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Microstructural Transformations of a Duplex Steel Weld and their Influence on the Particle and Cavitation Erosion Resistance

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The microstructural transformations which took place during the welding of duplex steel as well as their influence on the resistance to particle erosion wear and cavitation erosion wear were investigated. A sample was cut from a 1.4462 rolled steel plate and heat treated in order to obtain a microstructure which would resemble, as closely as possible, the actual welded microstructure. Qualitative and quantitative microstructural analyses were performed on the samples. The influence of the sigma phase and its volume fraction (obtained by annealing at 800 °C) was investigated, as well as the influence of the various ferrite/austenite ratios (obtained by annealing in the 1100 °C —1300 °C temperature range) on particle erosion and cavitation erosion resistance. It was found that the microstructural transformations which took place in the weld zone and the heat affected zone significantly influence resistance to wear in the investigated cases.

Mikrostrukturne promjene u zavaru dupleks-čelika i njihov utjecaj na otpornost eroziji krutim česticama i kavitacijskoj eroziji

Izvornoznanstveni članak

U radu je istražen utjecaj mikrostrukturnih promjena, nastalih pri zavarivanju dupleks-čelika, na otpornost eroziji krutim česticama i kavitacijskoj eroziji. Uzorci su izrezani iz valjane ploče dupleks čelika 1.4462 i toplinski obrađeni tako da im se mikrostruktura što više podudara s mikrostrukturom realno zavarenog spoja. Na uzorcima je napravljena kvalitativna i kvantitativna analiza mikrostrukture. Istražen je utjecaj porasta volumnog udjela sigma faze (dobiven žarenjem na 800 °C) te utjecaj porasta omjera ferit/austenit (dobiven žarenjem na temperaturi od 1100 do 1300 °C) na otpornost eroziji krutim česticama i kavitacijskoj eroziji. Utvrđeno je da mikrostrukturne promjene koje nastaju u metalu zavara i zoni utjecaja topline dupleks čelika imaju veliki utjecaj na otpornost trošenju ispitanih slučajeva.

1. Introduction

Duplex steels, together with austenite, ferrite, martensite and precipitation-hardened steels form a group of stainless steels. The whole group of stainless steels is characterized by their monostructure, while duplex steels are the only members of the group which have a biphase structure composed of ferrite and austenite in approximately the same amounts. A balanced ferrite-austenite ratio is ensured by the use of basic alloying elements (chrome and nickel) and other alloying elements (nitrogen, molybdenum, copper, silicon and tungsten). Together with the chemical composition, the heat treatment regime, i.e. the rate of cooling in the first place, plays an important role in obtaining the required structure. Such a microstructure contributes to good properties of these steels, thus making them superior to other stainless steels and steels from other groups for certain applications. Duplex steels rank highly primarily due to their good combination of mechanical properties and excellent corrosion resistance. Therefore, they have found a wide field of application in the petrochemical, food, chemical, pulp and paper, petroleum, and transport industries and in tanker building. Standard austenite stainless steels are being replaced by duplex steels in various steel structures [1-2].

Good weldability of these steels also contributes to their wide application. Welding is the fastest, the most cost-effective and the safest modern process of inseparable joining and one can hardly find a modern industrial product without a welded joint. On the other hand, a welded joint is often a weak point in the structure. As heat is always involved in welding, some changes occur in the basic microstructure of duplex steels composed of about equal amounts of ferrite and austenite.

The disturbance of the balanced ferrite/austenite ratio of duplex steels together with harmful precipitates in the heat-affected zone have the effect of reduction in toughness and of lower corrosion resistance in the region of a welded joint. A careful selection of a welding process and adequate welding conditions can reduce the intensity of microstructural transformations, but these transformations cannot be entirely avoided.

With a steady increase in consumption and particularly with new applications of these steels, their tribological properties, together with their corrosion and mechanical properties have grown in importance. It is mostly true for the 1.4462 steel (UNS S31803), whose use has been constantly increasing over years [3-4]. Extensive research and tribological awareness can considerably reduce the losses caused by friction and wear. The adverse effects of wear can be avoided if one knows the resistance of the material to a particular wear mechanism, [5].

