UDK 669.14.018.8:620.17:519.68
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
MTAEC9, 45(4)369(2011)

PREDICTION OF THE MECHANICAL PROPERTIES OF CAST Cr-Ni-Mo STAINLESS STEELS WITH A TWO-PHASE MICROSTRUCTURE

NAPOVED MEHANSKIH LASTNOSTI LITIH Cr-Ni-Mo NERJAVNIH JEKEL Z DVOFAZNO MIKROSTRUKTURO

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Prejem rokopisa – received: 2011-03-07; sprejem za objavo – accepted for publication: 2011-03-15

The results of mechanical tests on Cr-Ni-Mo stainless steels were analyzed to find a correlation between the Charpy-V impact toughness (*CVN*), the Vickers hardness (HV5) and the tensile strength R_m with the time and temperature of isothermal ageing. These tests were performed on three alloys with different chemical compositions and delta ferrite contents. The alloys were designated as the volume fractions of *A* (2 %), *B* (11 %) and *C* (with 27 % of delta ferrite). All the results were then described with the most suitable function. After that, a computer program for the prediction (calculating) of the mechanical properties (impact toughness C*VN*, Vickers hardness HV5 and tensile strength R_m) was made. The program application was written in the Visual Basic 6 environment. With this program it is possible to predict the change of the *CVN*, HV5 and R_m of Cr-Ni-Mo stainless steels depending on time, aging temperature and the delta ferrite content of the material for aging temperatures from 290 °C to 350 °C (step 10 °C), and delta ferrite content from 2 % to 27 % (step 1 %). To avoid mistakes and to focus on a time period of practical importance, the aging time is limited to 40 years. The principle used here allows us to predict the mechanical properties of other materials with any other chemical composition. However, the confirmation of this requires additional experimental data.

Keywords: Cr-Ni-Mo stainless steels, impact toughness, Vickers hardness, tensile strength, delta ferrite content, empirical method, program application, Visual Basic 6

Na osnovi mehanskih preizkusov na Cr-Ni-Mo nerjavnem jeklu smo izvršili analizo vpliva temperature in časa izotermnega žarjenja na Charpy-V udarno žilavost (*CVN*), trdoto po Vikersu (HV5) in natezno trdnost (R_m). Mehanske preizkuse smo izvršili pri treh zlitinah z različno kemijsko sestavo in vsebnostjo delta ferita. Zlitine smo označili z volumenskimi deleži ***A*** (2 %), ***B*** (11 %) in ***C*** (27 % delta ferita). Vse eksperimentalne rezultate smo opisali z najbolj primerno empirično funkcijo. Potem smo izdelali računalniški program za napoved (izračun) mehanskih lasnosti (*CVN*, HV5 in R_m) v odvisnosti od časa in temperature izotermnega žarjenja (staranja). Programska aplikacija je napisana v okolju Visual Basic 6. S tem programom je mogoče predvideti spremembo *CVN*, HV5 in R_m Cr-Ni-Mo nerjavnega jekla, odvisno od časa, temperature staranja in vsebnosti delta ferita v materijalu, za temperature staranja od 290 °C do 350 °C (korak 10 °C) in vsebnosti delta ferita od 2 % do 27 % (korak 1 %). Da bi se izognili napakam in se osredinili na časovno obdobje, ki ima praktični pomen, je čas omejen za obdobje 40 let. Z uporabo istega načela je tudi mogoče napovedati mehanske lastnosti drugih materialov z drugačno kemično sestavo. Za potrditev tega potrebujemo nove eksperimentalne podatke.

Ključne besede: nerjavna jekla Cr-Ni-Mo, udarna žilavost, trdota po Vikersu, natezna trdnost, vsebnost delta ferita, empirična metoda, programska aplikacija, Visual Basic 6

1 INTRODUCTION

The idea is to make a computer-program application able to simulate the process of aging of Cr-Ni-Mo stainless steels with a two-phase microstructure. These steels are used for the structural elements of older nuclear power plants [1,2,3]. On the basis of the input data (aging time, aging temperature and delta ferrite content of the steel) this program calculates and predicts the impact toughness, hardness and tensile strength of a given steel. It is also able to draw diagrams for the change of each mechanical property with respect to the aging time. This program is based on pure experimental results and methods.

2 EXPERIMENTAL PART

2.1 Experimental data

The results obtained on three different alloys, designated as *A* (with the volume fraction 2 % of δ-ferrite), *B* (11 %) and *C* (27 %) were used [4]. The alloys were aged (isothermally annealed) for up to two years at three different temperatures, 290 °C, 320 °C and 350 °C, for one day, seven days, one month, six months, one year and two years. The impact toughness (**Table 3**), Vickers hardness (**Table 4**) and tensile strength (**Table 5**) were determined on these samples. The tests were also performed before the aging. All the tests were performed at room temperature (20 °C). The average delta ferrite content (**Table 2**) was determined with a FERITSCOPE MP30, Fisher, Germany.

