DISQUISITION ON MATERIAL PARAMETERS AND THEIR INFLUENCE ON WEAR RATES AT HIGH TEMPERATURES

H. WINKELMANN[A1)], M. VARGA[A)], E. BADISCH[A)]
[a)] AC²T research GmbH, Viktor Kaplan-Straße 2, 2700 Wiener Neustadt, Austria
[1)] Corresponding author. E-mail address: winkelmann@ac2t.at (H. Winkelmann)

ABSTRACT

The aim of this work is to find correlations of hard phase content and matrix type with hot hardness and wear rates in the cyclic impact abrasion test at high testing temperatures. Several materials with different matrix types and varying hard phase content have been investigated regarding their wear behaviour as well as their hot hardness up to 800°C. The hot hardness and hard phase content then was correlated to the wear rates using statistical methods. Materials with comparable matrix properties and higher hard phase content always have higher hot hardness and these parameters are statistically dependent so correlation of wear rate with hot hardness is statistically sufficient. It was found, that within the same material the wear rate is correlated to the hot hardness as long as there is no significant change in the wear mechanism. When the matrix of the material changes the hot hardness can not be directly correlated to the wear rate any more. It was also found that among all materials tested those with an austenitic matrix generally have higher wear resistance even if they have the same hot hardness.

Keywords*:* high temperature, wear, hot hardness, tribology

INTRODUCTION

During previous investigations [1-7] a good understanding for wear mechanisms at high temperatures could be developed. So a special material which should perform well under impact-abrasion condition at high temperature was developed and set into comparison to previously investigated materials. Four materials with different matrix types and varying hard phase content have been investigated regarding their wear behaviour as well as their hot hardness up to 800°C. The hot hardness and hard phase content then was correlated to the wear rates using statistical methods.

EXPERIMENTAL

Materials tested

In these studies an austenitic stainless steel (material A), a high speed tool steel (HSS, material B), a complex Fe-Cr-C-Nb-Mo-W-B alloy with fine microstructure (material C) and the new material, a Ni-based PTA (plasma transfer arc) welded alloy reinforced with WC particles (material D), were investigated. The materials investigated and their chemical compositions are given in Table 1, for material D just the matrix compo-Sition is given in the table and 60 mass. % WC are added during the welding process. The microstructures of the alloys are shown in Figure 1. Materials A and D have been chosen

in order to compare the influence of hard phase content in a matrix which is temperature resistant. By comparing materials B and C the influence of size and structure of the hard phases in a matrix which changes with temperature was investigated. Due to the better abrasion resistance caused by the hard phases, it was expected [8-10] that materials C and D generally behave "better", meaning lower wear rates, in the HT-CIAT.

Characterisation of the microstructure has been done by optical microscopy (OM), after etching with 5 vol.% solution of nitric acid in ethanol, and scanning electron microscopy (SEM + EDS). Quantitative analysis of the microstructure was carried out by the use of Imtronic Image C software. Hardness measurements at room temperature (RT) were done with Vickers hardness HV10, since hot hardness is easier to be investigated at higher loads. To determine the hardness of each phase in the microstructure, e.g. hard particles and metallic matrix, microhardness testing HV0.1 was used. Quantitative wear characterisation has been done by gravimetric mass loss of the specimens during wear testing. Qualitative characterisation of worn surfaces has been carried out by evaluating of macroscopic and cross-section images, as described above, and by SEM investigations.

Table 1. Chemical composition and hardness of the alloys investigated

		A	**B**	**C**	**D**
		Austenite 1.4841	Tool Steel 1.3343	complex Fe-Cr-C-Nb-Mo-W-B alloy fine microstructure	Ni Base PTA alloy; (Matrix composition) coarse microstructure
		No heat treatment	Heat treated at 1160°C	MAG - welding	PTA - welding
		Low hard phase content		High hard phase content	
		0 wt. %	15 wt. %	54 wt. %	60 wt. %
Chemical composition [wt. %]	Base	Fe	Fe	Fe	Ni
	C	0.08	0.9	1.3	0.2
	Cr	24.8	4.1	15.4	
	Ni/Fe	19.8	-	-	3
	Si	1.7	0.25	0.5	3.5
	Mn	1.2	0.3	0.2	
	Nb	-	-	4.2	
	B	-	-	4.2	2.3
	others (Mo, V, W)	-	13.2	11.5	-
RT-Hardness [HV10]		150	850	900	780

For the samples of alloy A (Fig. 1a) the hardness was determined as 150 HV10. There was no heat treatment done for material A.

