UDK 669.01:620.18:539.42
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
MTAEC9, 43(4)179(2009)

THE MECHANICAL PROPERTIES OF TWO-PHASE Fe-NiCrMo ALLOYS AT ROOM TEMPERATURE AND 290 °C AFTER AGEING IN THE TEMPERATURE RANGE 290–350 °C

MEHANSKE LASTNOSTI DVOFAZNIH ZLITIN Fe-NiCrMo PRI SOBNI TEMPERATURI IN PRI 290 °C PO STARANJU V RAZPONU TEMPERATURE 290 °C DO 350 °C

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Prejem rokopisa – received: 2009-02-19; sprejem za objavo – accepted for publication: 2009-03-09

Fe-NiCrMo alloys were aged for up to 17 520 h in the temperature range 290-350 °C to achieve the spinodal decomposition of δ-ferrite. The tensile properties and the Charpy notch toughness were determined at room temperature and at 290 °C. The ageing affected the tensile properties only a little, but decreased very strongly the notch toughness and to a greater extent the content of α-ferrite. The tensile properties were lower at 290 °C than at room temperature and the difference was virtually independent of the content of ferrite. The notch toughness was significantly higher at 290 °C, and the difference amounted to three times the lowest toughness of the aged alloy with the maximum content of δ-ferrite. The different effects of ageing are explained in terms of the ferrite microhardness, the strain hardening of the austenite and the mechanisms of deformation and fracturing.

Key words: Fe-NiCrMo alloys, microstructure, spinodal decomposition, tensile properties, notch toughness, testing temperature

Zlitine Fe-NiCrMo so bile starane do 17 520 h pri temperaturah med 290 °C in 350 °C zaradi spinodalne razgradnje trdne raztopine v δ-feritu. Določene so bile raztržne lastnosti in zarezna žilavost po Charpyju pri sobni temperaturi in pri 290 °C. Staranje malo vpliva na raztržne lastnosti, a močno zmanjša zarezno žilavost, in to tem bolj, čim več je v zlitini ferita in čim bolj je napredoval spinodalen proces. Raztržne lastnosti so bile nižje pri temperaturi 290 °C kot pri sobni temperaturi, razlika pa je bila praktično neodvisna od vsebnosti ferita in od stopnje spinodalnega procesa. Zarezna žilavost je bila večja pri 290 °C kot pri sobni temperaturi in razlika je bila trikratna pri najnižji izmerjeni žilavosti starane zlitine z največ ferita. Različen vpliv staranja na lastnosti je razložen z upoštevanjem trdote δ-ferita, deformacijske utrditve avstenita ter mehanizmov plastične deformacije in preloma.

Ključne besede: zlitine Fe-NiCrMo, spinodalni razpad, raztržne lastnosti, zarezna žilavost, temperatura preizkusa

1 INTRODUCTION

In alloys with a high content of chromium the solid solution of chromium and nickel or cobalt in α-iron is not stable. In the temperature range up to approximately 750 °C the solid solution is decomposed with a spinodal process into two constituents: one enriched in chromium and the other in nickel or cobalt[1]. Both phases retain the initial α-iron lattice but have a different lattice parameter that depends on the composition of the solid solution. The lattices of both phases accommodate with elastic internal stresses that increase the hardness and brittleness, and after magnetisation give the alloy hard-magnetic properties[2]. The kinetics of decomposition depends on the diffusional transport of atoms in a substitutional solid solution. The rate of diffusion depends strongly on the temperature and it is very slow in the temperature range in which alloys of this type are operating in nuclear power plants. In the same conditions of temperature and time, the solid solution in austenite is stable; it may change only with the precipitation of carbides if the content of carbon is above the solubility limit that depends on the temperature. At higher temperatures the spinodal decomposition is replaced by the formation of σ phases that also decrease the mechanical properties at room temperature[3]. In the process of spinodal decomposition, the properties of alloys with a two-phase microstructure of austenite and δ-ferrite are changed, depending on the volume share of ferrite and the extent of the decomposition, respectively, and the difference in the chemical composition and the lattice parameters between both spinodal constituents.

In some nuclear power plants essential parts of the equipment are manufactured from Fe-Ni-Cr-Mo alloys and may have, depending of the chemical content of alloying elements and impurities as well as the eventual thermal history, a different content of δ-ferrite formed with equilibrium or non-equilibrium solidification. The operation temperature of nuclear power plants is relatively low, in many plants it is around 300 °C, and the process of spinodal decomposition is very slow, as is the rate of change of the properties. For this reason, in this work the ageing was performed at a relatively low temperature and for a time that should suffice for a reliable evaluation of the kinetics and mechanisms of the changes of the properties of built-in alloys.

In the investigation of the instability of the properties of Fe-Ni-Cr-Mo alloys with a two-phase microstructure[4] it was established that the change of properties was greater for an alloy with 14.5 % of δ-ferrite than for an alloy with 8.5 % of δ-ferrite when ageing in the temperature range 300–400 °C, while at higher temperatures the ageing effect was smaller. In[5] these findings we confirmed and found that the content of δ-ferrite determined from the Schaeffler diagram was unreliable and that its distribution in as-cast alloys is inhomogeneous and can vary in the range 1.5 to 22.5 for the same cast piece. The ageing effect on Charpy toughness was very strong in temperature range 303 °C to 325 °C and the initial toughness was achieved again after annealing at 550 °C. Of several processes that could affect the alloys' properties, the main embrittlement process is the spinodal decomposition[6]. A correlation was developed[7] for the assessment of the thermal embritlement and the prediction of changes in the fracture and Charpy and tensile properties of as-cast two-phase alloys. The use of small specimens for the investigation of in-service-aged elbows gives reliable values for the J-Δa results in conditions where strongly deviating specimens are rejected[8]. The low-cycle fatigue increases rapidly with the increase of the ageing time[9]. An essential difference in the properties obtained at room temperature and at 300 °C for aged alloys with a different content of δ-ferrite is observed in ref. 10.