Table 1: Average chemical composition of the selected alloys in volume fractions (ϕ/%)
Tabela 1: Povprečna kemična sestava izbranih zlitin (ϕ/%)

	A	*B*	*C*
C	0.06	0.07	0.06
Si	0.43	0.67	1.68
Mn	1.59	1.04	0.67
P	0.03	0.03	0.03
S	0.01	0.01	0.01
Cr	18.0	21.7	20.8
Ni	11.9	11.0	9.0
Mo	1.84	2.03	2.46

Table 2: Average delta ferrite content (ϕ/%)
Tabela 2: Povprečna vsebnost delta ferita (ϕ/%)

Alloy	*A*	*B*	*C*
Delta ferrite content	2	11	27

Table 3: Average Charpy impact toughness; *CVN*/J
Tabela 3: Povprečna udarna žilavost po Charpyju; *CVN*/J

Alloy	A	B	C
Initial state	130	134	107
Aging time (h)	Aging temperature 290 °C		
24	138	109	127
168	163	87	123
720	119	117	120
4320	101	108	113
8760	149	103	61
17520	121	62	53
Aging time (h)	Aging temperature 320 °C		
24	145	112	106
168	112	80	108
720	106	94	54
4320	176	57	33
8760	113	33	48
17520	105	34	30
Aging time (h)	Aging temperature 350 °C		
24	155	112	103
168	102	69	76
720	155	47	28
4320	145	50	19
8760	100	34	21
17520	99	38	14

Table 4: Average Vickers hardness H_V/HV5
Tabela 4: Povprečna trdota po Vickersu H_V/HV5

Alloy	A	B	C
Initial state	138	174	207
Aging time (h)	Aging temperature 290 °C		
24	135	167	208
168	132	171	213
720	139	170	210
4320	132	166	207
8760	140	164	208
17520	133	174	218
Aging time (h)	Aging temperature 320 °C		
24	134	169	208
168	133	168	212
720	134	172	220
4320	134	173	221
8760	134	175	224
17520	139	183	238
Aging time (h)	Aging temperature 350 °C		
24	133	163	210
168	141	174	214
720	139	182	228
4320	131	181	230
8760	134	181	233
17520	153	187	248

Table 5: Average tensile strength R_m /MPa
Tabela 5: Povprečna natezna trdnost R_m /MPa

Alloy	A	B	C
Initial state	371	556	684
Aging time (h)	Aging temperature 290 °C		
24	472	552	675
168	489	560	714
720	503	550	712
4320	501	561	682
8760	501	561	732
17520	479	560	705
Aging time (h)	Aging temperature 320 °C		
24	481	546	666
168	494	556	717
720	480	570	732
4320	490	568	722
8760	491	580	696
17520	492	604	765
Aging time (h)	Aging temperature 350 °C		
24	488	560	695
168	485	563	713
720	490	571	733
4320	486	594	766
8760	485	608	760
17520	495	610	824

2.2 Modelling of the functions

The methodology of this procedure is explained on the alloy *C* and the impact-toughness results, as an example. All the results were introduced into a diagram and the characteristic points of the impact-toughness functions for all three aging temperatures are generated. For this operation we used a simple program for drawing diagrams called Graph [5]. The distribution of these characteristic points is shown in **Figure 1**. Each point represents the average value of the impact toughness obtained by the Charpy-V test. Then the program generates automatically the most suitable and optimum function (**Figure 2**), which for the impact toughness is:

$$CVN = \frac{a + b \cdot t}{1 + c \cdot t + d \cdot t^2} \quad (1)$$

The most suitable and appropriate selected empirical functions describing the change of hardness and tensile strength with time at a constant temperature are:

$$H_V = a \cdot t^b \quad (2)$$

$$R_m = a \cdot t^b \quad (3)$$

where *CVN* (J) is the impact Charpy-V toughness, *a, b, c, d* are the empirically determined materials coefficients, and *t* (h) is the time

2.3 Creating a database of functions

Only functions for the temperatures 290 °C, 320 °C and 350 °C could be developed from the available experimental data. However, the goal was also to predict the changes of the impact toughness at intermediate temperatures in between the experimental temperatures, i.e., for (300, 310, 330 and 340) °C. It was assumed that the