For the sample charge of Alloy B the hardness is measured as 850 HV10. Alloy B was heat treated at 1160°C and followed with two times annealing at 570°C.

Alloy C, deposited onto mild steel plates using standard GMAW welding process, shows a macro-hardness of 900 HV10.

Alloy D was deposited onto mild steel plates using PTA welding procedure at AC²T. It consists of 60 mass. % tungsten carbide and 40 mass. % Ni-based matrix. Tungsten carbide powder and Ni-based powder were mixed before welding and fed to the welding nozzle. The tungsten carbide particle size used was 63-180 µm. The compound hardness of the welded deposit at RT is 780 HV10, while the hardness of the carbides is 2000-2500 HV0.1.

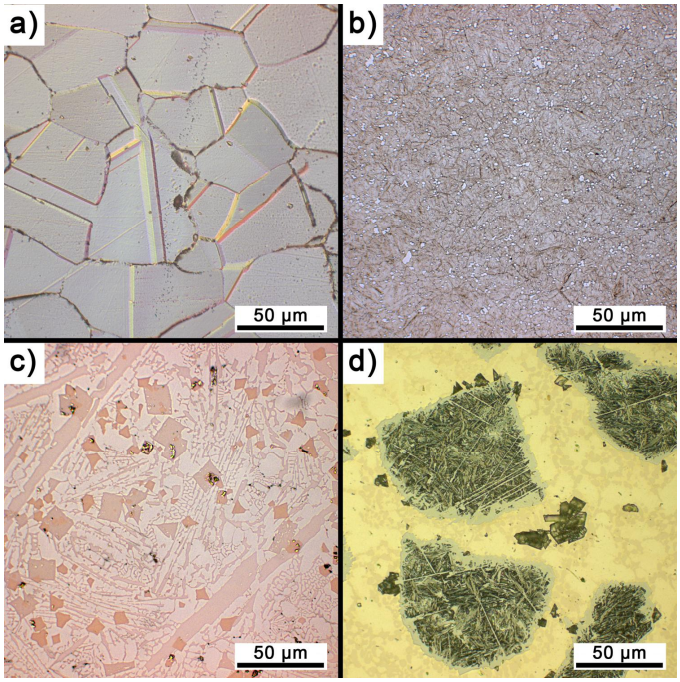

Figure 1. Microstructure of alloys investigated:
(a) A: austenite, (b) B: M2 tool steel,
(c) C: complex Fe-Cr-C-Nb-Mo-W-B and
(d) D: Ni-Base PTA welded alloy.

The microstructure is given in Fig. 1d, where it can be seen that the carbide matrix interface is approximately 5 µm, so the carbides are well bonded to the matrix. The chemical composition of the matrix is given in Table. 1.

Hot hardness measurements

The changes in the materials which occurred through the thermal aging during annealing are permanent and irreversible, but also temporary (reversible) material softening occurs when the temperature increases. Therefore the hardness of the material during its use in high temperature application is usually lower than its hardness at room temperature. For a good understanding of wear mechanisms at high temperatures, knowing the actual hardness of a material at the testing temperature thus is crucial.

The hot hardness of the materials investigated was measured in a high temperature Vickers hardness test rig (Figure 2) specially developed by the Austrian Center of Competence for Tribology (AC²T). In the test rig, vacuum conditions make it possible to measure the hardness up to a temperature of 800°C. The materials have been tested with a load of 98 N (HV10). At least 5 indents have been performed at each testing temperature for statistical reason. The hardness measurement was done at RT by means of OM. Of course there is some experimental error since the indents are made at temperature but measured at room temperature, i.e. after thermal contraction, which results in slightly too high hardness values, but the error is a maximum of 2% and thus can be regarded as negligible.