2 EXPERIMENTAL WORK

Three alloys with the compositions in **Table 1** were prepared by melting in a laboratory induction furnace from the same raw materials and cast into square ingots of 100 mm thickness. The average contents of δ ferrite were 2 %, 11 % and 27 %. In the two alloys with lower contents of ferrite, this phase was formed mostly during the solidification of grain boundaries, forming a network that was more closed with a higher content of ferrite (**Figure 1 and 2**). It is concluded that δ-ferrite solidified from the residual melt, enriched in elements that improve the stability of ferrite in the equilibrium binary and ternary systems. In the alloy with the highest content of ferrite the microstructure is explained by the start of solidification with the formation of ferrite and the subsequent solidification with the formation of austenite in a peritectic reaction between the solid ferrite phase and the melt enriched in elements stabilising the γ-phase (**Figure 3**). All the alloys were assumed to be suited for the investigation because in all these the δ-ferrite constituent of the microstructure were embedded in austenite.

All the alloys were aged for a time up 4 320 h for the tensile tests and up to 17 520 h for the Charpy notch tests and hardness at three temperatures: 290 °C, 320 °C and

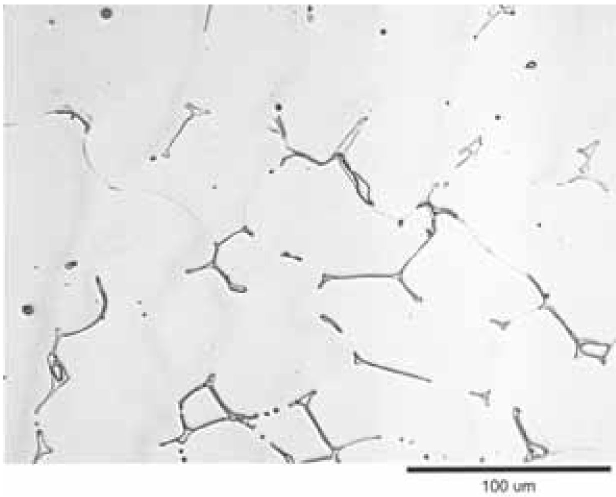

Figure 1: Microstructure of the alloy with 2 % of δ-ferrite
Slika 1: Mikrostruktura zlitine z 2 % δ-ferita

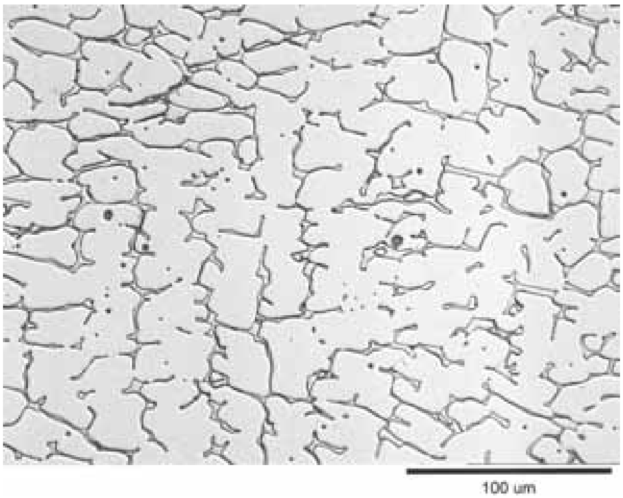

Figure 2: Microstructure of the alloy with 11 % of δ-ferrite
Slika 2: Mikrostruktura zlitine z 11 % δ-ferita

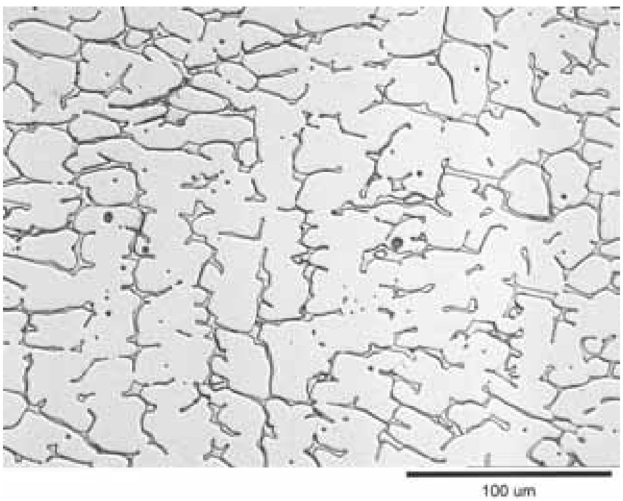

Figure 3: Microstructure of the alloy with 27 % of δ-ferrite
Slika 3: Mikrostruktura zlitine s 27 % δ-ferita

350 °C. It was assumed that the rate of spinodal decomposition depended on the exchange of atoms between both phases with volume diffusion. The diffusion rate is about 3 times greater at 350 °C than at 290 °C. It was thus expected that the ratio of the rates of spinodal decomposition was equal and that after 17 520 h of ageing at 350 °C the decomposition of the solid solution would be achieved at 290 °C, after a much longer ageing time at 290 °C. This assumption does not imply that the effect of ageing on properties is equal for both temperatures. The answer to these questions, observations of spinodal constituents with transmission electron microscopy would be necessary.