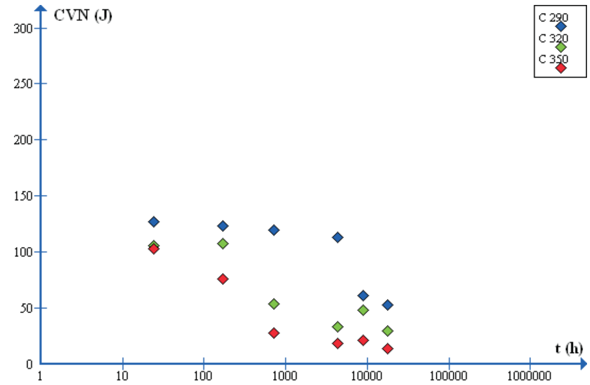


Figure 1: Distribution of the impact-toughness characteristic points of alloy *C*, at 290, 320 and 350°C
Slika 1: Karakteristične točke udarne žilavosti zlitine *C*, pri (290, 320 in 350) °C

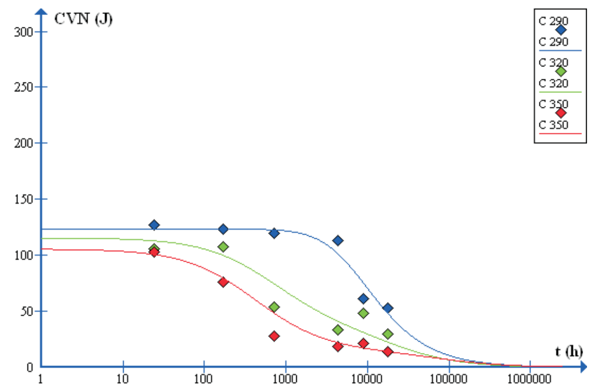


Figure 2: Impact-toughness functions of alloy *C*, at (290, 320 and 350) °C
Slika 2: Funkcije udarne žilavosti zlitine *C*, pri (290, 320 in 350) °C

functions of the temperatures 300 °C and 310 °C lie between the functions for 290 °C and 310 °C, while the functions for 330 °C and 340 °C lie between 320 °C and 350 °C.

For the determination of the characteristic points of the functions for intermediate temperatures some characteristic mathematical relations were used. The relation (4) is determined on the basis of the diagram in **Figure 3**, where all the important points for the temperatures

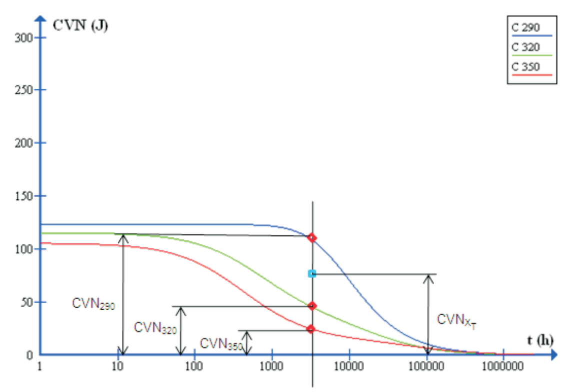


Figure 3: Characteristic values from equation (4)
Slika 3: Značilne vrednosti iz enačbe (4)

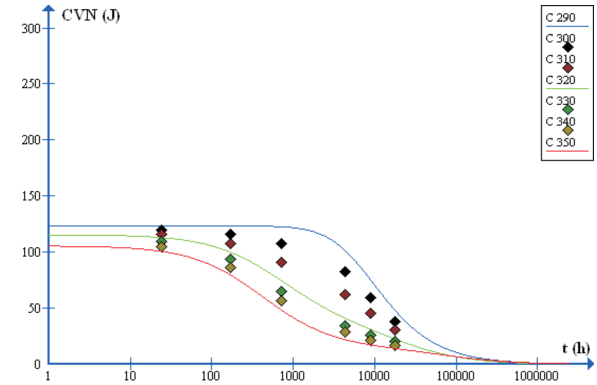


Figure 4: Calculating the points for the (300, 310, 330 and 340) °C functions
Slika 4: Izračun točk za funkcije (300, 310, 330 in 340) °C

between 290 °C and 320°C are marked. The same principle is used for the temperatures between 320 °C and 350°C and the relation (5) was obtained.

$$(CVN_{290}-CVN_{320}):(CVN_{290}-CVN_{x_1})=(320-290):(x_1-290)$$
$$\Rightarrow (CVN_{290}-CVN_{x_1})\cdot(320-290)=(CVN_{290}-CVN_{320})(x_1-290)$$
$$\Rightarrow CVN_{290}-CVN_{x_1}=\frac{(CVN_{290}-CVN_{320})\cdot(x_1-290)}{320-290} \tag{4}$$
$$\Rightarrow CVN_{x_1}=\frac{(CVN_{290}-CVN_{320})\cdot(x_1-290)}{320-290}$$

$$(CVN_{320}-CVN_{350}):(CVN_{320}-CVN_{x_1})=(350-320):(x_1-320)$$
$$\Rightarrow (CVN_{320}-CVN_{x_1})\cdot(350-320)=(CVN_{320}-CVN_{350})(x_1-320)$$
$$\Rightarrow CVN_{320}-CVN_{x_1}=\frac{(CVN_{320}-CVN_{350})\cdot(x_1-320)}{350-320} \tag{5}$$
$$\Rightarrow CVN_{x_1}=\frac{(CVN_{320}-CVN_{350})\cdot(x_1-320)}{350-320}$$

