



ADVANCED METHODS FOR CHARACTERISATION OF ABRASION/EROSION RESISTANCE OF WEAR PROTECTION MATERIALS

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Abstract: In many field of industry, abrasion and erosion processes are dominant wear mechanisms that reduce lifetime of costly machine parts. Wear resistance against abrasion and/or impact or the ability to withstand other complex mechanical actions are often required. In order to quantify the specific properties of material that are applied in such fields, several test methods are in use. A certain discrepancy can be seen between the systems approach and the aim to get information about suitability of materials for practical applications simply from specific material tests. This paper gives an overview over a selection of relevant test equipment and procedures. In addition, some examples are given for advanced studies on materials behaviour combining tribological test, material analyses respectively materialography, and mathematical methods in order to support – for selected cases – the acquired correlation of materials properties and wear resistance under severe conditions.

Keywords: hardfacing materials, abrasive wear, impact, test methods, morphology, wear modelling.

1. INTRODUCTION

Abrasive wear [1] is a widely dominant wear mechanism especially in a lot of industrial applications [2, 3]. According to a “classic” definition by SAE [4] abrasive wear concerns the removal of material from a surface by mechanical action of abrasive (hard) particles in contact with the surface. Arbitrary classifications of abrasive wear are based on observed conditions [4]:

Gouging Abrasion: The result of this type of abrasive wear is the removal of large particles from a metal surface. Worn surfaces show heavy gouges.

High Stress Grinding Abrasion: This type of abrasive wear occurs during the progressive fragmentation or grinding of the abrasive which was initially of small size and takes place on the surfaces employed to grind the abrasive. The wear is believed to be caused by concentrated compressive stress at the point of abrasive contact and to result from plastic flowing and fatiguing of ductile constituents and cracking of hard

constituents of the metal surface. The use of the words “high stress” in this classification is intended to imply that the crushing strength of the abrasive is exceeded.

Low Stress Scratching Abrasion or Erosion: The result of this type of abrasive wear is scratching of the metal surface, and the scratches are usually minute. The stress imposed on the abrasive particle does not exceed the crushing strength of the abrasive.

Abrasive counterparts or particles are grooving the functional surfaces of machine components or parts, like tools, guidances, and raceways, under various tribological interactions. Numerous basic operations to process raw materials, among them crushing, classifying or conveying, are typical for mining, steel and many other industries, and unavoidably related to abrasion and different damaging effects due to abrasive particles, like erosion, peening-like processes and also impacting. Core components of converting plants such as crushers are exposed to heavy wear and require

efficient surface protection measures in order to avoid costly downtimes and to reduce costs for expensive spare parts [5]. Both wear resistance against abrasion and/or impact or the ability to withstand other complex mechanical actions are often required to maintain the material's structure and shape of machine components and to extend the lifetime of machinery equipment efficiently [6].

2. CONDITIONS FOR SPECIFIC TEST PROCEDURES

Different wear mechanisms and the resulting wear amount show a major influence on both the affected materials and the abrasive matter, e.g. depending on the kinematic and kinetic properties of abrasive particles, which is not surprising from a tribological point of view.

Though the systems' approach should govern the considerations of wear behaviour a prevailing attitude can be observed in order to characterise the applicability of materials for certain conditions simply from material oriented tests. This is especially true for the design and selection of hardfacing materials like iron-based alloys that are to protect machinery equipment. The selection of the most effective wear protection solution, especially in case of combined wear, is either related to longterm practical experiences, in situ tests or to applying alloys according to their hardness or the content of specific hard phases such as tungsten carbide. Simplified tests are feasible in terms of economic restrictions and the need for statistically relevant results in a reasonable time frame. Thus a number of test methods have been introduced, more or less helpful for qualifying application oriented material properties with regard to tribological behaviour.

Yet it is unavoidable to study into detail the material behaviour and the material structure being aware of the specific stresses and wearing conditions that obviously vary according to the concerned application each.

In spite of expectations that might arise from practical engineering it is not seriously possible to characterize the tribological performance of materials simply from a single test. In order to evaluate the wear resistance under different fields of operational demands it is necessary to make use of several test methods that not only provide abrasion but also other types of tribological stresses. This means that also the combination of stress variants have to be considered, which can be e.g. combination of abrasion and impacts, or additional stressing through high temperature. Another special condition could be due to corrosive

effects which may occur through different media (liquids, gases).

Of course, it have to be considered different levels of tribological stresses that vary – in the scope of this paper – from “mild abrasive wear” to heavy wearing conditions due to large abrasives and/or high local stresses due to specific contact forces or impacting

3. TEST METHODS FOR ABRASION/ EROSION AND COMBINED STRESSES

3.1 Rotary Platform Double-Head Abrader

This type of setup is primarily used for tests under mild abrasion conditions and commonly known as the TABER ® Rotary Platform Abraser [7]. This “abrader” was already developed in the 1930's in order to provide accelerated wear testing as it has been used for research and development, quality and process control, and generally for material evaluation. Several test procedures have been introduced into industrial, national, and international standards, e.g. [8 – 10]. The Taber Abraser generates a combination of rolling and rubbing to cause wear to the tested material or surface, respectively, being in contact with bonded abrasive particles (**Figure 1**).