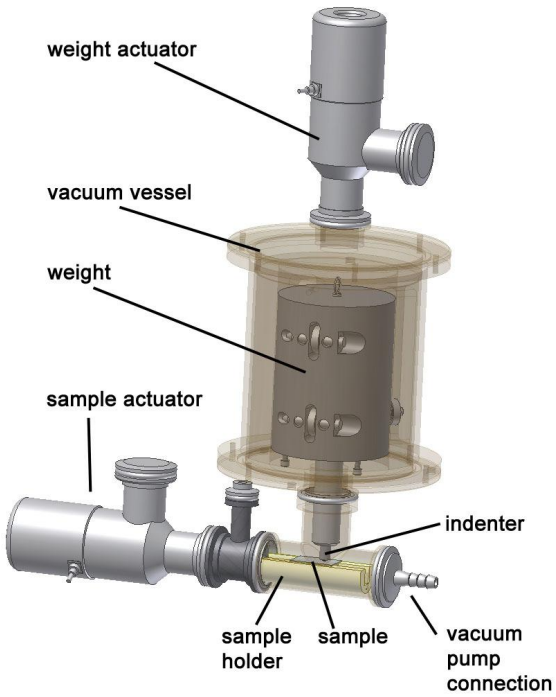

Figure 2. Hot hardness measurement system developed by AC²T.

The measured hot hardness of the different materials was then correlated to the wear rates and the wear mechanisms that have been found in the High Temperature Cyclic Impact Abrasion Test (HT-CIAT) and helped to develop a wear model.

High Temperature Cyclic Impact Abrasion Test (HT-CIAT)

The HT-CIAT was developed at AC²T to determine the behaviour of materials in cyclic impact abrasive environment at elevated temperatures (Figure 3a). The test principle is simply based on potential energy which is cyclically turned into kinetic energy by free fall. The samples are fixed at 45° to vertical and are intermittently hit by the plunger at a given frequency, while a constant flow of abrasive is running between the sample and the plunger, as shown in Figure 3b.

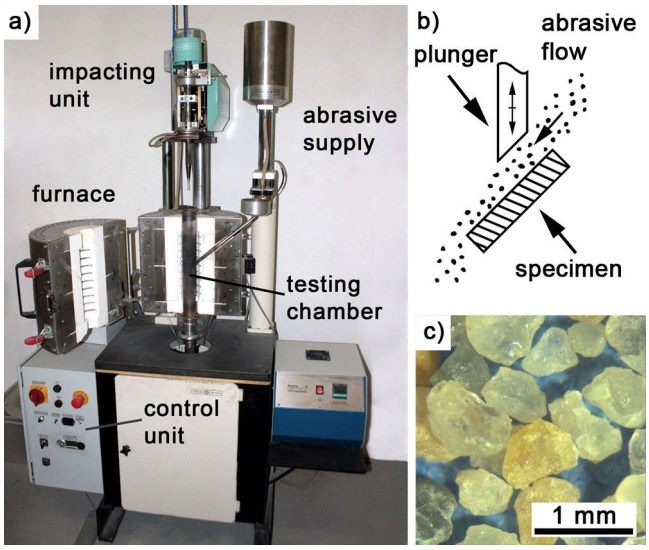

Figure 3. (a)View of the High Temperature Cyclic Impact Abrasion Tester (HT-CIAT), (b) testing principle (45° impact angle with abrasives tested) and (c) abrasive.

The abrasive material used for 3-body-contact was silica sand with a particle size of 0.4-0.9 mm at angular shape and a flow rate of 3 g/sec. The sample dimensions were chosen as plates 25 × 35 × 8 mm thickness and the tested surface was ground with a 120 µm grinding disc, where a Ra value of approximately 0,04 µm was reached. For the plunger the material EnDOtec DO*70 (48 HRC, Table 2) at a diameter of 8 mm was used. Before the test the surface of the plunger was grinded to the same surface roughness the sample.

Table 2. Chemical composition of the plunger material (wt. %).

C	*Si*	*Mn*	*S*	*Cr*	*Ni*	*W*	*Fe*	*Co*
1.7	1	0.5	0.01	29	0.1	8	2.5	bal.

The testing parameters of the test series are summarised in Table 3. Impact energy of the plunger, angle of impact and frequency were chosen as 0.8 J, 45° and 1.9 Hz. The total number of testing cycles was fixed to 7,050 which correlate to a testing duration of approximately 1 hour. Experiments were

carried out from RT up to 750°C (Tab. 3). After the test the samples were air cooled to RT within ~60 min.