With the help of these two relations (4 and 5) all the characteristic points for all the functions were calculated. During the next step the functions were determined and generated. These functions now describe the way that the impact toughness of alloy *C* changes with time, at ageing temperatures of (290, 300, 310, 320, 330, 340 and 350) °C. The same principle as for the impact toughness was used to determine the functions for the Vickers hardness (2) and the tensile strength (3), for all three alloys *A, B*

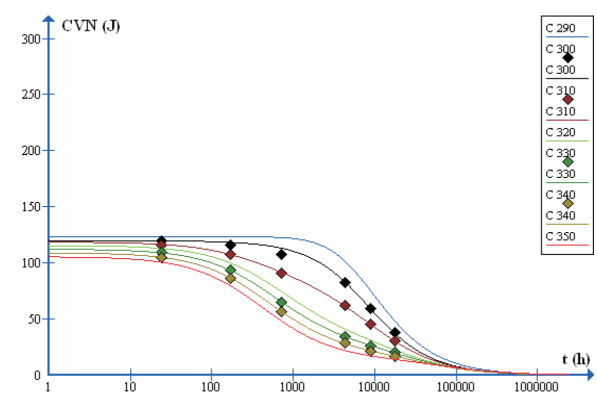


Figure 5: Generating the functions for (300, 310, 330 and 340) °C
Slika 5: Prikaz generiranja funkcij od (300, 310, 330 in 340) °C

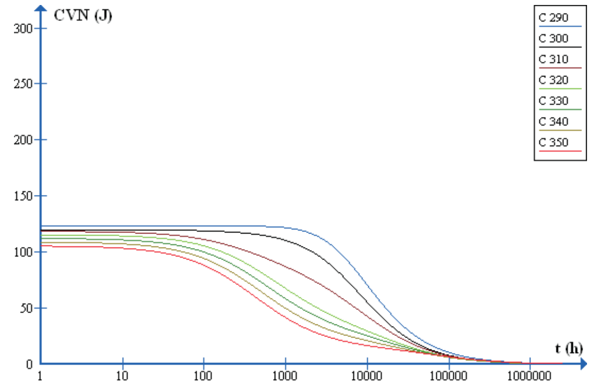


Figure 6: All *C* functions from 290 °C to 350 °C
Slika 6: Vse *C* funkcije od 290 °C do 350 °C

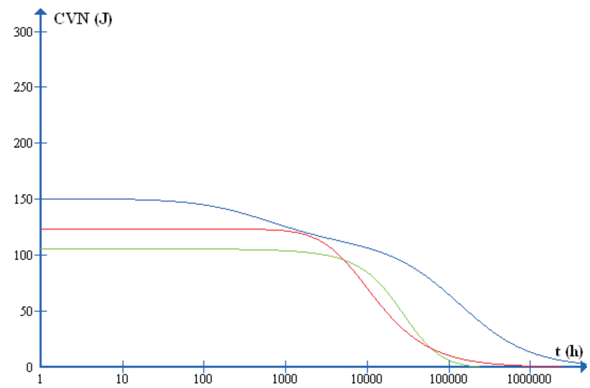


Figure 7: Functions of alloy *A* (blue), *B* (green) and *C* (red) at an aging temperature of 290 °C
Slika 7: Funkcije zlitin *A* (modra), *B* (zelena) in *C* (rdeča) pri temperaturi staranja 290 °C

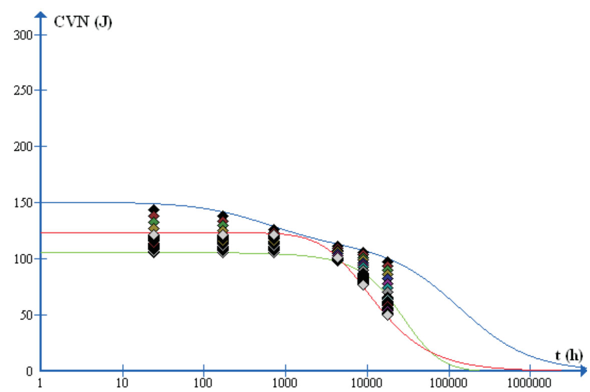


Figure 8: Calculating the points for functions with a delta ferrite content between (2, 11 and 27) %, at an aging temperature of 290°C
Slika 8: Izračun točk za funkcije z vsebnostjo delta ferita med (2, 11 in 27) % pri temperaturi staranja 290 °C