Tensile properties and Charpy notch toughness of aged specimens were determined at room temperature and at 290 °C, operating temperature of parts in a nuclear power plant. The hardness and microhardness were determined only at room temperature. Austenite does not fracture with cleavage, thus according to[8], the very wide spread of Charpy results were rejected as a result of the local, greatly increased content of ferrite in the specimen with a small section. Most of the specimens strongly deviating from the parallels and clearly deviating in the curve depicting the effect of ageing time were found for the Charpy specimens.

Table 1: Chemical composition of the examined alloys
Tabela 1: Kemična sestava zlitin

Alloy	Elements, *w*/%						
	C	Si	Mn	P	S	Ni	Cu	Mo
I	0.06	0.43	1.59	0.03	0.01	11.9	18	1.84
II	0.07	0.67	1.04	0.03	0.01	11	21.7	2.03
II	0.06	1.68	0.67	0.03	0.01	9	20.8	2.46

3 HARDNESS AND MICROHARDNESS

The ageing time at 350 °C does not affect the hardness of the alloy with 2 % of δ-ferrite; only very slightly does it affect the hardness of the 11 % ferrite alloy, and slightly the hardness of the 27 % ferrite alloy (**Figure 4**).

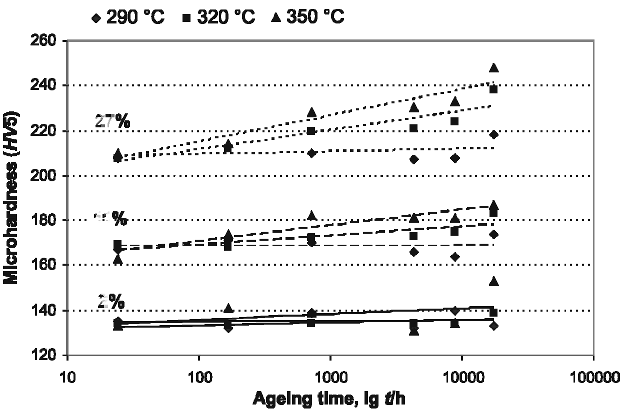

Figure 4: Hardness of all three alloys with the dependence on the ageing time
Slika 4: Trdota vseh treh zlitin v odvisnosti od časa staranja

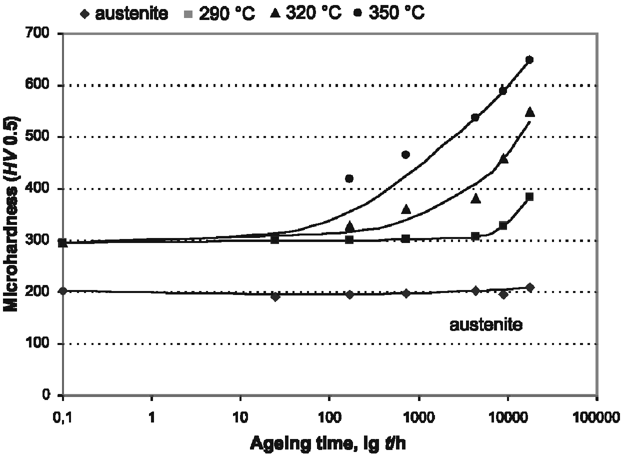

Figure 5: Microhardness of δ-ferrite and austenite in the 27 % ferrite alloy and the dependence on the ageing time at 350 °C
Slika 5: Mikrotrdota δ-ferita in avstenita v zlitini s 27 % ferita v odvisnosti od časa staranja pri 350 °C

At a lower ageing temperature the changes of hardness were also small for the 27 % ferrite alloy. The ageing time does not affect the austenite microhardness and increases the microhardness of the ferrite (**Figure 5**). The increase is larger and faster for the ageing temperature of 350 °C. For this alloy, the initial microhardness of the ferrite was increased by 82 % after 4 320 h of ageing, doubled after 8 760 h and increased by 2.2 times after 17 520 h of ageing. The chemical composition of the δ-ferrite is similar in all the alloys. It can thus be assumed that the hardness of this phase increased with the ageing time in a similar way also for the alloys with a lower content of α-ferrite. The minor share of ferrite in the alloys explains why the ageing affected the alloys' hardness to a much smaller extent than the microhardness of the ferrite.

4 TENSILE PROPERTIES

In **Figures 6, 7 and 8** the effect of ageing time is shown for the yield stress at room temperature and at 290 °C. In the 2 % ferrite alloy, the yield stress at room temperature is slightly decreased during the ageing at all three tested temperatures. For the alloy with 11 % of ferrite a similar yield-stress decrease is found for the ageing temperatures of 290 °C and 320 °C, while when ageing at 350 °C the yield stress is slightly increased. For the alloy with 27 % of ferrite the yield stress is increased at all ageing temperatures. Compared to the increase of the ferrite microhardness, which amounts to 82 % after 4 320 h of ageing, the increase of the yield stress is much lower; it amounts to only approximately 4 %. It is assumed that the small decrease of the yield stress is due to the relaxation of the cooling stresses in both low-amount ferrite alloys.