Hard particle erosion is an example of wear in which the loss of the material from the surface of a solid body is caused by relative motion of a fluid containing these hard particles. Hard particles which are carried by the fluid hit the surface of a solid body and cause its wear. The dominant wear mechanism is either surface abrasion or fatigue, depending on the impact angle between hard particles and the surface of the solid body. If the impact angle is low, the dominant wear mechanism is abrasion; in the case of a high impact angle when the hard particles hit the surface almost vertically, the dominant wear mechanism is surface fatigue. In the former case we talk about abrasive erosion and in the latter about particle impact erosion, [6].

Cavitation erosion is a phenomenon which can be defined as wear or progressive deterioration of solid surfaces caused by cavitation. Cavitation (lat. *Cavum* – cavity) is a complex physical phenomenon which can be described in simple terms as the creation and implosion of water vapour bubbles in a fluid [7].

In a fluid, water vapour bubbles can be created in three different ways:

- By diffusion of dissolved gases,
- By lowering the pressure in the fluid at a constant temperature,
- By increasing the temperature of the fluid at a constant pressure.

In the first two cases we deal with gaseous and vapour cavitation, and in the third case we deal with boiling. Cavitation occurs when pressure decreases to the vaporization pressure of the fluid at approximately constant temperature, and boiling occurs when temperature increases at constant pressure, Figure 1.

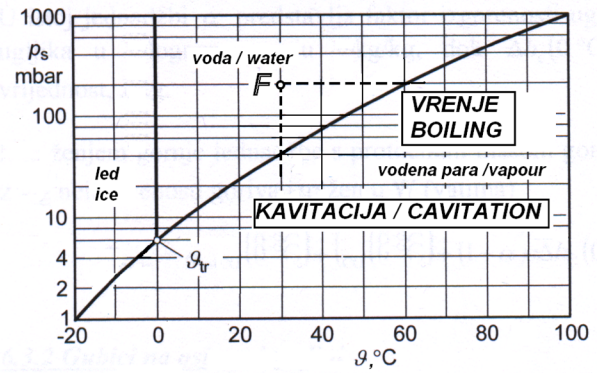

Figure 1. *p-T* diagram of water

Slika 1. Fazni dijagram za vodu

When water vapour bubbles are carried by the flow into the high pressure region, they implode, often very strongly, thus causing erosion, vibrations, noise, etc. At increased pressure, the vapour in a bubble cannot retain this state and it condenses. Since the volume of the condensed water is much smaller than the volume of vapour from which it has been created, a cavity forms. The liquid around these bubbles flows into the cavity at a high speed due to the pressure difference. If implosion takes place in the vicinity of a solid wall, the high pressure which accompanies implosion, can cause material erosion.

The main features of microbombarding, to which the surface of a solid wall is exposed when the implosion of numerous small water vapour bubbles takes place in its surrounding, are as follows:

- *Very high level of stress* which can reach several hundreds MPa, even GPa, which substantially exceeds the yield stress of most materials.
- *The stress is localized* to a very small area in the range of several micrometers to several hundreds of micrometers.
- *The stress is short-termed* – the duration of stress is several microseconds.

The standard testing of the material resistance to cavitation erosion according to the ASTM G 32-98 Standard is carried out in vibratory cavitation.

Vibratory cavitation occurs due to the inertness of the liquid to follow rapid movements of a vibratory body. Its specific characteristic is that in vibratory cavitation there are pressure changes on the same spot, which cause the creation and implosion of bubbles. While the vibratory surface is moving away, underpressure is created, and in the next moment, as the vibratory surface returns, the liquid and the vibratory surface collide, and the underpressure changes immediately into high pressure, causing the implosion of bubbles. The implosion of a high number of bubbles in the vicinity of a solid wall causes

wear, i.e. the erosion of the surface. The dominant wear mechanism in cavitation erosion is the material fatigue. The rate of deformation produced by the cavitation impact can be compared to the rates of deformation induced by the projectile impact or an automobile tyre explosion, [7]. In addition to a high rate of deformation, cavitation erosion is also characterized by localized volume deformation and by repeated impact. All these factors contribute to the modification of a surface layer microstructure and to material fatigue. That is why the deterioration of the material caused by cavitation erosion has specific characteristics and is different from any other type of material deterioration.

2. Experimental investigations and results

2.1. Tested material

A test sample was cut from a rolled plate made of 1.4462 duplex steel. The chemical composition of the sample presented in Table 1 was determined in the Laboratory for metal analysis at the Faculty of Mechanical Engineering and Naval Architecture in Zagreb.

