CREATION OF SHOCK-ABRASION RESISTANCE BUILD-UP METAL USING PHYSICO-CHEMICAL MODEL OF HIGH TEMPERATURE PROCESSES

K. Borodianskiy¹, V. Mazurovsky¹, M. Zinigrad¹, A. Gedanken²

¹College of Judea and Samaria, Faculty of Natural Science, Ariel, Israel

²Bar-Ilan University, Department of Chemistry, Ramat-Gan, Israel

ABSTRACT. Build-up metal for shock-abrasion resistance was in the focus of the work, where the mathematical model of physico-chemical high temperature processes developed by the authors in their previous works was used. A computer program based on the model permitted forecasting of the required chemical composition and structure of the build-up metal.

Flux-cored wires were fabricated from a cold-rolled ribbon (1008 steel) and filled with a powder mixture. Low carbon steel (A 516) was used as the base metal.

The specimens were prepared by 3-layered build-up. The prepared specimens were tested using: Light Microscopy, Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Analysis (EDS), Hardness Measurements and Shock-Abrasion Resistance Measuring Device.

The results of the mentioned tests confirmed the correct calculation of the model and good shock-abrasion resistance of the suggested build-up metal.

Introduction.

Fusion welding is a very complicated process. This is multiphase system with a non uniform temperature field and complex mass and heat transfer processes which are occurring on the metal–slag and metal–gas boundaries and determine the chemical composition of the weld metal and as the result determine its structure and mechanical properties.

The mechanical properties of the weld deposit are determined not only by the chemical composition of the metal, the nature of the crystallization of the weld has also a great influence on its properties.

More than 50 years, Schaeffler diagram is an important tool to predict Cr-Ni austenite, austenite-ferrite or austenite-martensite weld with carbon content of up to 0.12%. Chemical composition of alloying elements is a main regulator for receiving required microstructure according to Schaeffler diagram. However, it does not allow determining the composition and volume of carbide phases. Furthermore, if carbon content in weld is over 0.12% as it is presented in this work, the forecast agreement with actual data is markedly reduced due to an intense consumption of carbon and carbide-forming elements by the process of carbide formation. Firstly, it could be attributed to the fact that the carbide formation process in weld is not taken into consideration (as mentioned above), and secondly, it is caused by using constant empiric coefficients in the equations determining Cr and Ni equivalents.

Schaeffler diagram was modified and presented in our previous works [1-2], to provide a more accurate prediction of weld structure as follows:

- taking into consideration of the carbide formation process;

- implementation of variable coefficients in Cr and Ni equivalents equations (the coefficients should depend on the concentration and mutual influence of alloying components, and on the carbide formation process in the weld);

- incorporating of phase percentage lines for interphase areas (i.e., the areas which contain two or more phases, as performed by Schaeffler diagram for austenite-ferrite area).

Using this modified Schaeffler diagram and the model explained in [1-8] we presented the work which task was creation shock-abrasion resistance build-up metal.

THEORETICAL PRINCIPLES

The task of this work is developing of a new flux-cored wire for forming of build-up layer with shock-abrasion resistance properties. The inverse problem of flux-cored wire computation has been solved (using mentioned model) which can provide us with the required chemical composition of build up metal and as the result it can give us the required mechanical properties, in our case shock-abrasion resistance properties. These required properties are achieved by austenite-martensite matrix structure with 10 wt. % of carbides uniformly distributed in it.

Austenite face centered cubic structure allows holding a high proportion of carbon in its solution. In our case austenite is used for shock resistance thanks to its energy absorbance ability. Martensite is body centered tetragonal where the carbon atoms constitute a supersaturated solid solution and as a result it has the hardest and strongest microstructure. Therefore martensite will be good for abrasion resistance according to its mechanical properties. The stable carbide phase brings the better toughness and abrasion resistance and also ensures uniform distribution of the hardness properties.

The design tool was an expert system based on a systematic approach to the design object, mathematical modeling of a technological welding process [1, 4-7] and computer simulation of the microstructure formation of the weld metal. The mathematical model permits prediction of the composition of the weld metal as a function of the compositions of the starting materials and the technological parameters of the welding process. Prediction of the microstructure of the weld metal is based on computer simulation of a modified Schaeffler diagram and the process of carbide formation in steels [1-3].