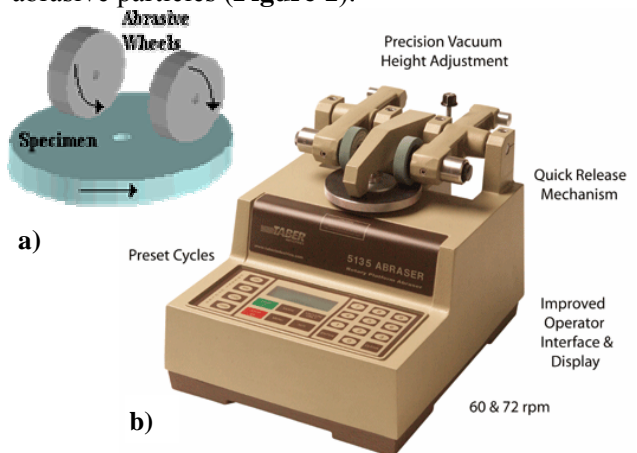


Figure 1. Rotary Platform Abraser – a) test principle; b) test setup (acc. Taber ® Industries [7])

Abrasives are applied in wearing rollers (abrading wheels) of different composition (hard particles and binder). Test specimens disks are spun on a turntable and are abraded by a pair of abrading wheels for a specified number of cycles under a specified load. The test method specifies that the change in haze of the test specimen be determined as a measure of abrasion resistance. It is more common, however, to see abrasion resistance reported as the change in mass of the test specimen or change in mass per number of cycles. Mass change is due to material loss from abrasion.

Thus wear is normally quantified as cumulative mass loss of the plate mating against the wheels, or as a “Taber Wear Index” (mass loss relating to 1000 cycles) typically after a test run of several 1000 cycles, with a typical test load (wheel load) of 10.2 N (corresponding to a mass of 1000 g).

Such type of abrasion tester is a versatile tool with many regular test options as to type of wheel compositions. But it offers also the opportunity to create specific combinations of test samples, e.g. to invert the function of the samples, this means to place the abrasives into the rotating base plate which then produces wear of the counteracting wheels. Depending on the abradant type and test specimen, the surface of the abrasive component may change (becomes clogged) due to the transfer of material from the test specimen to the abrading wheel, and thus must be cleaned at frequent intervals or replaced. The test conditions are comparatively mild due to the given level of load. This may be the reason that this type of test – in spite of its awareness level – is mainly used for testing of coatings and different types of surface finishing.

3.2 Spherical abrasion test method

The spherical abrasion test method has been introduced as Calowear® respectively Calotest (R) Tester by CSM Instruments SA [11] as an instrument for a simple identification of coating thickness but also to investigate the abrasive wear behaviours of coated and uncoated materials.

The determination of the wear coefficient is carried out by the wear crater technique. Thereby a steel ball rolls over a sample (in a special setup / CSM rig, **Figure 2a** and **2b**, or even on real parts, **Figure 2c**) with defined parameters, like rotation speed and normal load, covered with an aqueous suspension of abrasive material (silicon carbide or aluminium oxide powder). This ball generates a spherical crater which will be sized with an optical objective. These measured diameters correspond to the abrasive wear coefficient.

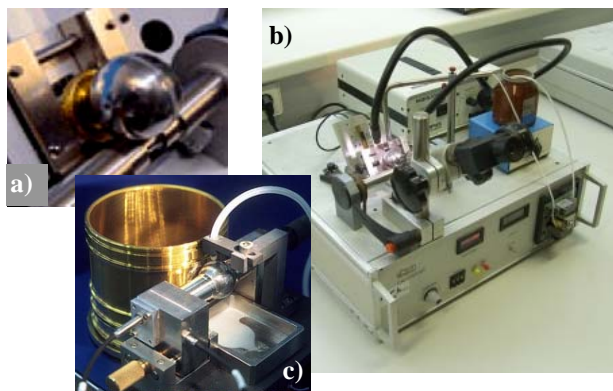


Figure 2. Spherical abrasion test method – a), b) CSM [11]; c) source: www.pvd-coatings.co.uk

3.3 Continuous Abrasion Test (CAT) – Dry-sand wheel test

Abrasion tests with 3-body-abrasion condition under comparatively low stress can be carried out according to ASTM G65 [12] on a dry-sand rubber-wheel tester (see **Figure 3**). Different option or variants are used. Procedure A is a relatively severe test which will rank metallic materials on a wide volume loss scale from low to extreme abrasion resistance (**Table 1**). It is particularly useful in ranking materials of medium to extreme abrasion resistance. Procedure B is a short-term variation of Procedure A for less resistant materials whereas Procedure C is a short-term variation of Procedure A to be used for thin coatings.

Rotation speed and normal load are kept constant (for Procedure A at 200 min⁻¹ and 130 N respectively) over a sliding distance of 4309 m. Ottawa silica sand at grain size of 212 – 300 µm is used as abrasive. Abrasion test results are reported as volume loss in cubic millimetres (!) for the particular test procedure specified.