Table 1. Chemical composition of the material
Tablica 1. Kemijski sastav materijala

Sadržaj elementa, % / Chemical composition, %								
C	Ni	Cr	Mn	Si	P	S	N	Mo
0,018	5,49	22,68	1,87	0,28	0,027	0,0004	0,15	2,88

Table 2. Results of quantitative analysis of microstructure
Tablica 2. Rezultati kvantitativne analize mikrostrukture

Specimen	Heat treatment	Volume portion of phases, %		
		austenite	ferrite	σ-phase
O	base metal	50	50	0
1	1100 °C / 30 min	39	61	0
2	1200 °C / 30 min	22	78	0
3	1250 °C / 30 min	14	86	0
4	1300 °C / 30 min	9	91	0
I	800 °C / 1 h	68	26	6
II	800 °C / 2 h	78	12	10
III	800 °C / 3 h	81	6	13
Z	weld metal	59	41	0

When a material is being welded, intensive structural changes take place in a relatively confined space. In the heat affected zone, from the weld metal to the base metal, the microstructure depends on temperature and time, and changes actually at each point, as this is the way the temperature changes in welding. It is impossible to take specimens from the heat affected zone of the welded joint that would be large enough for testing. Therefore, a sufficient amount of base material was adequately heat treated in order to obtain a microstructure which would resemble, as closely as possible, the actual welded microstructure found in different heat affected zones. For the purpose of this research, a number of specimens were heated at temperatures in the range of 1100 and 1300 °C during 30 minutes in order to obtain different ferrite/austenite ratios. The heating was carried out in a vacuum furnace at an appropriate underpressure. The specimens were quenched in nitrogen. Three specimens were annealed at a temperature of 800 °C in order to induce the sigma phase formation. The duration of annealing varied from 60 to 180 minutes. One specimen was cut out from the base material and one from the weld metal. The welding process was carried out by the FCAW process, i.e. a gas-shielded flux-cored arc welding process in which a tubular electrode filled with flux and an external shielding gas are used. The added material is marked as Cromacore DW 329AP Duplex and classified according to the AWS A5.22-95 standard as E2209T1-4/1, and according to the EN 12073 standard as T 22 9 3 N L.

- Specimen «**1**» heated at 1100 °C
- Specimen «**2**» heated at 1200 °C
- Specimen «**3**» heated at 1250 °C
- Specimen «**4**» heated at 1300 °C