Table 3. Testing parameters used in HT-CIAT.

Parameter	*Value*
Impact energy	0.8 J
Impact angle	45°
Frequency	1.9 Hz
Testing cycles	7,050
Abrasive material	Silica sand
Abrasive flow	3 g/s
Abrasive size, shape	0.4-0.9 mm, angular
Abrasive hardness	1000-1200 HV
Atmosphere	Ambient
Test temperatures	RT, 500°C, 600°C, 650°C, 700°C, 750°C

Characterisation of the wear behaviour was done by measuring the weight loss of the samples, by means of OM, stereo microscopy (SM) and SEM. The topography of the worn samples has been evaluated with a confocal microscope (Figure 4).

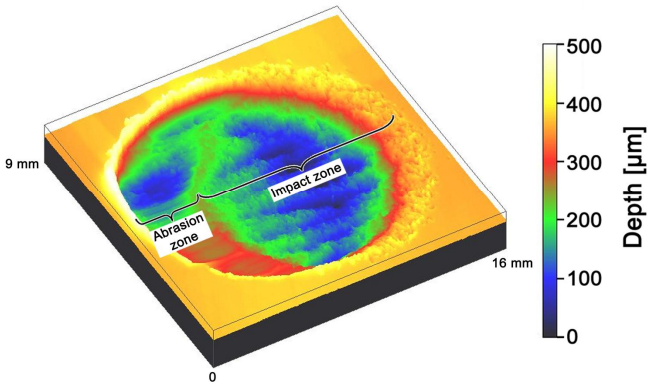

Figure 4. Surface topography obtained in the confocal microscope and used for volumetric wear calculation.

By comparing the area of a worn sample with an original sample the volumetric loss of the worn area can be calculated. Through this method the volumetric wear can be measured directly, which is sometimes advisable. Due to oxidation effects at higher temperatures, the samples or the sample substrate can gain weight, and so the wear cannot be measured in terms of mass loss directly after high testing temperatures. So when there are no austenite (or other oxidation-resistant) substrates/ materials available (or possible due to sample preparation) two solutions are feasible. One solution is to parallel run oxidation dummies and subtract the oxidation weight gain of the dummy from the tested sample, and calculate the volume loss via the density of the sample afterwards. But in this case often the already mentioned approach via measuring the volume loss directly in the confocal microscope is advisable.

Statistical analysis

Hot hardness and HT-CIAT wear rates were investigated using the multiple regression analysis. The functional form used for statistical modelling was linear in unknown coefficients, so that the model could be used in the form:

$$y = \beta_0 + \sum_i^n \beta_i x_i + \varepsilon \qquad (1)$$

Where y is the response variable (HT-CIAT wear rate), x_i are the normalised independent variables, β_i express unknown model coefficients, n stands for the number of the independent variables and ε is a random deviation or residual.

The influence of hard phase content was statistically evaluated with variance analysis. Statistical calculations were done with Statgraphics statistical package (Statpoint, Inc, USA). In the described way all relevant material parameters for wear loss in abrasive environment could be defined.

RESULTS

Hot hardness data

The hot harndess results can be found in Figure 5.

For material A it can be seen that the relatively low hardness slowly decreases with temperature. The loss of hardness is stronger from RT to 300°C than from 300°C to 700°C. It can bee seen that from RT to 800°C the hardness drops by half from 175 to 80 HV10. After the hot hardness test the room temperature hardness is the same as before test for this material.

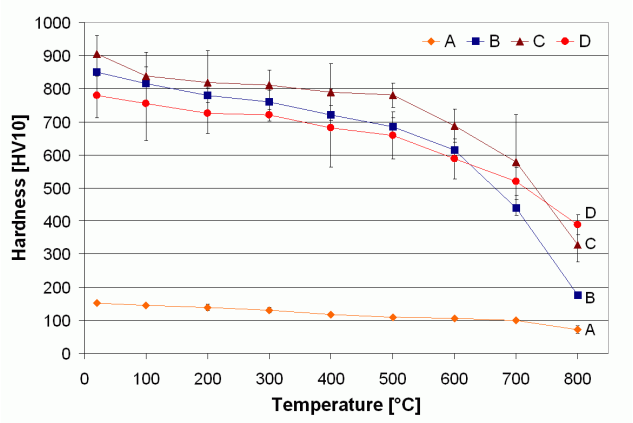

Figure 5. Hot hardness HV10 determined at temperatures from RT up to 800°C.