At 290 °C the yield stress is lower for all alloys than at room temperature, and the effect of the ageing time is

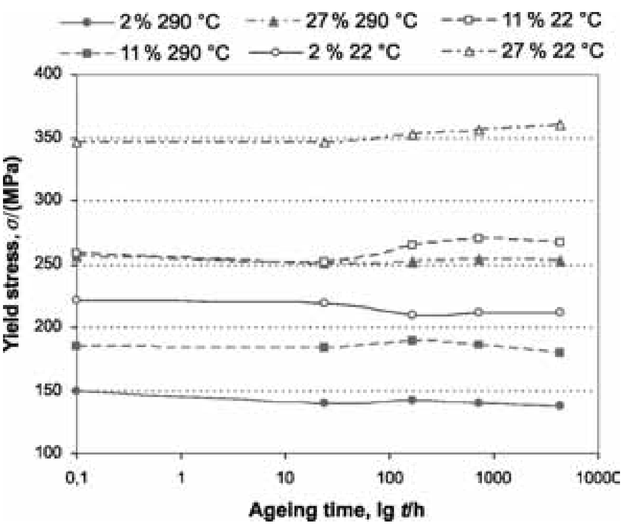

Figure 6: Effect of ageing time at 290 °C on the yield stress for all alloys at room temperature and at 290 °C
Slika 6: Vpliv trajanja staranja pri 290 °C na mejo plastičnosti vseh zlitin pri sobni temperaturi in pri 290 °C

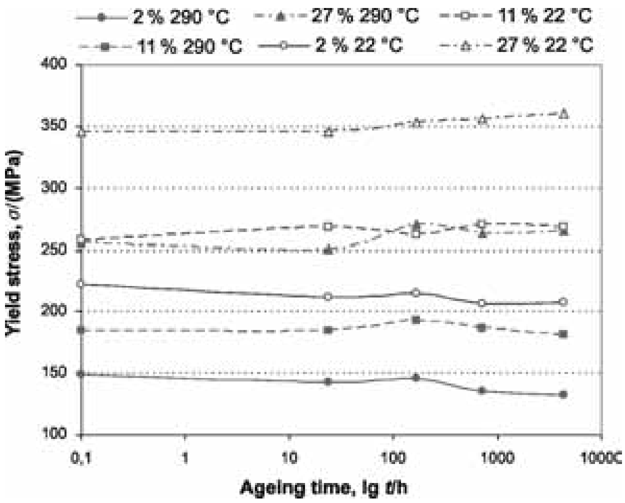

Figure 8: Effect of ageing time at 350 °C on the yield stress at room temperature and at 290 °C for all alloys
Slika 8: Vpliv trajanja staranja pri 350 °C na mejo plastičnosti vseh zlitin pri sobni temperaturi in pri 290 °C

similar for the alloy 1. The yield stress is not affected by the ageing for the alloy with 11 % of ferrite. It is constant for the alloy with 27 % of ferrite during ageing at 290 °C, slightly increased during ageing at 320 °C, and increased a great deal at both test temperatures after ageing at 350 °C.

Ageing at 290 °C and 320 °C has no effect on the tensile strength at room temperature and at 290 °C for the 2 % and 11 % ferrites (**Figure 9, 10 and 11**). For the alloys with 11 % and 27 % ferrite the tensile strength is increased only at room temperature. At both higher ageing temperatures the tensile strength increases with the ageing. The increase is greater at 350 °C, when the strength at room temperature and at 290 °C, compared to the initial value it is higher by 12 % and 10 %, respectively. Again the increase of the tensile strength is much smaller than the increase of the ferrite hardness.

The elongation is very slightly affected by the ageing of all alloys at 290 °C and 320 °C, while after ageing at 350 °C it is lower due to the higher content of ferrite (**Table 2**). It is not affected significantly by the ageing time and temperature at both testing temperatures and for all the alloys it is lower during testing at 290 °C.

For all the alloys the reduction of the area is virtually unaffected by the content of ferrite and the ageing time at 290 °C and 320 °C. At room temperature it is virtually equal for all the alloys and ageing conditions (**Table 3**). For all the alloys it is significantly lower at 290 °C and

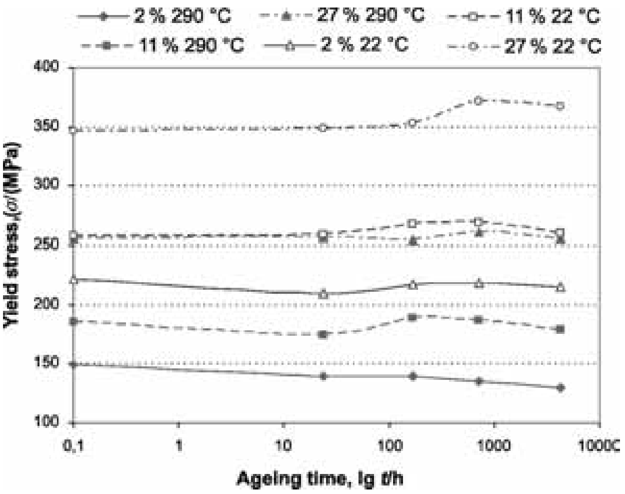

Figure 7: Effect of ageing time at 320 °C on the yield stress for all alloys at room temperature and at 290 °C
Slika 7: Vpliv trajanja staranja pri 320 °C na mejo plastičnosti vseh zlitin pri sobni temperaturi in pri 290 °C

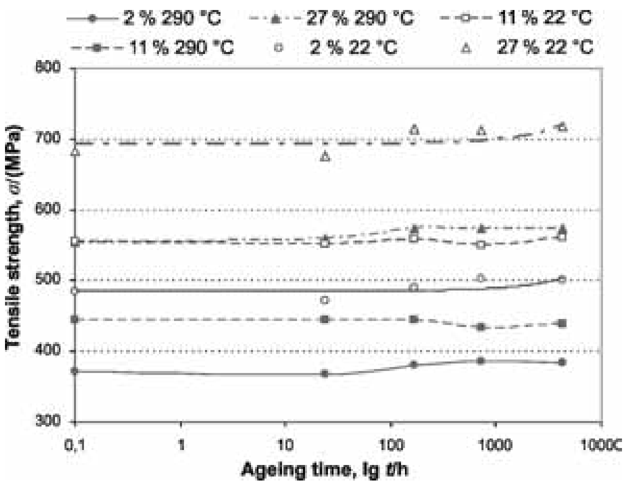

Figure 9: Effect of ageing time at 290 °C on the tensile strength of all alloys at room temperature and at 290 °C
Slika 9: Vpliv časa staranja pri 290 ºC na raztržno trdnost vseh zlitin pri sobni temperaturi in pri 290 °C