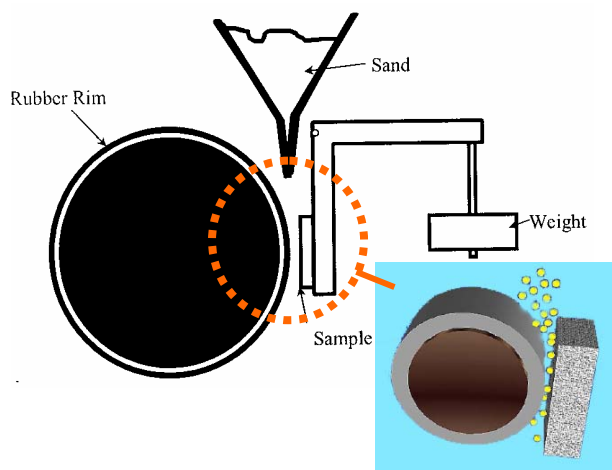


Figure 3. Dry-sand wheel tester according ASTM G65

Table 1. Testing parameters used in HT-ET

Parameter	Value
Normal load	45 – 200 N
Disc diameter	229 mm (9 inches)
Rotating speed	200 min ⁻¹
Relative velocity	2.4 m/s
Abrasive	Silica sand (Ottawa type); 212 – 300 µm
Feed rate of abrasive	300 – 600 g/min
Size of samples	25 mm × 75 mm
Test duration	40 min

Modifications of the G65 tests consider additional features, e.g. to run the test specimen (especially cemented carbides) in a wet slurry condition with a 6.65 inch steel wheel according ASTM B-611 [13]. Similarly, tests with the slurry modification and special 7-inch rubber wheels can

be performed as described in ASTM G-105 [14]. Such methods are especially used to determine the resistance to abrasive wear of ferrous materials for applications involving slurry abrasive media (e.g. tilling soils and earth moving,) but can also be seen as “Recommended Practice for Determining Resistance to Abrasive Wear of ferrous metals using Rubber Wheel Abrasion Machine”, recommended by the Society of Automotive Engineers [15].

3.4 High-temperature erosion test (HT-ET) – 2-body erosion

Solid particle erosion tests can be performed in a centrifugal four-channel accelerator [16] where up to 20 specimens can be treated simultaneously under identical testing conditions (**Figure 4**). Examples of testing parameters are given in **Table 2**.

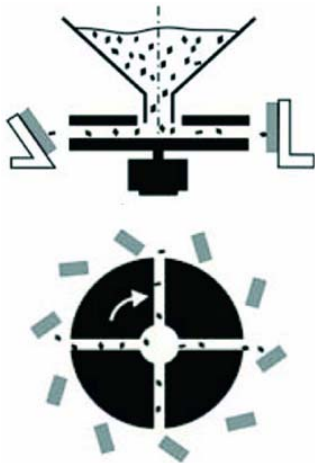


Figure 4. High temperature erosion test (HT-ET)

Table 2. Testing parameters used in HT-ET

Parameter	Value
Impact velocity	80 m/s
Impact angles	30°, 90°
Erodent	Silica sand; 0.1 – 0.3 mm
Total weight of erodent	6 kg
Test temperatures	RT, 300, 500, 650 °C

The erosion rate is determined as a volume loss of the target sample per mass of abrasive particles hitting the target (mm³/kg). An accuracy of 0.1 mg is obtained for the target mass loss measurements. Each wear test is to be repeated three times.

For specific requirements investigation of steady state erosion rate was made as a function of the impact angle at the abrasive particle velocity of 80 m/s [17]. The abrasive particles used in this work were angular silica particles at a typical grain size of 0.1 – 0.3 mm. Erosion tests may be conducted at impact angles of 30° and 90°, respectively.

To study erosion at elevated temperature, the centrifugal apparatus was put into the heated test chamber where tests at enhanced temperatures were carried out at 300, 500 and 650 °C.

3.5 High-temperature continuous impact abrasion test (HT-CIAT) – 3-body impact abrasion

The HT-CIAT was developed at AC²T to determine the behaviour of materials in continuous impact abrasive environment at elevated temperatures [17, 18]. Test principle is based on potential energy which is cyclic turned into kinetic energy by free fall. The samples are fixed in 45° and get continuously hit by the plunger, while a constant abrasive flow is running between the sample and the plunger as shown in (**Figure 5**). The testing parameters are summarized in **Table 3**. Impact energy, angle of impact and frequency are chosen as 0.8 J, 45° and 2 Hz, respectively. The total number of testing cycles is fixed to e.g. 7.200 which correlate to a testing duration of 1 hour.