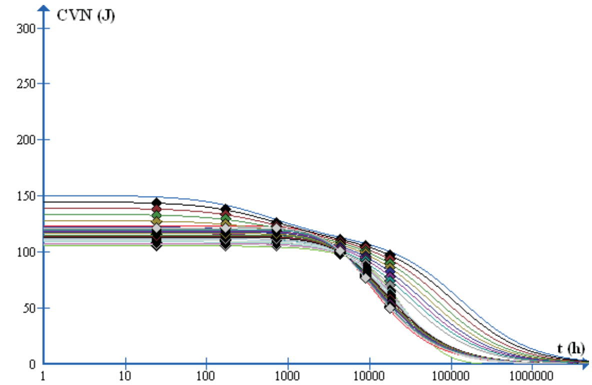


Figure 9: Generating the functions for all delta ferrite contents between (2, 11 and 27) %, at an aging temperature of 290 °C
Slika 9: Generiranje funkcij za vse vsebnosti delta ferita med (2, 11 in 27) %, pri temperaturi 290 °C

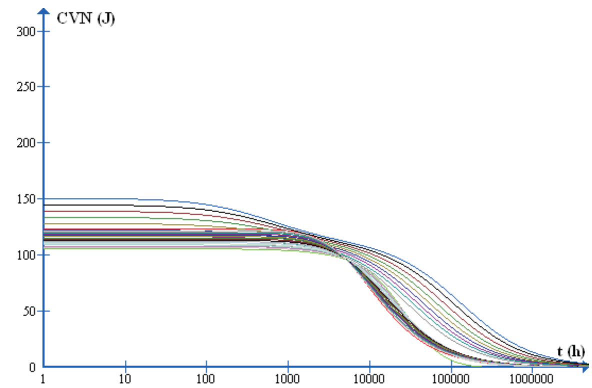


Figure 10: Functions for delta ferrite contents between (2, 11 and 27) %, at an aging temperature of 290 °C
Slika 10: Funkcije za vsebnosti delta ferrita med (2, 11 in 27) %, pri temperature staranja 290 °C

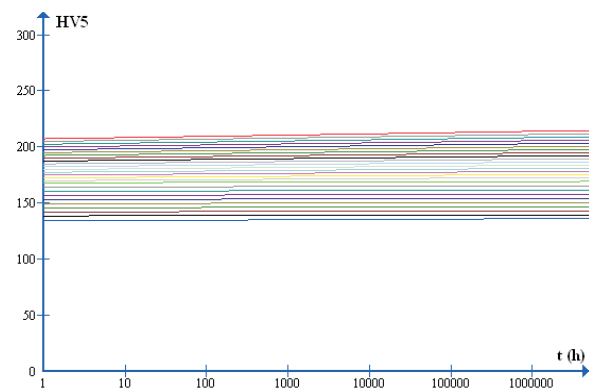


Figure 11: Functions of Vickers hardness for delta ferrite contents between (2, 11 and 27) % and an aging temperature of 290°C
Slika 11: Funkcije Vickersove trdote za vsebnosti delta ferita med (2, 11 in 27) % in temperaturo staranja 290 °C

and *C*. Subsequently, the functions had to be divided according to the temperatures, i.e., divided into 7 groups for the ageing temperatures (290, 300, 310, 320, 330, 340 and 350) °C. The functions of the alloys *A*, *B* and *C* at the ageing temperature of 290 °C are shown in **Figure 7**. At the next step the functions for the alloys which have a delta ferrite content between the three characteristic values of (2, 22 and 27) %, were determined by covering of all the delta ferrite contents between 2 % and 27 % (step 1). This is shown in **Figures 8, 9 and 10**. The same principle is used for calculating the functions for the Vickers hardness and tensile strength changes. These

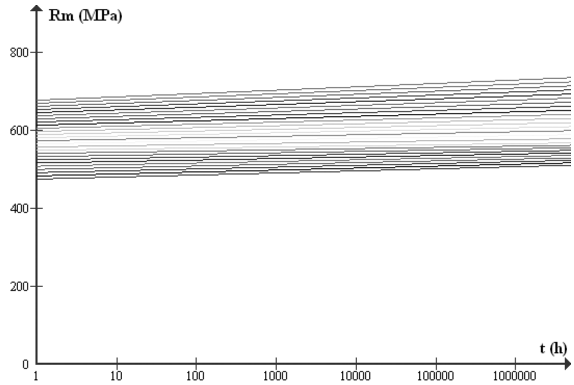
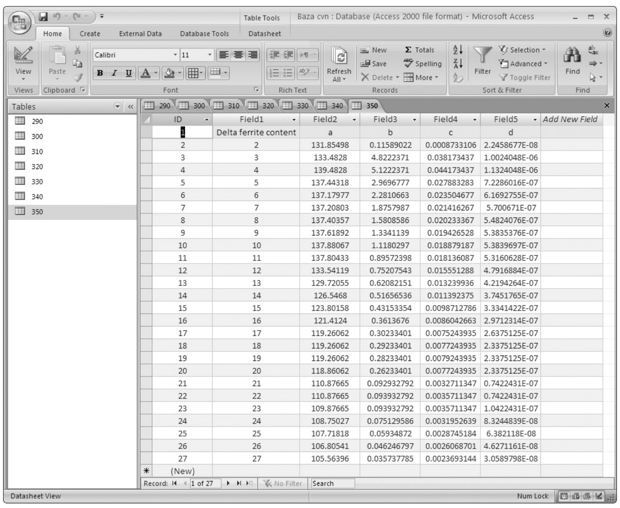


