength and plasticity measured by specimens elongation and reduction of area. However the noticed rise of its hardness suggests that its impact toughness may be reduced. The specimens aged in 700°C for 600 min showed drastic drop of plasticity in relation to initial state, that is associated with structural transformations and a high share of the brittle σ-phase in microstructure.

SSR tests conducted in boiling $MgCl_2$ environment has proved that ageing at 500°C results in increasing stress corrosion susceptibility of the steel along with extending duration time of ageing. Participation of stress corrosion in damaging the specimens in as-received state (in SSR test conditions) reached from 16 to 28 % - depending on an assumed criterion of assessment (En, RA, E). The tests on specimens aged in 500°C showed much greater participation of stress corrosion in damaging process in relation to that of the specimens in as-received state. When the criterion of drop in plasticity of material, measured by the relative elongation ($E_{rel}$) and relative reduction of area ($RA_{rel}$), is assumed, it can be observed (Fig.3) that the participation of stress corrosion in damaging process of the specimens aged for 600 min, increased from 16 to 45 % and from 28 to 63 %, respectively. The growing susceptibility to stress corrosion can be explained by an increased amount of the α' precipitates, as well as a lower concentration of chromium around the precipitates [9]. Stability of passive layer in these zones becomes lower, hence participation of electrochemical factor in the damaging process becomes prevailing.

SSR tests carried out in $MgCl_2$ environment on specimens aged in 700°C temperature showed a different behaviour of the material. It turned out that susceptibility to stress corrosion of the specimens decreases along with ageing time extending (Fig. 4). Low corrosion resistance was found for the specimens aged for 6 min. It proves that structural transformations occurred though optical microscopic examinations has not confirmed this. The lowering of stress corrosion resistance should be considered as associated with occurrence of the phase γ2. This phase which adheres to σ -phase precipitates is characteristic of a lower amount of Cr and Mo, that, like in case of the specimens aged in 500°C, is conductive for development of electrochemical corrosion as it facilitates decohesion of material in presence of tensile stresses. If such mechanism is assumed, one can expect a growing participation of stress corrosion in damaging process of specimens along with extending time of ageing in 700°C. The greater amount of the released σ-phase and the secondary austenite $\gamma_2$ should be conductive to stress corrosion developing. However, along with extending time of ageing in temperatures above 650°C a greater role is played by diffusion processes [10]. High diffusion rate of elementary substances within ferritic matrix makes it possible to supplement chromium and molybdenum in the depleted zones adhering to the s-phase precipitates, that results in corrosion susceptibility lowering. The specimens aged for 600 min in 700°C showed the lowest susceptibility to stress corrosion. Damaging the specimens was mainly caused due to action of mechanical factor.

However the improved resistance to stress corrosion cracking of duplex steel aged for a longer time at temperatures over 650°C is not of a significant importance, as the appearance of a large amount of the s-phase in microstructure of the steel makes its plasticity significantly lower, that eliminates it from implementation in practice.

## Conclusions

1. Ageing 2205 duplex steel at 500°C temperature did not cause structural changes which could be revealed by using optical microscopy technique.
2. Rise of steel hardness along with ageing time extending shows that precipitation processes, probably α' phase forming, have occurred.
3. Ageing in 500°C temperature even for a short time (6 min) significantly lowers resistance to stress corrosion cracking of the steel; and, extension of ageing time of the steel increases its susceptibility to stress corrosion.
4. Ageing the duplex steel at 700°C temperature resulted in precipitation the s-phase as well as the secondary austenite $\gamma_2$ in its structure.
5. Low resistance to stress corrosion was found in the specimens aged for 6 min at 700°C temperature.
6. Extending the ageing time at 700°C caused participation of stress corrosion in damaging process of specimens under SSR test conditions, smaller.

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