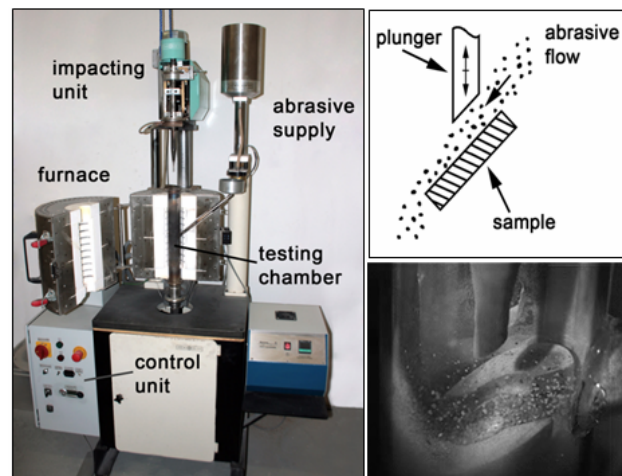


Figure 5. High temperature continuous impact abrasion test (HT-CIAT)

Table 3. Testing parameters used in HT-CIAT

Parameter	Value
Impact energy	0.8 J
Impact angle	45°
Frequency	2 Hz
Testing cycles	7.200
Abrasive material	Silica sand; 0.4 – 0.9 mm; angular
Abrasive flow	3 g/sec
Test temperature	RT, 600 °C

The abrasive material used for 3-body-contact is typically silica sand of angular shape with a particle size of 0.4 – 0.9 mm. Typical flow rate is 3 g/sec. Experiments can be carried out at room temperature but also at elevated temperatures (600 °C).

The plunger material used at these tests normally is a Co-rich high speed steel.

Characterisation of wear behaviour is done by measuring the weight loss of the samples (accuracy, 0.1 mg), by standard optical microscopy (OM) and scanning electron microscopy (SEM). Also cross-sections images of the worn specimen area have been made to analyse the predominant mechanisms e.g. carbide breaking, cold work hardening, composite layer formation and changes in the matrix caused by high temperature.

3.6 Continuous impact abrasion test (CIAT) – 2-body impact abrasion

Wear tests on a specially designed impeller-tumbler apparatus (CIAT) enable experimental simulation of combined impact and abrasion. This testing device consists of a slowly rotating outer tumbler and a fast rotating inner impeller at a rotation speed of 60 and 650 min^{-1} , respectively, where the testing specimens are mounted on [19 – 21]. The tumbler is filled with a defined amount of abrasive, and is responsible for a controlled flow of abrasive particles hitting the fast moving testing specimens (see **Figure 6**).

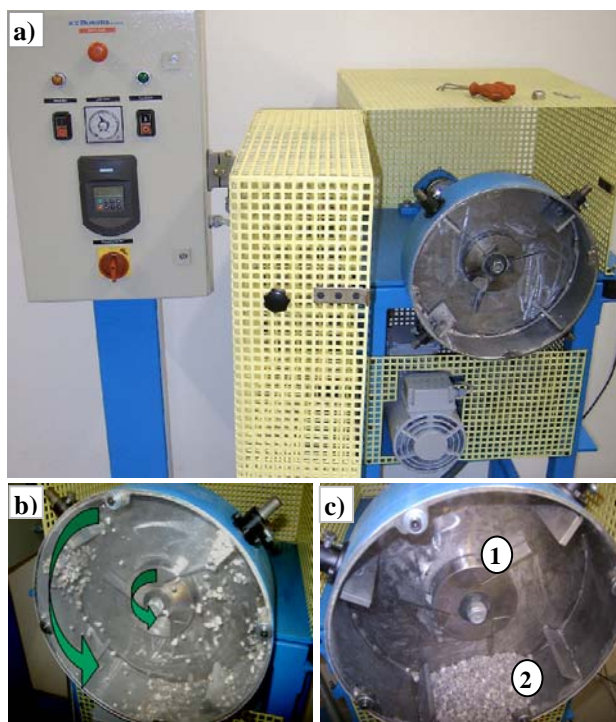


Figure 6. Continuous impact abrasion tester (CIAT), a) test setup; b) impeller-tumbler principle; c) 1 – impeller with samples to be tested, 2 – tumbler with filling (abrasive particles)

Due to the kinematical situation the particles get in contact with the specimen (surface exposed to abrasive particles, about $2.5 \times 1.0 \text{ cm}$) at an impact velocity of approximately 10 m/s. As abrasive for the experiments 1 kg of coarse corundum particles

(5 – 10 mm) for high impact loading is used. In this case (depending on the particle mass) a single particle impact energy of 28 mJ is applied.

Typical duration of the runs is defined by 20 minutes. It is recommended to repeat each test at least 3 times for statistic calculation. The CIAT wear rate is calculated in volume loss divided by testing time and mass of abrasive particles used. Wear characterization is done by gravimetric mass loss of the testing specimen during wear testing.

4. COMPLEMENTARY INVESTIGATIONS

4.1 Hardness mapping

Characterization of mechanical properties of materials and especially of different phases and structural details of materials can be done by hardness measurements. Those investigations are typically carried out with a standard Vickers hardness technique HV5 for macroscopic hardness. To determine hardness of each phase in micro-structure, e.g. hard particles and metallic matrix, HV0.1 is used.

It is very useful to make use of an autosampling device which provides multiple equidistant indents of a selected rectangular zone.