The next step in the work was preparing of the required wire for build-up process.

A cold-rolled ribbon (1008 steel) was filled with a powder mixture calculated using the mentioned model. The main alloying elements, in final “pr.12” wire, were: graphite (carbon), ferrotitanium, chromium and nickel powders. From Hume-Rothery rules and from [9] it is known that the crystal structures of the solute and the solvent must be the same, in our case the mentioned alloying elements should be dissolved in FCC structure (austenite phase structure). It is also known that the size difference between solute and solvent must be $< \sim 15\%$.

Table 1 Atomic radii of the metals and its lattice structures [9].

Element	Lattice Structure	Atomic Radii (Å)
γ - Fe	FCC	1.27
Cr	FCC	1.28
Ti	BCC	1.45
Ni	FCC	1.24

Austenite and carbide are the only phases crystallize during primary crystallization process. As we see from Table 1, chromium and nickel dissolves well in the austenite formed matrix. However, titanium, because of its high difference in atomic radii as compared to γ -iron and because of its different lattice structure, poorly dissolves in austenite. Group IV metals (titanium) tend to form in a single phase mono-carbides with a limiting stoichiometry near $MC_{1.0}$. This carbide can be described as a close packed titanium lattice with the carbon atom in the center of the octahedral interstices . If these octahedral sites are not all occupied, the unoccupied sites may be considered as vacancies and their stoichiometry will be TiC_x , where $0.5 \leq x \leq 1$.

Some amount of chromium also forms carbides but its structure is very complicated. It can be some possibilities of chromium carbide formation. More possible form in alloying steels, where chromium concentration is more than 5 wt.% is $Cr_{23}C_6$. This carbide has a complicated FCC lattice which cell consists from 92 chromium atoms and 24 carbon atoms [9].

By the end of the secondary crystallization, the stable carbide phases will be stay and residual amount of the alloying metals will be dissolved in the metal matrix.

Our assumption that during impact loading some amount of metastable austenite which formats in the metal matrix, will absorb part of the impact energy and transforms into martensite and carbide phases, that will improve shock-abrasion resistance of the build up metal [2].

These alloying elements were supposed to increase the strength and toughness of the build up metal and this assumption was examined and the obtained results described below.

RESULTS OF COMPUTATION

The required properties for shock-abrasion resistance were the input in our computer program. The output is presented in table 2 where we can see the needed alloying elements and their wt. % of the flux and wt. % of the final wire.

Table 2 presents chemical composition of the base metal (A 516), wire band (cold-rolled ribbon, 1008 steel) and alloying elements the band was filled with.

Table 2 Flux cored wire “Pr.12” for shock-abrasion resistance (computer output).

Flux - cored electrode (FCE) formula Pr.12:												
Core composition												
Component	Density	Quantity in 100kg of the FCE, kg							Relation in the dray mixture			
	g/cm3								of the flux, %			
FeCrC	3.480					11.170					41.860	
Ferro-Titanium	3.150					8.130					30.490	
Ni powder	2.960					4.470					16.740	
CaF ₂	1.390					2.910					10.920	
Composition of the base materials and the build-up layers, wt%												
	C	Si	Mn	Cr	W	V	Mo	Ti	Al	Nb	Fe	Ni
A 516	0.280	0.300	1.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	98.350	0.001
Electrode bend	0.080	0.030	0.500	0.120	0.015	0.010	0.100	0.010	0.010	0.005	98.820	0.250
Required weld	1.000	0.600	0.800	5.500	0.000	0.000	0.000	2.000	0.030	0.000	86.568	3.500
Layer 1	0.960	0.481	0.543	5.304	0.008	0.049	0.099	2.004	0.415	0.003	86.324	3.483
Layer 2	1.141	0.529	0.421	6.713	0.011	0.062	0.125	2.536	0.525	0.004	83.129	4.408
Layer 3	1.189	0.542	0.389	7.088	0.011	0.065	0.132	2.680	0.554	0.004	82.279	4.654

EXPERIMENT

Flux cored wire with diameter 1.7 mm was prepared on a drawbench.