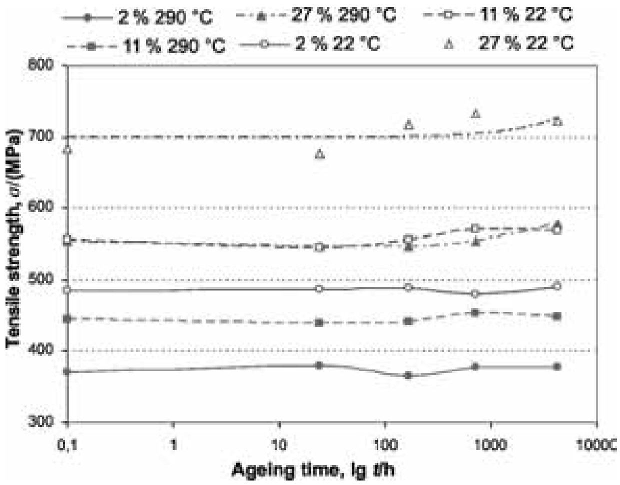

Figure 10: Effect of ageing time at 320 °C on the tensile strength at room temperature and at 290 °C for all alloys

Slika 10: Vpliv časa staranja pri 320 °C na raztržno trdnost vseh zlitin pri sobni temperaturi in pri 290 °C

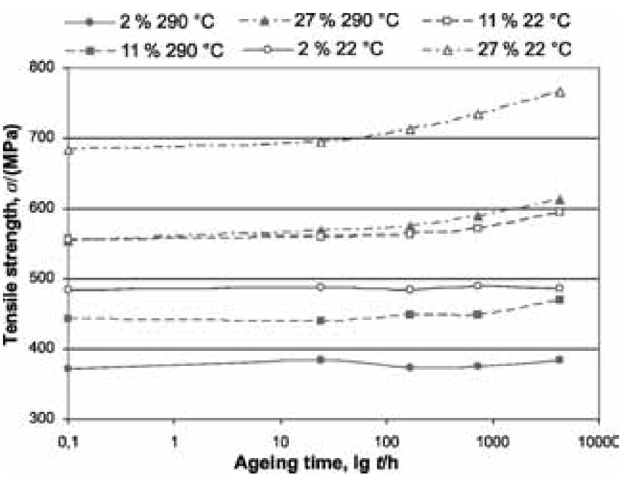

Figure 11: Effect of ageing time at 350 °C on the tensile strength at room temperature and at 290 °C for all alloys

Slika 11: Vpliv časa staranja pri 350 °C na raztržno trdnost vseh zlitin pri sobni temperaturi in pri 290 °C

Table 2: Effect of ageing time at 350 °C on the elongation at room temperature and at 290 °C

Tabela 2: Vpliv časa staranja na raztezek pri sobni temperaturi in pri 290 °C

δ-ferrite (w/%)	2		11		27	
Ageing time	Test temperature					
	22 °C	290 °C	22 °C	290 °C	22 °C	290 °C
0 h	51	35	45	36	40	28
24 h	54	39	46	40	37	30
168 h	54	34	52	36	37	28
720 h	48	38	48	36	37	27
4320 h	51	34	44	33	33	26

Table 3: Effect of ageing time at 350 °C on the reduction of area at room temperature and at 290 °C

Tabela 3: Vpliv časa staranja na kontrakcijo pri sobni temperaturi in pri 290 °C

δ-ferrite (w/%)	2		11		27	
Ageing time	Test temperature					
	22 °C	290 °C	22 °C	290 °C	22 °C	290 °C
0 h	64	61	68	62	64	47
24 h	68	58	62	58	68	51
168 h	67	56	63	58	67	50
720 h	68	56	61	60	64	50
4320 h	66	50	60	56	60	46

Table 4: Yield stress reported for the 2 % ferrite alloy at room temperature and 290 °C; ageing temperature 350 °C

Tabela 4: Razmerje proti meji plastičnosti zlitine z 2 % ferita pri sobni temperaturi in pri 290 °C; temperatura staranja 350 °C

δ-ferrite (w/%)	2		11		27	
Ageing time	Test temperature					
	22 °C	290 °C	22 °C	290 °C	22 °C	290 °C
0 h	1	1	1.14	1.24	1.52	1.71
24 h	0.94	0.96	1.18	1.24	1.52	1.68
168 h	0.95	0.98	1.15	1.29	1.55	1.74
720 h	0.91	0.92	1.19	1.19	1.57	1.70
4320 h	0.92	0.89	1.18	1.22	1.59	1.79

Table 5: Tensile strength reported for the 2 % ferrite alloy at room temperature and 290 °C; ageing temperature 350 °C

Tabela 5: Razmerje proti raztržni trdnosti zlitine z 2 % ferita pri sobni temperaturi in pri 290 °C; temperatura staranja 350 °C

δ-ferrite (w/%)	2		11		27	
Ageing time	Test temperature					
	22 °C	290 °C	22 °C	290 °C	22 °C	290 °C
0 h	1	1	1.15	1.19	1.41	1.49
24 h	1.0	1.05	1.15	1.18	1.43	1.52
168 h	1.0	1.01	1.16	1.28	1.47	1.55
720 h	1.0	1.01	1.18	1.28	1.51	1.53
4320 h	1.0	1.04	1.22	1.27	1.58	1.59