4.2 Single impact test (SIT)

The utmost stress which can occur during abrasion/erosion process is high energy impact of abrasive particles. In order to study such single damaging events, wear tests at high impact loading can be performed on a drop hammer apparatus [22]. The SIT was developed at AC²T to characterise the impact resistance of materials against impacts with high energies (up to 80 J). The test principle is based on potential energy converted into kinetic energy by a free falling “hammer” of a total mass $m = 13.3 \text{ kg}$, which drops down very close to the edge of the deposit material (see **Figure 7**).

The sample is hit by the sharp edge of the hammer top of conical shape (5° angle). Fall height of the hammer can be varied in wide range, so that the critical drop energy without breakout of the edge can be detected for the different materials (alloys, welding deposits, etc.) investigated. The impact leaves a dent on the sample, which is firmly fixed so they cannot dodge during impact. The samples’ deformation due to the impact is analysed, primarily by quantifying the length (diameter) and depth of the indent. From the latter the angle of the deformed area (impacted zone) can be calculated which provides information about the relation between elastic and plastic deformation of the material [22].

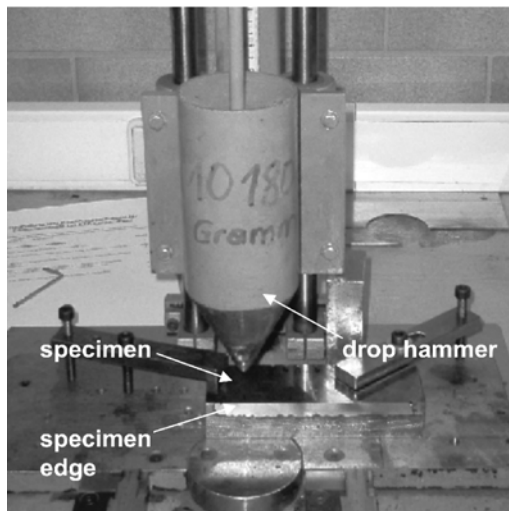


Figure 7. Single impact tester (SIT) – drop hammer with conical top

Fracture surface analysis should be carried out after drop hammer testing in order to correlate the results with fracture surface analysis, especially studying microstructure and interfacial bonding behaviour of precipitations in metallic matrix [21].

4.3 Single Abrasion Test (SAT) – Scratch test

Whereas most of classical abrasion test methods are simulating a multi-particle abrasion process where a high number of particles are attacking the surface of a sample over a defined period of time, in contrast to this the scratch-test method can be used to simulate an ideal single-contact abrasion process. In general, a very hard indenter (diamond) is used to simulate the contact situation between a hard particle and a wearing surface in application. Such type of investigation can be considered as generalisation of hardness testing.

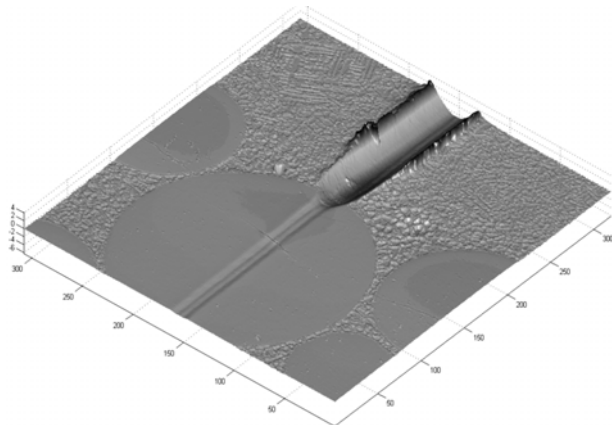


Figure 8. 3D-image of the scratch mark, 50 μm -indenter, $F_N = 5\text{ N}$, across differently hard phases

Based on this modelling situation, it can be assumed that the deformation occurs in the counterpart material whereas on the diamond indenter no significant deformation appears. [23]

5. ADVANCED EVALUATION OF ABRASION/ EROSION RESISTANCE – EXAMPLES

5.1 Comparison of alloys under abrasion and impact

The main objective of this study [20] was to evaluate the wear behaviour for pure abrasion and for combined wear of iron-based alloys which are typically applied as hardfacing coatings by gas metal arc welding. A crack free martensitic Fe-Cr-C alloy containing finely precipitated Niobium carbides (A) was tested against a conventional hypereutectic Fe-Cr-Nb-C alloy (B) already well described in literature and thus a “reference material”. Besides these lower alloyed materials on basis Fe-Cr-B-C (hypoeutectic C; hypereutectic D) were set into comparison with a new complex Fe-Cr-W-Mo-Nb alloy with high boron content (E) and a synthetic multiphase alloy on iron base with around 50 wt. % tungsten carbides (F), too. The microstructures of these materials are shown in **Figure 9**.