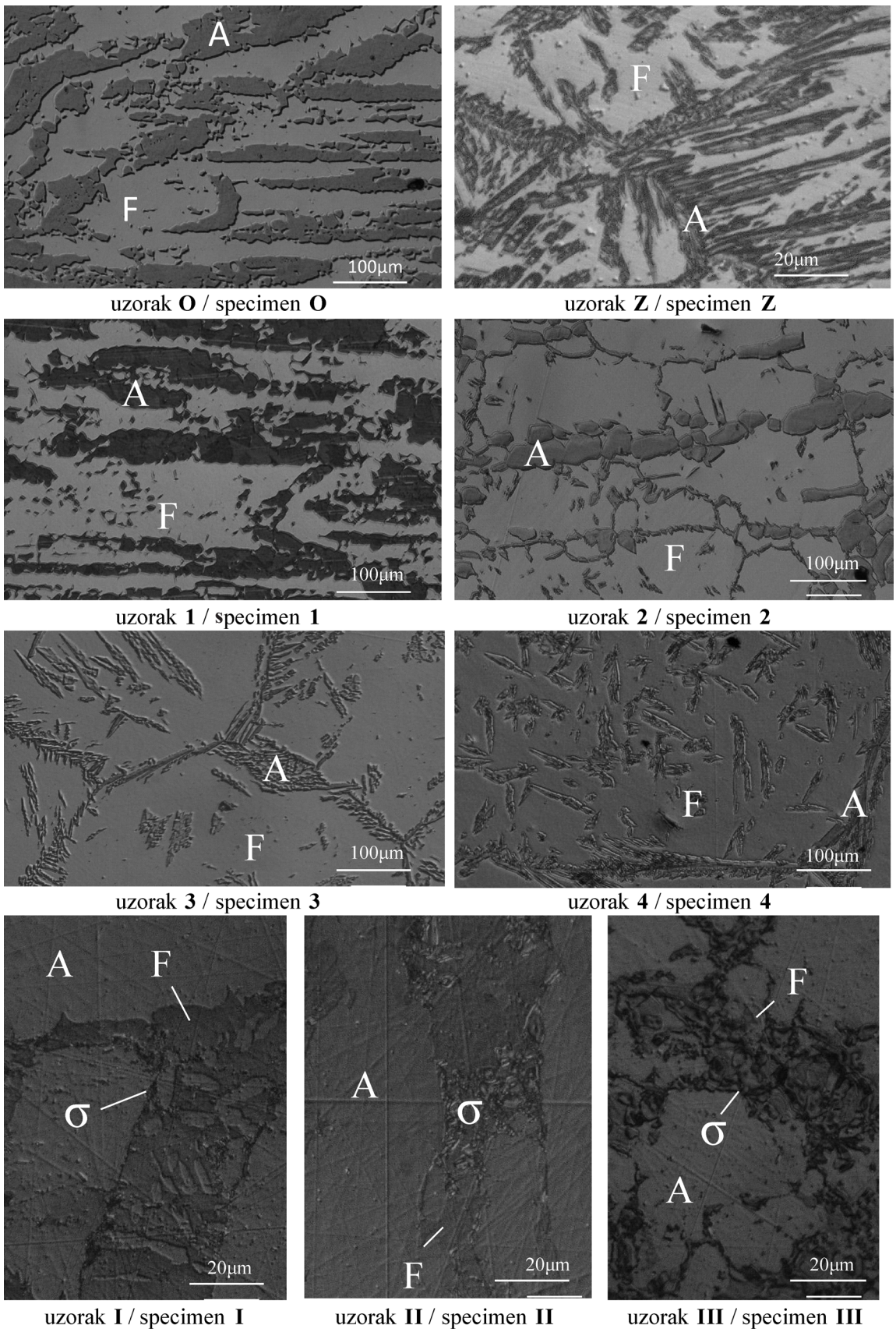

Figure 2. Microstructure of specimens

Slika 2. Mikrostruktura ispitanih uzoraka

- Specimen «**I**» heated at 800 °C for 60 minutes and quenched in air
- Specimen «**II**» heated at 800 °C for 120 minutes and quenched in air
- Specimen «**III**» heated at 800 °C for 180 minutes and quenched in air
- Specimen «**Z**» cut out from the weld metal
- Specimen «**O**» cut out from the base metal.

A qualitative and a quantitative analysis of the microstructure, testing of resistance to hard particle erosion and of resistance to cavitation erosion were carried out on these specimens.

2.2. Analysis of microstructure

A qualitative analysis of microstructure was carried out in the Laboratory for materialography of the Department of Materials at the Faculty of Mechanical Engineering and Naval Architecture in Zagreb. Photographs of microstructures of particular samples, taken at an optical microscope, are shown in Figure 2.

The qualitative analysis of microstructure was conducted using an automated system for image analysis. Measurement results (mean values of 20 measurements) are presented in Table 2.

2.3. Hard particle erosion

Resistance to hard particle erosion was tested in the Laboratory of tribology at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb. The tested surface was hit by a jet of free falling OTTAWA AFS 50/70 dry quartz sand abrasive particles. The testing lasted 60 minutes. Resistance to erosion wear was expressed through mass loss from the specimen surface.

Figure 3 shows the surface of the specimen after 60 minute exposure to hard particle erosion, and the diagrams in Figures 4 and 5 show the mass loss for all specimens.