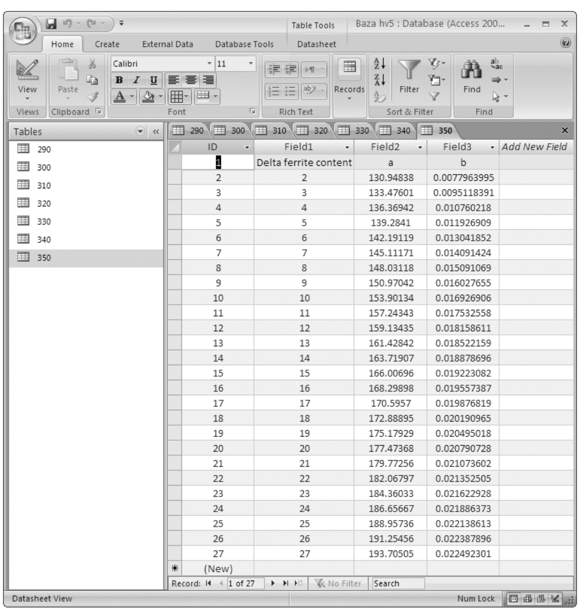
Figure 12: Functions of tensile strength for delta ferrite contents between 2 % and 27 % and an aging temperature of 290°C
Slika 12: Funkcije natezne trdnosti za vsebnosti delta ferita med 2 % in 27 % ter temperaturo staranja



Baza cvn : Database (Access 2000 file format) - Microsoft Access

ID	Field1	Field2	Field3	Field4	Field5
1	Delta ferrite content	a	b	c	d
2	2	131.85498	0.11589022	0.0008733106	2.2458677E-08
3	3	133.4828	4.8222371	0.038173437	1.0024048E-06
4	4	139.4828	5.1222371	0.044173437	1.1324048E-06
5	5	137.44318	2.9696777	0.027883283	7.2286016E-07
6	6	137.17977	2.2810663	0.023504677	6.1692755E-07
7	7	137.20803	1.8757987	0.021416267	5.700671E-07
8	8	137.40357	1.5808586	0.020233367	5.4824076E-07
9	9	137.61892	1.3341139	0.019426528	5.3835376E-07
10	10	137.88067	1.1180297	0.018879187	5.3839697E-07
11	11	137.80433	0.89572398	0.018136087	5.3160628E-07
12	12	133.54119	0.75207543	0.015551288	4.7916884E-07
13	13	129.72055	0.62082151	0.013239936	4.2194264E-07
14	14	126.5468	0.51656536	0.011392375	3.7451765E-07
15	15	123.80158	0.43153354	0.0098712786	3.3341422E-07
16	16	121.4124	0.3613676	0.0086042663	2.9712314E-07
17	17	119.26062	0.30233401	0.0075243935	2.6375125E-07
18	18	119.26062	0.29233401	0.0077243935	2.3375125E-07
19	19	119.26062	0.28233401	0.0079243935	2.3375125E-07
20	20	118.86062	0.26233401	0.0077243935	2.3375125E-07
21	21	110.87665	0.092932792	0.0032711347	0.7422431E-07
22	22	110.87665	0.093932792	0.0035711347	0.7422431E-07
23	23	109.87665	0.093932792	0.0035711347	1.0422431E-07
24	24	108.75027	0.075129586	0.0031952639	8.3244839E-08
25	25	107.71818	0.05934872	0.0028745184	6.382118E-08
26	26	106.80541	0.046246797	0.0026068701	4.6271161E-08
27	27	105.56396	0.035737785	0.0023693144	3.0589798E-08