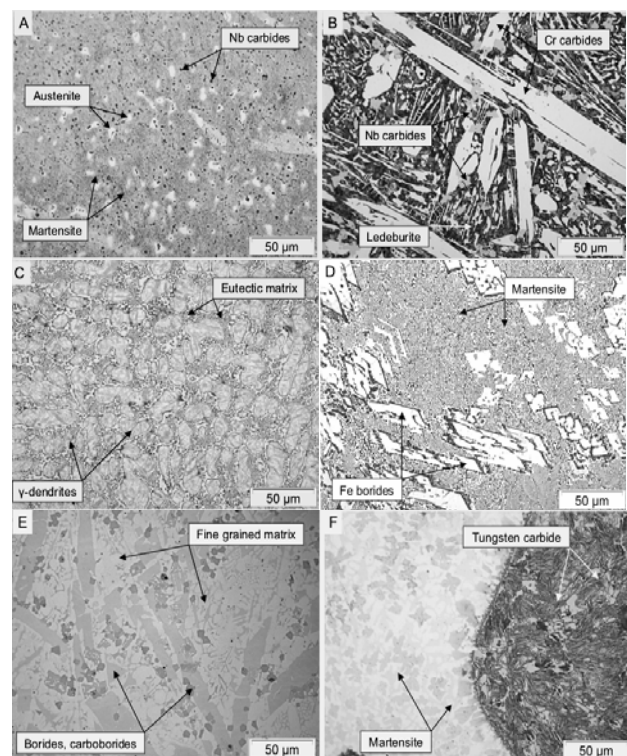


Figure 9. Microstructure of the investigated alloys

CAT (3-body abrasion) tests were performed Using ASTM G65 dry-sand rubber wheel tester (Procedure A). The comparison of the materials' behaviour both concerning their hardness (HV5) and their abrasion resistance is shown in **Figure 10**.

High abrasive wear is observed for alloy A which is in good agreement with the relative low hardness (see **Figure 9**). The lowest abrasive wear resistance of the hardfacing alloys investigated was observed for alloy C.

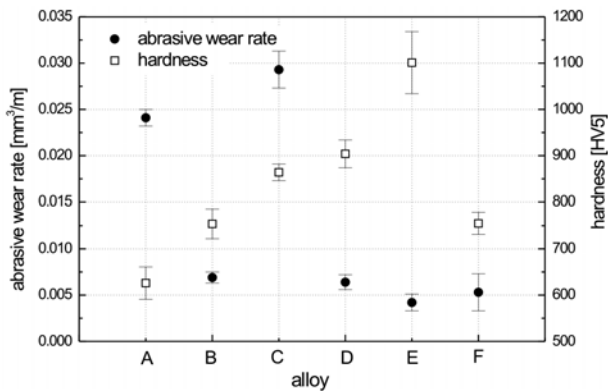


Figure 10. Abrasion behaviour and hardness – comparison of the 6 tested alloys

The influence of coarse primary precipitations on abrasive wear resistance can be seen for alloys C and D, both alloys exhibiting similar macroscopic hardness.

As well continuous impact abrasion tests (CIAT) at different impact levels were performed on the hardfacing alloy variants, some results of which are depicted in **Figure 11**.

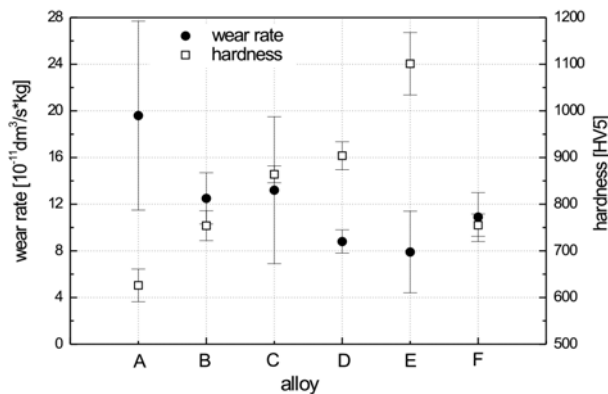


Figure 11. Abrasion behaviour (wear rate at low impact level, fine-grained silica sand with 1.6. – 2.2 mm size) and hardness – comparison of the 6 tested alloys

The lowest wear rates are obtained for alloys E and F. Alloy E combines high density of carboborides with a very hard and tough matrix. This microstructure is related to the complex composition, to the high boron level, a sufficient content of carbide and boride forming elements like Cr and V. It can be seen from the evaluation that the testing parameters (i.e. the impact level) show a specific influence on the results depending on the alloy structure. [20]

5.2 Continuous impact abrasion test under different test parameters

This example gives an overview over a principle study [24] comparing the wearing effects of five different kinds of abrasives on samples of two different materials (Fe-based hardfacing alloys), the main components of which are as follows:

Alloy A: <1 % C, 6 % Cr, 3 % Nb;
martensitic structure, 780 HV_{0.1}
Alloy B: 5.5 % C, 21 % Cr, 7 % Nb
Fe/Cr carbides, 1600 HV_{0.1}

The test conditions (**Table 4**) for the impeller-tumbler device provided a controlled flow of abrasive particles hitting the fast moving test specimens mounted on the impeller.