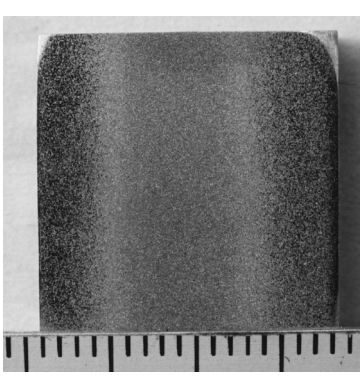

Figure 3. Eroded surface of specimen O

Slika 3. Erodirana površina uzorka O

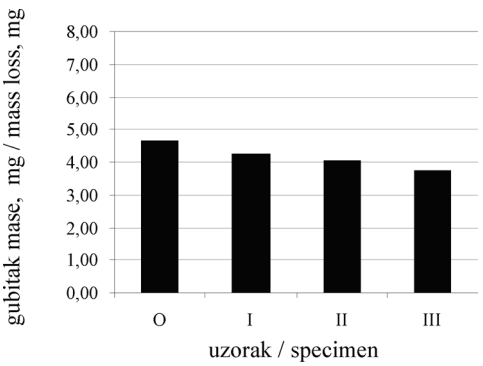

Figure 4. Mass loss of specimens O, I, II i III

Slika 4. Gubitak mase uzoraka O, I, II i III

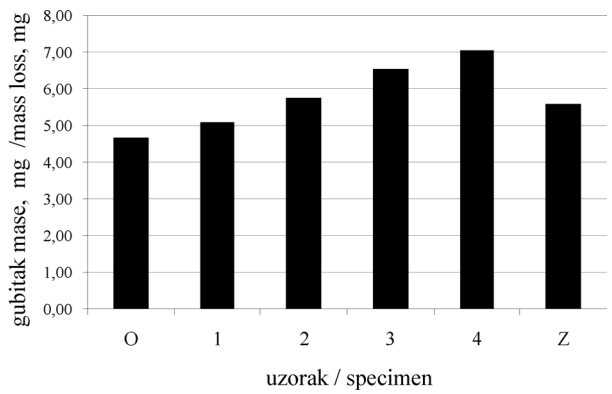

Figure 5. Mass loss of specimens O, 1, 2, 3, 4 and Z

Slika 5. Gubitak mase za uzorke O, 1, 2, 3, 4 i Z

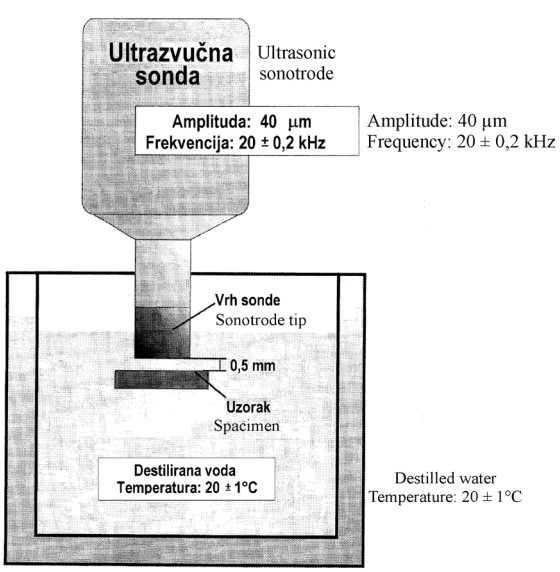

Figure 6. Position of the specimen in a cavitation erosion tester

Slika 6. Položaj uzorka kod ispitivanja otpornosti na kavitacijsku eroziju

2.4. Cavitation erosion

Resistance to cavitation erosion was tested at the Institut für Werkstoffe der Ruhr-Universität Bochum. The standard test method for cavitation erosion is given by the ASTM G 32-98 standard, [9]. The so-called indirect method in which the specimen is put opposite to a vibratory probe (and not on its tip) was applied for testing, see Figure 6. The duration of surface exposure to cavitation was 20000 seconds.

Test results of resistance to cavitation erosion are presented by a diagram in Figure 7. The specimen surface exposed to cavitation with a duration of 20000 seconds is shown in Figure 8.