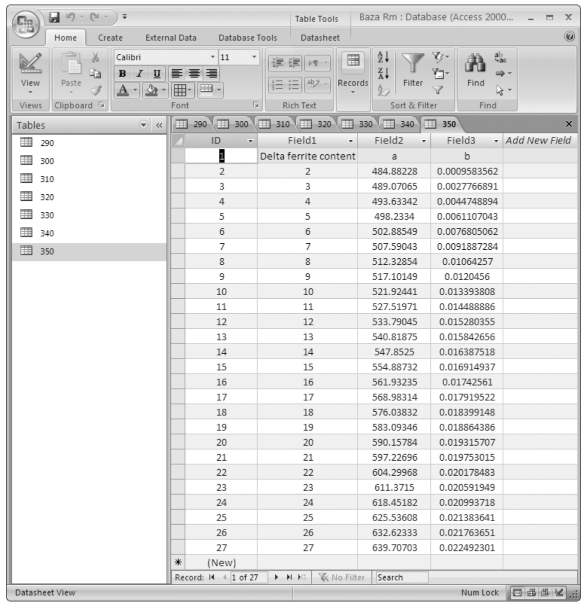
Figure 13: Database of functions of the impact toughness
Slika 13: Baza podatkov funkcij udarne žilavosti



Baza hv5 : Database (Access 200...

ID	Field1	Field2	Field3
1	Delta ferrite content	a	b
2	2	130.94838	0.0077963995
3	3	133.47601	0.0095118391
4	4	136.36942	0.010760218
5	5	139.2841	0.011926909
6	6	142.19119	0.013041852
7	7	145.11171	0.014091424
8	8	148.03118	0.015091069
9	9	150.97042	0.016027655
10	10	153.90134	0.016926906
11	11	157.24343	0.017532558
12	12	159.13435	0.018158611
13	13	161.42842	0.018522159
14	14	163.71907	0.018878696
15	15	166.00696	0.019223082
16	16	168.29898	0.019557387
17	17	170.5957	0.019876819
18	18	172.88895	0.020190965
19	19	175.17929	0.020495018
20	20	177.47368	0.020790728
21	21	179.77256	0.021073602
22	22	182.06797	0.021352505
23	23	184.36033	0.021622928
24	24	186.65667	0.021886373
25	25	188.95736	0.022138613
26	26	191.25456	0.022387896
27	27	193.70505	0.022492301

Figure 14: Database of functions of the Vickers hardness
Slika 14: Baza podatkov funkcij Vickersove trdote



Baza Rm : Database (Access 2000...

ID	Field1	Field2	Field3
1	Delta ferrite content	a	b
2	2	484.88228	0.0009583562
3	3	489.07065	0.0027766891
4	4	493.63342	0.0044748894
5	5	498.2334	0.0061107043
6	6	502.88549	0.0076805062
7	7	507.59043	0.0091887284
8	8	512.32854	0.01064257
9	9	517.10149	0.0120456
10	10	521.92441	0.013393808
11	11	527.51971	0.014488886
12	12	533.79045	0.015280355
13	13	540.81875	0.015842656
14	14	547.8525	0.016387518
15	15	554.88732	0.016914937
16	16	561.93235	0.01742561
17	17	568.98314	0.017919522
18	18	576.03832	0.018399148
19	19	583.09346	0.018864386
20	20	590.15784	0.019315707
21	21	597.22696	0.019753015
22	22	604.29968	0.020178483
23	23	611.3715	0.020591949
24	24	618.45182	0.020993718
25	25	625.53608	0.021383641
26	26	632.62333	0.021763651
27	27	639.70703	0.022492301

Figure 15: Database of functions of the tensile strength
Slika 15: Baza podatkov funkcij natezne trdnosti

functions (the example of the aging temperature of 290 °C) are shown in **Figures 11 and 12**.

2.3.1 Saving the functions in the Microsoft Office Access database

As we can see, the selected functions are determined with different coefficients. The functions for the impact toughness with four, and functions for Vickers hardness and tensile strength with only two, coefficients. For this reason, all the functions are saved into the database simply by saving their coefficients. Examples of functions saved are shown in **Figures 13, 14 and 15**.

2.4 Program application

The program application was written in the Visual Basic 6 environment and was connected, using the

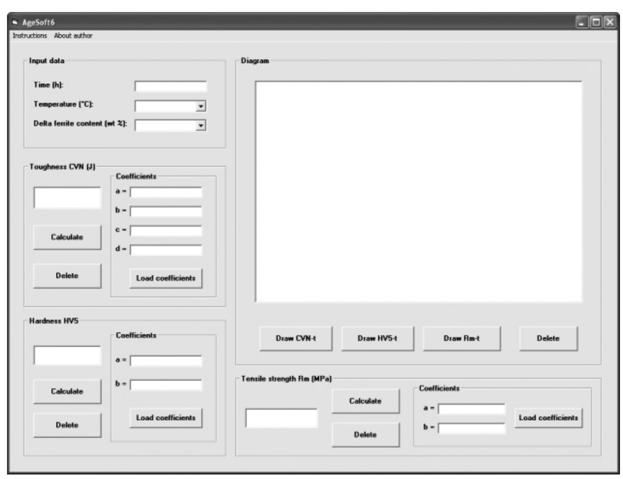


Figure 16: Main window of the "AgeSoft6" program
Slika 16: Glavno okno "AgeSoft6" programa