Next step in this work was manufacturing of the samples by build-up process which was preformed by welding machine Kemppi FU 30, PS 3500. The samples were prepared by 3 layers build-up metal. The technological parameters of the build-up process were:

- Current: 250A.
- Voltage: 35V.
- Feed speed: 180 m/h.
- Travel speed: 30 m/h.
- Polarity: Reverse.

The samples were tested on home made shock-abrasion resistance measuring device (Fig. 1).

Fig. 1: Shock-abrasion resistance measuring device.

- 1- Striker traffic direction
- 2- Spring
- 3- Driven pulley
- 4- Sand vessel
- 5- Drive movement of the striker
- 6- Sand jet
- 7- Striker
- 8- Build-up metal
- 9- Base metal
- 10- Frame
- 11- Belt
- 12- Electric motor
- 13- Drive pulley

The samples were subjects of the mechanic impact loading with the simultaneous continuous sea sand strew (85 gr/min) of pre-tested sand passed through 60 Mesh sieve.

RESULTS AND DISCUSSION

A 12.5 mm thickness sheet of low carbon steel, A 516, consisting of 73% ferrite and 27% pearlite phase microstructure, was used as the base metal. Its microstructure is presented in Fig.2.

Fig. 2 Microscope A 516 base metal sheet microstructure.

As we explained in theoretical principles, we need to receive mixed austenite-martensite phase matrix microstructure with uniformly distribution of the carbide phase. The prediction of the required microstructure of build up metal “Pr.12” presented on the Table 3.

Table 3 “Pr.12” predicted phase microstructure.

Type of structure	% of the structure
Austenite	41.39
Martensite	51.65
Carbide	6.97

It is very complicated to determine real phase microstructure, but we will present the received results and will discuss them.

On the 1-st layer (the layer which contacts base metal) microstructure (Fig. 3) we can determine martensite phase formatted. On the grain boundaries we can also determine carbide phase microstructure.

Fig. 3 Microscope 1-st layer "Pr.12" build-up metal microstructure.

The surface (3-rd layer build-up metal), as we see from Fig. 4, consists from martensite and austenite mixed phase microstructure and carbide stable phase.

Fig. 4 Microscope surface "Pr.12" build-up metal microstructure.

The same surface build-up metal microstructure made by Scanning Electron Microscope (SEM) presents on Fig. 5. Much higher magnification, using SEM on the same specimen, permit us to show the same phases microstructure presented on light microscopy on Fig. 4.

Fig. 5 Scanning Electron Microscope image of surface build-up metal microstructure.

Chemical analysis of the matrix was made with Energy Dispersive X-ray Analysis (EDS) and the received results are shown in table 4 and compared with the calculated, using the described model, results.

Table 4 Chemical composition of the weld by EDS analysis and model calculations.

Element	% El. SEM	% El. Calculated
C	0.97	1.189
Si	0.49	0.542
Mn	0.40	0.389
Cr	7.26	7.088
Fe	84.01	82.279
Ni	3.77	4.654
Ti	3.10	2.680

Fig. 6 EDS spectrum.

A little differences as seen in table 4, caused as the result of technique limitation. The detected chemical elements must be rounded to 100% and this limitation doesn't take into account some chemical inclusions that usually found in steels.

As we see from the presented results, the calculated and the real chemical composition results are closed, that emphasize the right calculations using the mentioned model.

Hardness tests were made by Rockwell Hardness Tester. The hardness of 3-rd layer of build up metal was 56 HRC what is better result than 90 HRB, the hardness of the base metal A 516 and emphasize the good shock-abrasion resistance.

The results after shock-abrasion tests are presented in Fig. 7. Tested samples were weighted every 5 minutes and the results of tested specimens presented as the plot of the weight loss per shocked area as a function of time:

$$\frac{\Delta m}{A} = f(t), \quad (4)$$

Fig. 7 Shock-abrasion test results as a function of time.

Fig. 7 shows the difference between base metal and build up-metal for shock-abrasion resistance. It is seen from the plot that the build-up metal improve the required resistance. We calculated and found that efficiency increases by 29%, which is in a good agreement with the declared aim of the current work.