Table 6: Elongation for the 11 % and 27 % ferrite alloys reported for the 2 % ferrite alloy at room temperature and 290 °C; ageing temperature 350 °C

Tabela 6: Razmerje proti razteznosti zlitine z 2 % ferita pri sobni temperaturi in pri 290 °C; temperatura staranja 350 °C

δ-ferrite (w/%)	2		11		27	
Ageing time	Test temperature					
	22 °C	290 °C	22 °C	290 °C	22 °C	290 °C
0 h	1	1	0.88	1.02	0.78	0.80
24 h	0.98	1.11	0.90	1.03	0.72	0.85
168 h	0.89	0.97	1.05	1.0	0.72	0.80
720 h	0.87	1.08	1.02	1.0	0.74	0.77
4320 h	0.94	0.97	0.97	0.94	0.66	0.74

Table 7: Reduction of area for the 11 % and 27 % ferrite alloys reported for the 2 % ferrite alloy at room temperature and 290 °C; ageing temperature 350 °C

Tabela 7: Razmerje proti kontrakciji zlitine z 2 % ferita pri sobni temperaturi in pri 290 °C; temperatura staranja 350 °C

δ-ferrite (w/%)	2		11		27	
Ageing time	Test temperature					
	22 °C	290 °C	22 °C	290 °C	22 °C	290 °C
0 h	1	1	1.06	1.01	1.0	0.87
24 h	1.06	0.95	0.97	0.85	1.06	0.84
168 h	1.05	0.92	0.98	0.95	1.05	0.82
720 h	1.06	1.0	0.95	0.98	1.0	0.92
4320 h	1.03	0.82	0.94	0.92	0.94	0.81

all ageing conditions and diminished the most after the ageing of the 27 % ferrite alloy at 350 °C.

The effect of the content of ferrite and ageing time on the change of the yield stress and the tensile strength at both testing temperatures after different ageing times at 350 °C is shown in **Tables 4 and 5**. Both properties are higher with an increased content of ferrite and are increased slightly more when testing at 290 °C than at room temperature. The data in **Tables 6 and 7** show that the initial elongation is less with a higher content of ferrite. For the 2 % and 11 % ferrite alloys the elongation is not affected by the ageing time at both testing temperatures, while it is slightly decreased with longer ageing. For the 27 % ferrite alloy the elongation is slightly greater when testing at 290 °C. The scatter of the test results was great for the reduction of area and, for this reason, the effect of ageing time at 350 °C is not clear; it is, however, very small. During testing at 290 °C the difference in the properties is greater. The yield stress and the tensile properties of the non-aged and aged alloys increase with the content of ferrite in a non-linear dependence, which is similar for the yield stress and the tensile strength.

5 NOTCH TOUGHNESS

In **Figures 12, 13 and 14** the effect of time for different ageing temperatures on the Charpy notch toughness is shown for both testing temperatures and the 2 %, 11 % and 27 % δ-ferrite alloys. With 2 % of ferrite and ageing at 290 °C and 320 °C the notch toughness starts to decrease gradually with an intermediate ageing time, and it is decreased to a value of about 80 % of the initial level after the longest ageing time of 17 520 h (2 years). With ageing at 350 °C the notch toughness drops after ageing for approximately 4 320 h when testing at room temperature and 290 °C to approximately 2/3 of the initial value. In all cases the notch toughness is higher when testing at 290 °C than at room temperature. The difference is about 30 J (16 %) for all the tested specimens.

The effect of ageing is stronger for the 11 % ferrite alloy. At room temperature the notch toughness starts to

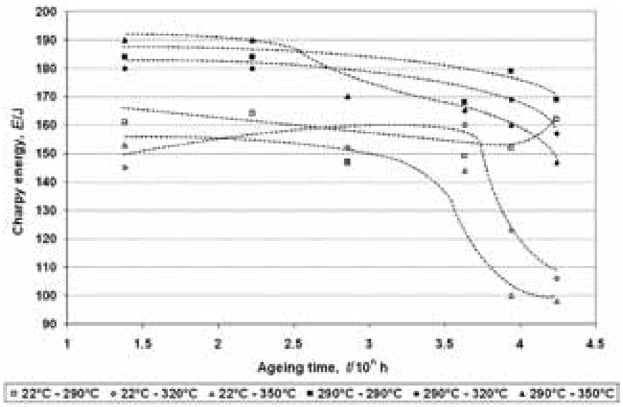

Figure 12: Alloy with 2 % of δ-ferrite. Effect of the ageing time at different ageing temperatures on the notch toughness at room temperature and at 290 °C[10]

Slika 12: Zlitina z 2 % δ-ferita. Vpliv trajanja staranja pri različnih temperaturah na zarezno žilavost pri sobni temperaturi in pri 290 °C

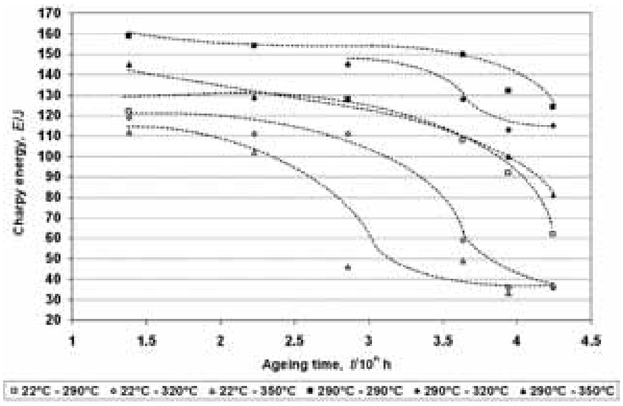

Figure 13: Alloy with 11 % of δ-ferrite. Effect of the ageing time at different ageing temperature on the notch toughness at room temperature and at 290 °C[10]