The hardness of material B slightly decreases from RT to 500°C and remains at about 770 HV10 at this temperature. From this point the hardness rapidly decreases with increasing temperature and drops significantly below 200 HV10 at 800°C. The latter behaviour is an indication for overaging of the secondary carbides. For material B the room temperature hardness after the hot hardness test is slightly reduced depending on the time of the test (which is not always the same, since the heating time to reach a specific sample temperature strongly depends on the size of the sample, vacuum conditions, etc.) to about 500 HV10. The irreversible hardness loss after a long time at 750°C was investigated in detail in [2]. The hardness drops irreversible to 290 HV (-69%).

Material C has a RT hardness of 900 HV10 which drops to about 840 HV10 quickly (100°C), but still has a high hardness of 780 HV10 up to 500°C, due to its fine microstructure. This fine structure is lost at temperatures > 500°C, so the hardness drops significantly from this point. At 700°C the remaining hardness is 570 HV10 from where it further drops down to 330 HV10 at 800°C. After the hot hardness test the room temperature hardness for this material drops to 670 HV10, which would further be reduced to 570 HV5 permanently (-44%) after longer time at 750°C [2].

Material D shows a constantly decreasing hardness with temperature. At RT the hardness is 750 HV10. At the highest testing temperature of 800°C the hot hardness of approximately 400 HV10 exceeds that of all other materials investigated. The matrix of material D is Ni-based, so the matrix structure remains the same also at high temperatures as 800°C. For material D the room temperature hardness after the test is the same as before the test.

HT-CIAT results

The materials investigated show very different wear behaviour in the HT-CIAT, depending on the hard phase content and the matrix condition, which may change with temperature. In Figure 6 the wear rates at different testing temperatures can be found for all the tested materials. It can be seen that wear rates are very different and also that the wear generally becomes more pronounced at higher temperature. Still it can be seen that some materials show a significant increase of the wear rate at specific temperatures. In post-test analyses of the worn samples, which were done in cross section and SEM, the changes of the wear mechanism at these critical temperatures have been revealed.

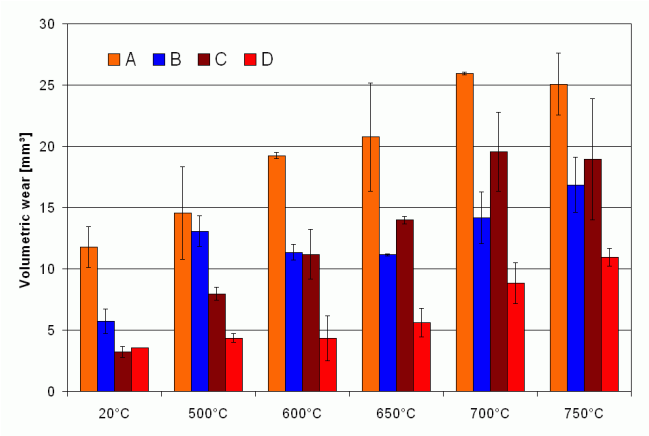

Figure 6. CIAT wear rates of the tested alloys at different testing temperatures.

The hardness of material A constantly drops, while the wear rate constantly increases. There are no hard phases present in this material, so the wear resistance is directly correlated to the hardness of the surface of the material. The surface of this material can form a mechanically mixed layer [3, 7], what also has influence on the wear rate.

For material B the hardness drops significantly beyond 600°C, what is an irreversible effect which becomes even more pronounced at 750°C, also the wear starts increasing beyond this temperature. Since this irreversible loss of hardness needs some time to "change the matrix properties" the wear rate (loss/time) at 750°C is expected to be higher at longer test duration.

For material C the hardness is always higher than for material B due to the high amount of hard phases. But also the matrix of material C changes irreversible and the hardness drops significantly beyond 600°C, what leads to increased wear. For material C another effect is found: Once the matrix properties changed, and the matrix got too soft to back up the hard phases or the matrix looses its ability to bind the carbides the wear is increased significantly.