Conclusions

1. A prediction of chemical composition, microstructure and shock-abrasion properties of build-up metal made by computer program based on the mathematical model of physico-chemical high temperature processes, were presented.
2. A flux-cored wire improving the required resistance was produced in accordance with calculated starting materials composition using the mentioned model of technological process.
3. Build-up samples have been prepared using this wire.
4. Full-scale tests including light and electron microscopy, EDS, hardness and micro hardness tests and shock-abrasion resistance, have been performed.
5. The presented results are confirming the adequacy of the computer calculation using the mentioned model.
6. The shock-abrasion resistance build up metal is only one of the problems which can be solved using the presented computer model.

Acknowledgement

The authors acknowledge Mrs. Nataly Litvak for her help in understanding light and scanning electron microscopy images.

REFERENCES:

- 1 Mazurovsky V., Zinigrad M., Leontev L., Lisin V.: 'Physicochemical Analysis and Phenomenological Model of Secondary Crystallization of a Metal in the Course of Welding'. *Glass physics and chemistry* 2004 31 (6) 73.
- 2 Mazurovsky V., Zinigrad M., Leontev L., Lisin L.: 'The main Principles of Development of Modern Surfacing Materials'. *Metal technology journal*, 2004, 7, 34.
- 3 Zinigrad M., Zalomov N., Mazurovsky V., Aksyutin O.: 'Computer Approach to the Development of Welding Materials'. Computer Technology in Welding, Copenhagen, TWI, 1998.
- 4 Mazurovsky B., Zinigrad M., Zinigrad A.: 'Mathematical Model of Weld Microstructure Formation'. Computer Technology in Welding and Manufacturing, Sydney, TWI, 2002.
- 5 Mazurovsky V., Zinigrad M., Leontev L., Lisin V.: 'The Phenomenological Model of Non- Equilibrium Crystallization and Strengthening Phase Formation Processes in the Weld'. Israeli- Russian Bi- National Workshop, Ariel, 2003.
- 6 Zinigrad M., Mazurovsky V., Borodianskiy K.: 'Computer Simulation of the Primary Crystallization Processes of a Metal during Welding'. International conference on Welding and Joining 2005 & Frontiers of Materials Joining, Tel-Aviv, 2005.
- 7 Mazurovsky V., Zinigrad M., Borodianskiy K.: 'Welding Materials Design'. *News of Tula University* 2005 3 225.
- 8 Zinigrad M., Mazurovsky V., Borodianskiy K.: 'Physico-Chemical and Mathematical Modeling of Phase Interaction taking place during Fusion Welding Processes'. *Material Science and Engineering Technology* 2005 36 (10) 489.
- 9 Goldstein M., Grachev S., Veksler Yu.: Special Steels. Moscow, Metallurgy, 1985.
- 10 Babu S., David S., Quintana M.: 'Modeling Microstructure Evolution in Self-Shielded Flux-Cored Arc Welds'. *Welding journal* 2001 80 (4) 98-s.
- 11 Kotecki D.: 'Forecasting Weld Microstructure'. *Advanced materials and processes* 2000 157 (6) 74.
- 12 Novion C. and Landesman J.: 'Order and Disorder in Transition Metal Carbides and Nitrides'. *Pure & Appl. Chem* 1985 Vol. 57 (10) 1391.
- 13 Grong O.: Metallurgical Modeling of Welding, 2-nd ed. London, The Institute of Materials Publishing, 1997.
- 14 Wayman M.: The Metals Black Book. Edmonton, CASTI Publishing, 1997.
- 15 Guliaev A.: Physical Metallurgy. Moscow, Metallurgy, 1977.
- 16 Oyama S.: The Chemistry of Transition Metal Carbides and Nitrides. London, Blackie Academic and Professional, 1996.
- 17 Hugosson H.: 'Theoretical Studies of Phase Stabilities and Electronic Structure in Molybdenum Carbide'. Licentiate Thesis in Physics, Uppsala, 1999.
- 18 Grossman J., Mizel A., Cote M.: 'Transition Metals and their Carbides and Nitrides: Trends in Electronic and Structural Properties'. *Physical review B*, 1999 60 (9) 6343.
- 19 Davis J.: Alloying, Understanding the Basics. Ohio, ASM International, 2003.