Slika 13: Zlitina z 11 % δ-ferita. Vpliv trajanja staranja pri različnih temperaturah na zarezno žilavost pri sobni temperaturi in pri 290 °C

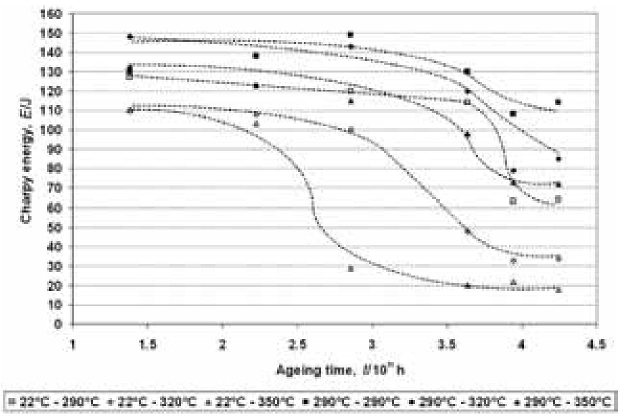

Figure 14: Alloy with 27 % of δ-ferrite. Effect of the ageing time at different ageing temperatures on the notch toughness at room temperature and at 290 °C[10].

Slika 14: Zlitina s 27 % δ-ferita. Vpliv trajanja staranja pri različnih temperaturah na zarezno žilavost pri sobni temperaturi in pri 290 °C decrease already after 168 h of ageing at 350 °C and 720 h at 290 °C. With longer annealing the notch toughness decreases faster, to approximately 35 J, thus to 30 % of the initial value. At the test temperature of 290 °C the notch toughness is higher by 30 J to 40 J (approximately 25 %) than at room temperature. The effect of ageing time is similar; it is, however, smaller and the minimum test value of 80 J is 2.3 times greater at 290 °C than at room temperature after the same ageing.

The initial notch toughness is similar for the alloys with 27 % and 11 % ferrite; however, the effect of ageing is enhanced for the 27 % ferrite alloy. The toughness starts to decrease after a similar ageing time as for the 11 % ferrite alloy; however, it decreases faster by increasing the ageing time, since by ageing at 350 °C the level of 35 J (approximately 1/3 of the initial value) is achieved already after 720 h and the toughness of approximately 20 J already after 4 320 h of ageing at 350 °C, and this remains unchanged also after the longest ageing time of 17 520 h. At the lower ageing temperature of 320 °C the decrease in the notch toughness is slower and then the final value of 33 J (32 % of the initial value) is achieved after 8760 h of ageing. During ageing at 290 °C the rate of decrease of the toughness is slower and the minimum value is approximately three times higher than for the 27 % ferrite alloy after the same ageing time at 350 °C.

For the 27 % ferrite alloy the notch toughness is higher when testing at 290 °C by about 25 J, and the minimum value after the longest ageing time at 350 °C is approximately three times greater than when testing at room temperature. The effect of the ageing temperature is similar as at room temperature; however, the differences after the longest annealing are smaller than those at room temperature.

An easier comparison of the effects of the content of ferrite and ageing temperature is possible from the relative values in **Table 8**. The data show that the effects of the content of ferrite and ageing temperature are much greater for the notch toughness than for the tensile properties. The notch toughness at room temperature is lower for all the alloys after the longest ageing at 290 °C; however, the decrease is stronger and virtually equal for the 11 % and 27 % ferrite alloys. A similar extent of notch-toughness lowering is found for the 2 % ferrite alloy after ageing at 320 °C, whereas it is much stronger and again virtually equal for the 11 % and 27 % ferrite alloys. After ageing at 350 °C the notch toughness is slightly diminished for the 2 % ferrite alloy, while it is diminished more for the 11 % ferrite alloy and even more for the 27 % ferrite alloy. In all cases the decrease of the notch toughness is lower when testing at 290 °C than at room temperature.

Table 8: Charpy notch toughness for all the alloys reported for the 2 % ferrite alloy at room temperature and 290 °C; ageing temperature 350 °C

Tabela 8: Razmerje proti zarezni žilavosti zlitine z 2 % ferita pri sobni temperaturi in pri 290 °C; temperatura staranja 350 °C

δ-ferrite (w/%)	2		11		27	
Ageing time	Test temperature					
	22 °C	290 °C	22 °C	290 °C	22 °C	290 °C
Ageing temperature 290 °C						
0 h	1	1	0.76	0.82	0.80	0.80
17 520 h	0.61	0.79	0.39	0.66	0.37	0.62
Ageing temperature 320 °C						
0 h	0.96	1.03	0.75	0.78	0.69	0.73
17 520 h	0.58	0.82	0.22	0.60	0.21	0.50
Ageing temperature 350 °C						
0 h	0.94	0.97	0.70	0.78	0.69	0.73
17 520 h	0.53	0.77	0.21	0.43	0.13	0.38

6 ANALYSIS OF THE EXPERIMENTAL FINDINGS

The effect of ageing temperature and time is explained by the extent of the completion of the spinodal decomposition of the solid solution in the δ-ferrite. For the tensile properties, the change is relatively small and, when detected, it increases continuously with the ageing time and it is greater with a higher ageing temperature. The Charpy notch toughness is decreased slowly in the first period and very fast after the level of the hardness of ferrite was achieved. The ageing time of the initial rapid decrease of the notch toughness is shorter with a higher ageing temperature. The lowest toughness was achieved at an ageing temperature of 350 °C. The hardness of the ferrite increased continuously at all the ageing temperatures and more rapidly at the higher temperature, and it was not finished even after the longest applied ageing at 350 °C, when the initial hardness was increased by 2.2 times. Thus, the increase of the ferrite hardness affects differently the tensile properties and the notch toughness.