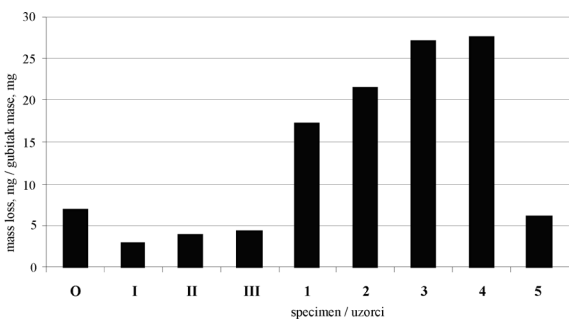

Figure 7. Mass loss of specimens after cavitation erosion test

Slike 7. Gubitak mase na uzorcima nakon ispitivanja kavitacijske erozije

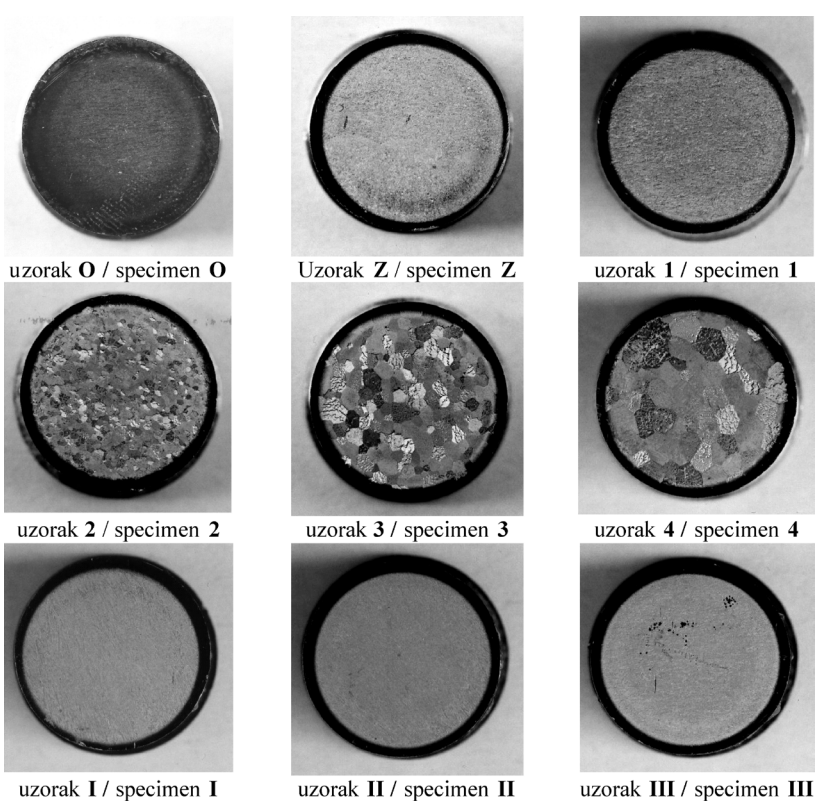

Figure 8. Surface of specimens after cavitation erosion test

Slika 8. Površina uzoraka nakon izlaganja kavitacijskoj eroziji

3. Test results and discussion

3.1. Comments on microstructure analysis results

The microstructure of specimen O is the microstructure of base material. It consists of austenite and ferrite in approximately equal volume portions.

The microstructure of specimens I, II and III is obtained by annealing the base metal at 800 °C for periods of 1, 2 and 3 hours. Annealing was performed in order to induce the sigma phase formation. The volume portion of sigma phase increases with the annealing duration. Sigma phase precipitates are primarily formed on ferrite/austenite boundaries and from there, they precipitate into ferrite. As the sigma phase is formed, ferrite disintegrates and its volume portion is significantly reduced, especially after the first hour, i.e. from 50 to 26 %. At the same time, the volume portion of austenite increases, Figure 9.

The annealing of the base material specimen for half an hour at 1100, 1200, 1250 and 1300 °C was performed in order to obtain a microstructure that is as similar as possible to the microstructure in the high-temperature heat affected zone (HT-HAZ).

The volume portion of rises increases with an increase in temperature, from the initial 50 % to 91 %, Figure 10.

Specimen 1, annealed at 1100 °C, has a microstructure very similar to specimen O.

In specimen 2, the original shape of austenite grains has almost disappeared, and the remaining austenite in such regions is located on the boundaries of ferrite grains.

Specimen 3 has a completely different structure type than specimen O. The duplex structure has been transformed into the so-called network structure. Austenite is mainly located on the boundaries of ferrite grains.

In specimen 4, due to a higher heating temperature, ferrite grains are significantly larger in size than those in specimen 3.

The microstructure of specimen Z is a typical cast structure composed of austenite and ferrite. The volume portion of austenite is larger than that of ferrite and it amounts to approximately 59 %.