For material D the hardness slowly drops with temperature also at temperatures beyond 600°C. For this material the wear rate is well correlated to the hot hardness since the wear mechanism remains the same at all temperatures investigated.

Correlation of hot hardness and hard phase content with wear rate at high temperatures

After correlating the HT-CIAT wear rates with the hot hardness, the results were statistically evaluated and a clear result could be found. Materials with an austenitic matrix show higher wear resistance at a specific temperature even if the hot hardness at this same temperature would be equal or even lower (Figure 7).

One reason could be the better matrix-carbide bonding of an austenitic matrix, but this thesis needs further investigations. Besides austenitic matrices generally have better corrosion resistance what also favours these materials in high temperature applications where oxidation might be a strong demand [6].

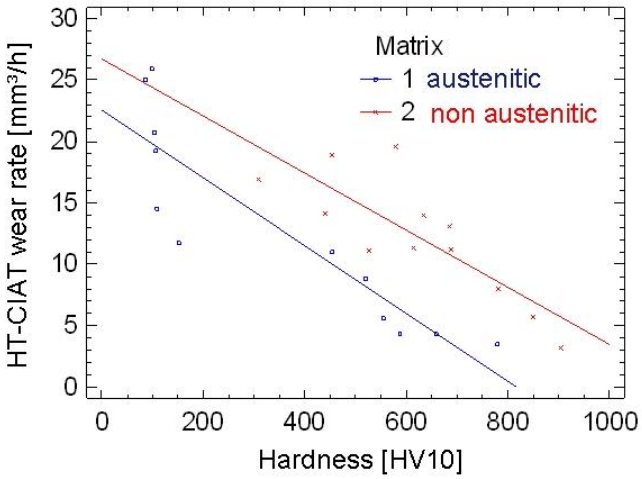

Figure 7. HT-CIAT wear rates correlated to hot hardness

Also the influence of the hard phase content on the wear rate was statistically correlated. In Figure 8 it can be clearly seen, that an increase of the hard phase content shows an improvement of the wear rate.

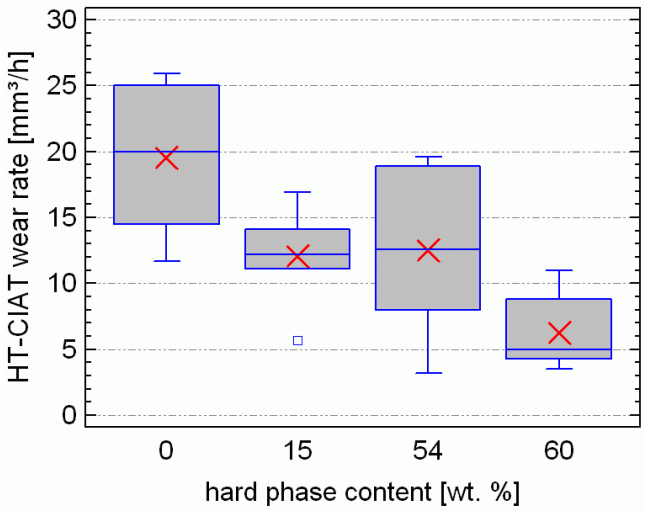

Figure 8. Box and whisker plot of HT-CIAT wear rates correlated to hard phase content.

In [1] a wear model for impact abrasion at high temperatures was presented and this model can be extended to Figure 9. For high application temperatures good matrix stability is necessary. On one hand it is important, that the hot hardness of the matrix remains on a high level and on the other hand results indicate that also the matrix-carbide bonding is important. For good impact resistance good ductility and a fine crystalline microstructure are of advantage [8]. In abrasive environments [10-12], a high hardness and a certain amount of hard phases are of advantage.