Table 4. Main properties of the abrasives and test conditions used for CIAT tests (impeller-tumbler device)

Abrasive	Steel grit	Quartz sand	Corundum	Steel balls	Glass balls
Parameter					
Size (mm)	0.2 – 1	1.6 – 2.2	5 – 10	4.8	5
Hardness (HV)	700	1000 – 1200	2100 – 2600	780	600
Energy/particle (mJ)	0.06	0.4	28	21	8.3
Abrasive mass (kg)	5	5	1	1	1
Test duration (min)	60	60	20	20	20
Specif. total energy (J/h)	4241	2088	5502	8190	3222

Due to the kinematical situation the particles get in contact with the specimen (surface exposed to abrasive particles, 25 × 10 mm²) at an impact velocity of approximately 10 m/s.

Quantitative wear characterization is been done by gravimetric mass loss measurement of the testing specimen after wear testing. Of course, a qualitative characterization of worn surfaces and worn edges has to be carried out, preferably by evaluating of macroscopic and cross-section images and by SEM investigations.

In the case of the selected parameters the wear mechanism is closer to an erosive process which explains the observed higher wear resistance of alloy B due to the higher hardness and the presence of a large amount of hard and wear resistant primary carbides. In general, it is observed that the mass loss of alloy B is higher compared to alloy A at high impact loading which is in good agreement with a predominant interaction of the abrasives with the hard phases where micro-cracking of the hard phases gets prevailing resulting in increased mass loss. For a single particle energy of higher than 8.26 mJ the embrittlement of hard phases is significant for the progress of material loss. Highest mass loss can be observed at the use of steel balls (see **Figure 12**).

It can be seen that for fine steel grit and fine quartz sand the abrasive component is dominating, which means that the proportion of abrasion is high compared to fatigue and impact. The load is too low for significant fatigue and single impacts are not strong enough for material separation.

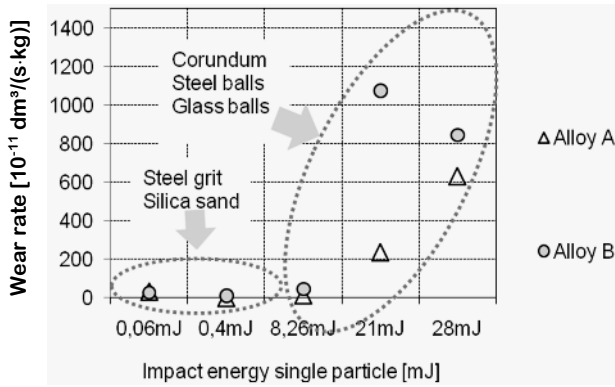


Figure 12. Influence of the single particle impact energy on the wear level of the tested alloys (low / high wear level)

The worn surface appears typical for rolling abrasive wear: neither wear caused by micro-fracture of hard phases nor fatigue of the matrix can be found at these low impacting energies caused by steel grit and quartz sand.

5.3 Wear modelling of Continuous Impact Abrasion Test at high impact loading

The single particle impact energy is assumed to be the main wear relevant parameter for this type of tribological stress and is therefore to be considered in the modelling of the deposited energy in the material [24].

Based on the available energy rate for fracture initiation E_b^* and a material related wear coefficient k the wear value W is given by Eq. 1 to

$$W = k \cdot E_b^* \quad (1)$$

Furthermore, the deposited energy E_d^* is calculated in Eq. 2 based on the kinetically deposited energy E_{kin}^* reduced by the ratio which is dissipated by fracture of abrasives.

$$E_d^* = \xi \cdot n_1 \cdot E_{kin}^* \quad (2)$$

where $\xi \cdot n$ is the correction of the number of theoretical impacts n_1 by the share of non broken particles. It is assumed that the abrasive particles are hitting normal to the surface whereas no tangentially grooving movement of the particles occurs. The material influence – which means the material specifically damaging energy content – is considered by an apparent critical energy density e_{CIAT} [J/mm³]. This critical energy density includes a plastic energy E_{pl}^* , an elastic rebound energy as well as an immediately fracture initiating remaining energy E_R^* . Wear volume W_v [mm³] can be calculated by Eq. 3:

$$W_v = E_d^* / e_{CIAT} \quad (3)$$

Verification of the wear modelling has been done for a Fe-based hardfacing alloy (<1 % C, 6 % Cr, 3 % Nb, 1.5 % others, i.e. Mo, V, W, Ti, Ni) by variation of single particle impact energy at the use of steel balls as well as corundum particles at fixed energy. Results obtained in CIAT system in correlation with wear data from modelling are illustrated in **Figure 13**.

From the depicted results a positive correlation between measured and calculated wear values of 0.96 can be stated, which means that measurement and calculation correlates by 0.84. The calculated values tend to higher values compared to measured ones. This deviation between measurement in CIAT and calculation can be explained by the interaction within the flow of particles with the result that the deposited energy is reduced significantly. According to this effect particle energy has been deposited only partially onto the surface area.