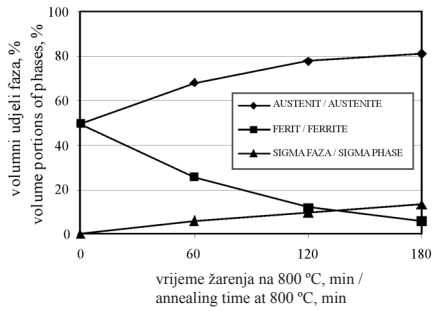

Figure 9. Influence of annealing duration at 800 °C on the volume portions of ferrite, austenite and sigma phase

Slika 9. Utjecaj trajanja žarenja na 800 °C na volumne udjele ferita, austenita i sigma faze

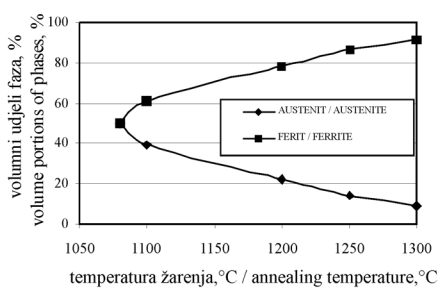

Figure 10. Influence of annealing temperature on the volume portions of ferrite and austenite

Slika 10. Utjecaj temperature žarenja na volumne udjele ferita i austenita

3.2 Comments on test results of resistance to hard particle erosion wear

All specimens annealed at 800 °C with a view to induce the sigma phase in the microstructure had a smaller mass loss than the basic specimen O which was not heat treated. With prolongation of the annealing time and sigma phase increase in the microstructure, the mass loss caused by erosion wear is reduced. A quantitative representation of this dependence is given in Figure 11. The trend in mass loss shown in the figure is most probably a consequence of a low impact angle between erosion particles and the specimen surface (30 °). This low impact angle does not result in a large amount of wear in hard and brittle materials, e.g. in the specimens with the sigma phase. As for ductile materials, low impact angles result in more pronounced signs of wear. This can account for a more intensive wear noted on specimen O than on specimens with the sigma phase (I, II and III).

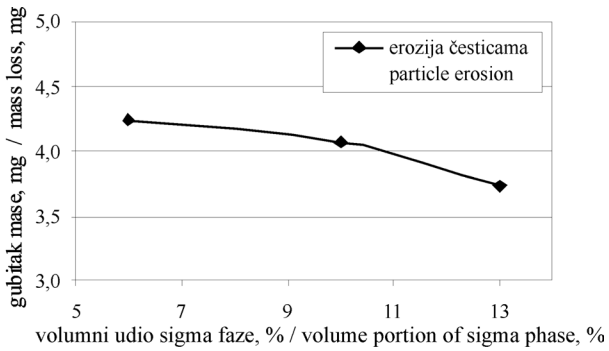

Figure 11. Influence of sigma phase increase on the mass loss caused by particle erosion

Slika 11. Utjecaj povećanja udjela sigma faze na gubitak mase kod erozije česticama

An increase in the volume portion of ferrite in the duplex steel microstructure is the cause of higher wear intensity in hard particle erosion. In Figure 12, this dependence is shown by a diagram. From the inclination of the curve, which becomes steeper as the volume portion of ferrite increases to approximately 78 % (by annealing at 1200 °C), one can conclude that the transformation from a duplex structure to a network structure enhances wear. The influence of the grain growth at 1300 °C on the material loss in hard particle erosion has not been recorded.

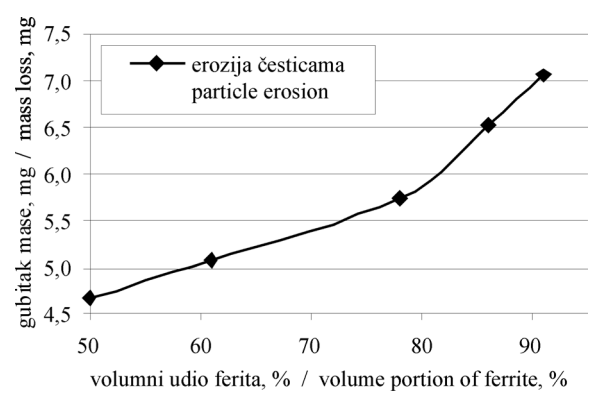

Figure 12. Influence of ferrite increase on the mass loss caused by particle erosion

Slika 12. Utjecaj povećanja volumnog udjela ferita na gubitak mase kod erozije česticama

3.3. Comments on test results of resistance to cavitation erosion

The influence of microstructural changes induced by the annealing of duplex steels at 800 °C on the material loss in cavitation erosion is very complex.

All specimens annealed at 800 °C have a significantly lower mass loss than the basic specimen O which has not been heat treated. This is caused by an increase in the volume portion of austenite, which is resistant to

cavitation erosion, and a decrease in the volume portion of ferrite which occurs simultaneously with the formation of sigma phase and growth in its volume portion.