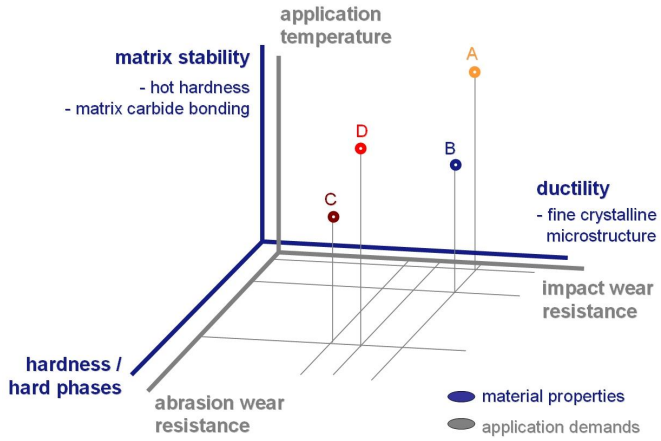

Figure 9. Model: material properties - material demands.

CONCLUSION

1) Matrix carbide bonding might be better for austenitic materials at high temperatures, but this thesis needs further investigations.

2) It could be shown that the wear rate is correlated to the hot hardness as long as the wear mechanism does not change.

3) Changes of microstructure or hard phase content influence the present wear mechanism. The change of wear mechanism has bigger influence on the wear rate than the hot hardness.

4) Results indicate that austenites generally have better wear resistance at high temperatures even if the hot hardness is equal or even lower at a specific temperature.

5) Statistical evaluation of the results indicates that a higher hard phase content shows an improvement of wear resistance in the HT-CIAT.

6) A wear model was presented, which could be extended to a comprehensive understanding of impact abrasion at elevated temperatures.

ACKNOWLEDGEMENTS

This work was funded from the "Austrian Kplus-Program" (governmental funding program for pre-competitive research) via the Austrian Research Promotion Agency (FFG) and the TecNet Capital GmbH (Province of Niederösterreich) and has been carried out within the "Austrian Center of Competence for Tribology" (AC²T research GmbH). The authors are also grateful to Böhler Edelstahl, Castolin Eutectic and voestalpine Stahl GmbH for active research cooperation.

REFERENCES

[1] Winkelmann, H., Badisch, E., Kirchgassner, M., Danninger, H.: Wear mechanisms at high temperatures – Part 1: Wear mechanisms of different Fe-based alloys at elevated temperatures. Tribology Letters 34, 155-166 (2009)

[2] Winkelmann, H., Varga, M., Badisch, E., Danninger, H.: Wear mechanisms at high temperatures – Part 2: temperature effect on wear mechanisms in the erosion test. Tribology Letters 34, 155-166 (2009)

[3] Winkelmann H., Badisch E., Varga M., Danninger H.: Wear Mechanisms at High Temperatures – Part 3: Changes of the Wear Mechanism in the Continuous Impact Abrasion Test with Increasing Testing Temperature. Tribol Lett, in press, DOI 10.1007/s11249-009-9534-3

[4] Roy M., Ray K.K., Sundararajan G.: Erosion-oxidation interaction in Ni and Ni-20Cr alloy. Metal and Mater Trans 32A, 1431-1451 (2001)

[5] Katsich C.: Werkstoffverhalten bei erhöhten Temperaturen unter abrasiver Beanspruchung. Master Thesis, University of Leoben (2010)

[6] Straffelini G., Trabucco D., Molinari A.: Oxidative wear of heat-treated steels. Wear 250, 485-491 (2001)

[7] Roy M., elevated temperature erosive wear of metallic materials, J. Phys. D: Appl. Phys. 39, 101-124 (2006)

[8] Kirchgaßner, M., Badisch, E., Franek, F.: Behaviour of iron-based hardfacing alloys under abrasion and impact. Wear 265, 772–779 (2008)

[9] Badisch E., Kirchgaßner M., Polak R., Franek F.: The comparison of wear properties of different Fe-based hardfacing alloys in four kinds of testing methods. Tribotest 14, 225-233 (2008)

[10] Badisch E., Mitterer C.: Abrasive wear of high speed steels: Influence of abrasive particles and primary carbides on wear resistance. Tribology International 36, 765-770 (2003)

[11] Francucci G., Sikora J., Dommarco R.: Abrasion resistance of ductile iron austempered by the two step process, J. Mater Sci Eng A 485, 46-54 (2008)

[12] Buchely M.F., Gutierrez J.C., Leon L.M., Toro A.: The effect of microstructure on abrasive wear of hardfacing alloys; Wear 259, 52-61 (2005)