It is assumed that the explanation is in the differences of the behaviour of the ferrite inserts by the axial deformation and the localised flexion deformation. With the axial deformation the aged ferrite inserts start to deform plastically at a sufficient level of strain hardening of the austenite, inducing only small changes in the elongation and a reduction of the area for different contents and microhardnesses of the aged ferrite and the different width of the austenite ligaments. For this reason, up to a microhardness of ferrite of *HV* 537 obtained after ageing for 4 320 h at 350 °C, the fracture surface of the tensile specimens is entirely ductile and dimpled, confirming that the ferrite and the austenite matrix are fractured after the cold deformation in the ductile mode.

The explanation of the initial slow decrease of the notch toughness is probably the same, while the phase of the rapid decrease of notch the toughness begins when the aged ferrite starts to fracture with clevage[2]. The difference in the behaviour of the ferrite of the same hardness with the flexion tests of the notched specimens is related to the difference in the mechanism and the rate of deformation and fracture. The deformation and fracturing of the Charpy specimens in the ductile range occurs in approximately 10^{-2} s, while the tensile test time is several orders of magnitude longer. The presence of the notch limits the volume of the plastic deformation and from the moment of the crack propagation from the notch the plastic deformation is limited to a layer of metal with a thickness of less than 50 μm on both sides of the crack lips[11], while the width of the plastic deformation in the phase of the increase of the reduction of the area of tensile specimens is much greater. The rapid plastic deformation with the Charpy test generates adiabatic heating of the deformed metal. For this reason, with the Charpy fracturing the temperature in the layer of the plastic deformation at the crack tip and both sides of the crack is increased, the more this happens the greater is the extent of plastic deformation in structural steels, even by several hundreds of °C[11]. These differences make the comparison of tensile and Charpy toughness values unreliable for the same alloy.

It is assumed that with localised plastic deformation the much stronger effect of ageing on the notch toughness than on the tensile properties may be explained by assuming that the ferrite with the hardness above a determined level started to fracture with cleavage ahead of the tip of the propagating crack. Ferrite inserts with very narrow cracks would also increase the local stress concentration and generate crack initials in austenite ligaments ahead of the tip of the propagating crack.

Most of the energy consumed for the brittle fracturing of structural steels is consumed for the elastic deformation that generates the stress concentration necessary to start the cleavage of ferrite at the notch tip[11]. With ductile fracturing of structural steels, 6 J to 7 J of energy is consumed for the elastic deformation before the plastic deformation is initiated. Generally, for the cleavage fracturing of structural steels below the brittle-fracture threshold, a similar energy is consumed. The content of δ-ferrite in the alloy with the lowest Charpy notch toughness of 20 J was 27 %. Assuming that the energy consumed for the fracturing of ferrite is proportional to its content in the alloy, it can be deduced that at the lowest level of Charpy toughens of 20 J, only approximately $(8 \times 0.27) = 2.1$ J are consumed for the fracture of the aged ferrite. Thus, with a level of 20 J, approximately 10 % of the energy is consumed for fracturing the aged ferrite and 90 % for fracturing the austenite ligaments. The total content and shape of the ferrite inserts could modify significantly the energy deduced for the Charpy cleavage of the ferrite. It can be reliably concluded that in reality the energy consumed for the cleavage of the ferrite could be only lower than the deduced value, while it is reliable to assume that the formation of the initial crack in the austenite ahead the fracture tip would also decrease the energy consumed for the fracture of the austenite.

Generally, it is found for low carbon iron alloys that by increasing the test temperature up to a level depending on the chemical composition and microstructure, the yield stress and the tensile strength are decreased and the elongation and the reduction of the area remain constant or are even slightly increased. Logically, the yield stress and the tensile strength are lower at 290 °C. However, a smaller elongation and a reduction of the area are found independently of the content and the microhardness of ferrite. The conclusion is that the lower tensile properties at 290 °C than at room temperature are very probably due to the lower intensity of the strain hardening by the axial tensile deformation at higher temperatures. The same explanation could also be applied for the greater Charpy notch toughness at 290 °C, since, it was found that the volume of plastic deformation before the crack is started at the notch tip is greater with lower strain hardening, while the energy spent in the crack propagation is virtually identical in both cases[11].

7 CONCLUSIONS

The following conclusions are suggested on the basis of the experimental findings and their explanation:

- the effect of the content of ferrite on the properties of non-aged two-phase Fe-Ni-Cr-Mo alloys is explained by the differences in the chemical composition and the linear grain size;
- the ageing affects the properties more with an advanced process of spinodal decomposition of the δ-ferrite. For this reason, the properties are changed more after equal ageing times at 350 °C than at 290 °C;
- the effect of ageing is relatively small for tensile properties. It is much greater for the Charpy toughness, which is diminished down to approximately 1/5 of the initial value after the longest ageing at the highest applied temperature;
- the tensile properties are lower at 290 °C than at room temperature, independent of the content of ferrite and the ageing. In contrast, the notch toughness is higher at 290 °C than at room temperature for all the ferrite contents and ageing temperatures;
- the difference in the properties at room temperature and 290 °C is explained in terms of the hardness of the ferrite, the strain hardening of the austenite and the difference in the mechanisms of plastic deformation and fracture propagation by the axial tensile test and the Charpy notch flexion test.

The authors are indebted to the Slovenian Research Agency and NPP Krško for their financial support of the project, to Mr. B. Breskvar for the preparation of alloys, Mr. D. Kmetič for the thermal treatments and Mr. B. Arzenšek for the mechanical tests.

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