With prolongation of the annealing time, the volume portion of sigma phase increases. With a rise in the sigma phase volume portion in the microstructure of duplex steel, the mass loss increases, i.e. the material becomes less resistant to cavitation erosion. The sigma phase is very hard and brittle and it reduces ductility and toughness to a high degree. As fatigue in the material is a dominant wear mechanism in cavitation erosion, such influence of the sigma phase is not unexpected.

The influence of the sigma phase increase on the mass loss in the resistance to cavitation erosion testing is given in the form of a diagram, Figure 13.

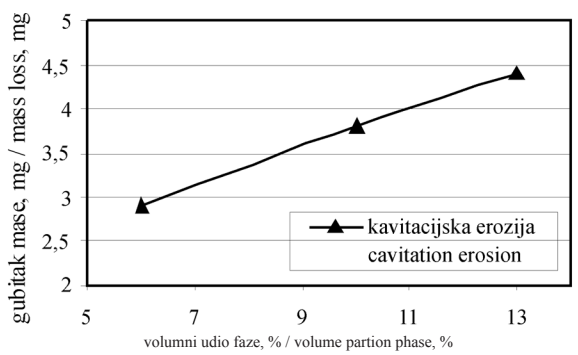

Figure 13. Influence of sigma phase increase on the mass loss caused by cavitation erosion

Slika 13. Utjecaj povećanja udjela sigma faze na gubitak mase kod kavitacijske erozije

In specimens annealed at temperatures between 1100 and 1300 °C, an increase in the volume portion of ferrite and a simultaneous decrease in the volume portion of austenite result in a reduction in the cavitation erosion resistance, as shown by the diagram in Figure 14.

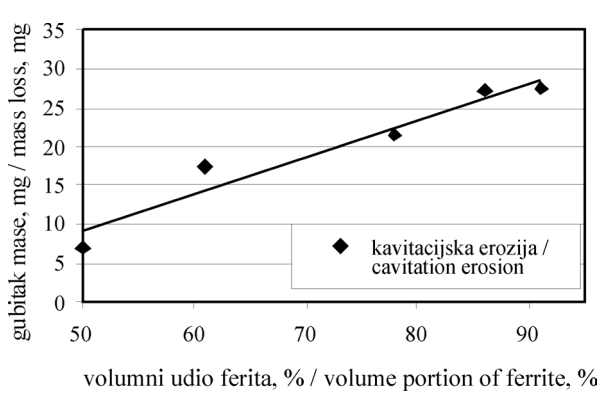

Figure 14. Influence of ferrite increase on the mass loss caused by cavitation erosion

Slika 14. Utjecaj udjela ferita na gubitak mase kod kavitacijske erozije

4. Conclusions

Based on the analysis of test results, the following conclusions can be made:

- With prolongation of the annealing time at 800 °C, the sigma phase volume portion increases.
- A rise in the annealing temperature from 1100 °C to 1300 °C results in an increase in ferrite volume portion from 50 % to 91 %. At a temperature above 1200 °C, the microstructure type changes, i.e. the duplex structure is transformed into a network structure. An annealing temperature increase from 1250 to 1300 °C is accompanied by the ferrite grain growth.
- Resistance to hard particle erosion wear rises with the sigma phase increase in the duplex steel microstructure.
- An increase in the ferrite volume portion reduces the erosion resistance. A greater reduction in the resistance is caused by the change in the type of structure which starts at ≈1200 °C when the duplex structure is transformed into the network structure.
- The resistance of welded metal to this type of wear is lower than the resistance of the base metal.
- Resistance to cavitation erosion of specimens with sigma phase is higher than the resistance of the base material. The difference between the two drops with the sigma phase increase.
- With a rise in the sigma phase, the mass loss increases, i.e. the material becomes less resistant to cavitation erosion. The sigma phase is very hard and brittle and it reduces ductility and toughness to a high degree. As fatigue in the material is a dominant wear mechanism in cavitation erosion, such influence of the sigma phase is not unexpected.
- An increase in the ferrite volume portion in the temperature range from 1100 to 1300 °C causes a significant reduction in the resistance to cavitation erosion.

  A change in the type of the structure further reduces the resistance.

  Resistance to cavitation erosion of weld metal is approximately the same, or even a bit higher than the resistance of the base material, probably due to a higher volume portion of austenite.

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