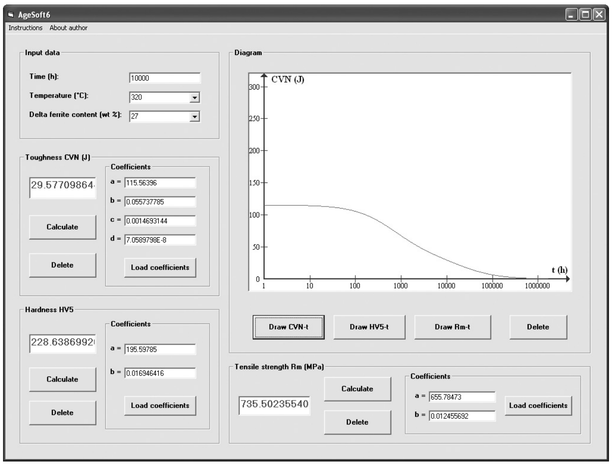


Figure 17: Calculated values
Slika 17: Izračunane vrednosti

program code, with Microsoft Office database of functions. The main window of this program, called "AgeSoft6", is shown in **Figure 16**. The working principle of "AgeSoft6" is very simple. The user first inputs the "input data" and then on the basis of the input data, the software selects the appropriate function from the database. Next, the software includes the function coefficients into the equation, written in program code and calculates the results. Except for the modes for calculating the mechanical properties, there is also a mode for drawing the diagrams that show us how each function of each mechanical property changes over time. One example with calculated values and the *CVN*-t diagram for the alloy with 27 % of delta ferrite, aged at 320 °C for 10 000 h, is shown in **Figure 17**.

3 RESULTS AND DISCUSSION

With this program it is possible to predict the affect of the ageing time, temperature and the content of delta ferrite, for ageing temperatures from 290 °C to 350 °C (step of 10 °C) and delta ferrite contents from 2 % to 27 % (step of 1 %) on the Charpy impact toughness (*CVN*), Vickers hardness (HV5) and tensile strength (R_m) of Cr-Ni-Mo stainless steels. Experimental results were available for an ageing time of 2 years. These results were used for the developing of functions that describe the change of the mechanical properties also for ageing times longer than 2 years. With the help of these functions the program calculates the mechanical properties for up to 40 years (350 400 h) of ageing. However, mistakes in the results can occur, due to possible technical mistakes during the mechanical tests performed. If the calculated value of the *CVN* is lower than 20 J the program gives an alarm with a warning that the *CVN* is below a critical value.

4 CONCLUSIONS

The developed program is purely empirical and is made on the basis of the experimental data obtained for Cr-Ni-Mo stainless steels, so it corresponds in principle only to these kinds of steels with these chemical properties and ageing conditions. To have more value the program must be more universal. Therefore, in the next stage of the development of this program, experimental data for cast Cr-Ni duplex stainless steels will be used. The creation of a universal computer program that describes the ageing behaviour of any type of steel is probably too optimistic and at the moment this task is too difficult.

5 REFERENCES

[1] Jelena V. Tuma, Borivoj Šuštaršič, Franc Vodopivec: The effect of ageing temperature and time on the mechanical properties of Fe-NiCrMo alloys with different contents of delta ferrite, *Nucl. Eng. Des.*, 238 (**2008**) 7, 1511–1517

[2] Jelena V. Tuma, Borivoj Šuštaršič, Roman Celin, Franc Vodopivec: The mechanical properties of two-phase Fe-NiCrMo alloys at room temperature and 290 °C after ageing in the temperature range 290–350 °C, Mater. Tehnol. 43 (**2009**) 4, 179–187

[3] Roman Celin, Jelena V. Tuma, Boris Arzenšek: Effects of ageing a two-phase Fe-NiCrMo alloy on the strain hardening at room temperature and at 290 °C, Mater. Tehnol. 43 (**2009**) 5, 251–255

[4] B. Šuštaršič, J. V. Tuma, D. Kmetič, R. Celin, B. Arzenšek, B. Breskvar, F. Vodopivec, M. Godec, T. Drglin, J. Janovec, I. Naglič, R. Šturm, L. Kosec, B. Kosec, P. Škraba, N. Grubeljak, P. McGuiness, B. Saje, Z. Račič, S. Šumlaj: Research of structural brittleness of two-phase stainless steels, Final report on the results of research project, Institute of metals and technology, University of Ljubljana, NTF-Department for materials and metallurgy, Ljubljana, 2004.

[5] Graph – is an open source application used to draw mathematical graphs in a coordinate system. The program makes it very easy to visualize a function and paste it into another program. It is also possible to do some mathematical calculations on the functions. Copyright © 2009 by Ivan Johansen