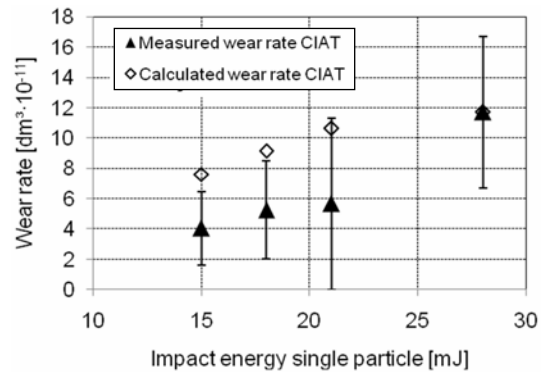


Figure 13. Wear rates of the investigated alloy obtained from CIAT – comparison with results from wear prediction based on the model according Eq. 1 to Eq. 3

5.4 Relating morphological parameters of multi-phase matrix-carbide materials to their abrasive wear behaviour

In order to study the possible correlation of specific structural parameters – especially volumetric carbide distribution – five different carbide-matrix coatings have been investigated with ASTM G65 abrasion wear rates [25]. For the investigations here described Ni-based matrix systems with enhanced contents of B and Si were used for coating of the ASTM G65 samples (**Table 5**):

Table 5. Composition properties and microstructure parameters of the tested specimens

Coating	Cr-content	WC-content	Particle size [μm]	Mean inter-particle distance [μm]
Type A	high	high	~130	291
Type B	low	high	100	357
Type C	low	high	~80	282
Type D	low	medium	63	241
Type E	low	low	63	546

For this study, the hardphase networks of laser claddings have been characterized by specific structural parameters, such as mean inter-particle distance, mean carbide diameter, carbide area fraction, and matrix hardness.

To generate quantitative values for the inter-particle distances a particular method was developed. It has become evident from regression analyses, that wear effects arising from carbide inter-particle distance surpass the influence of carbide diameter and that of carbide fraction. Only minor contribution to abrasive wear rates is related with matrix hardness.

Fundamental investigations on microstructures of white cast iron have shown that resistance to abrasion is highly influenced by carbide size and its inter-particle distance in relation to the size of abrasives [1]. More recent work of Doğan et al. [26] pointed out, that the role of inter-particle distance between carbides is assessed more decisively than carbide size for wear loss studies of materials.

The mean inter-particle distance L_{IPD} was evaluated by quantitative image analysis via *Leica Qwin* software applied on images from fine polished and chemically etched samples according Eq. 4:

$$L_{IPD} = \bar{L} + 3 \cdot S \quad (4)$$

where \bar{L} is the mean value of line distance distribution, and S is the concerned standard deviation.

Abrasion tests on a dry-sand rubber-wheel tester according to ASTM G65 procedure A were performed simulating conditions of three-body abrasion under low stress (testing conditions: rotational speed 200 min^{-1} , normal load 130 N, sliding distance 4309 m; Ottawa silica sand, abrasive grain size $212 - 300 \mu\text{m}$). For statistical calculation each test was repeated three times. The results are shown in **Figure 14**.

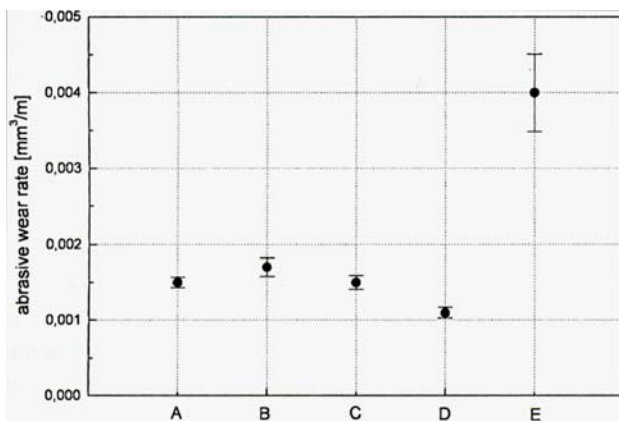


Figure 14. ASTM G65 (A) wear rates of the investigated Ni-based hardfacings

A multiple regression analysis (by statistical data processing tool *Statgraphics*, Statpoint Inc, USA) was used in order to correlate abrasion relevant material parameters (carbide volume fraction mean equivalent carbide diameter and L_{IPD}) with low stress wear rates. The functional form used for statistical modelling was linear in unknown coefficients, so that the model for the response variable (wear rate) y could be set as follows

$$y = \beta_0 + \sum_i^n \beta_i x_i + \varepsilon \quad (5)$$

where β_i stand for the unknown model coefficients, x_i are independent variables, n is the number of independent variables, and ε is a random deviation respectively residual.

Three different parameter models were considered for the three variables (area fraction, diameter and inter-particle distance). For simplification of modelling these parameters were set independent (though these variables are not independent!). The parameter model based on carbide fraction shows with $R^2 = 95\%$ (coefficient of determination) higher correlation than that based on carbides' diameter. Thus wear resistance can be much more addressed to carbide area fraction than to equivalent carbide diameter (results corresponding with investigations reported in literature [26]). Yet the model based on inter-particle distance shows superior fitting with $R^2 = 96\%$.

Multiple regression analysis of different parameter models enables better performance of the correlation. As it could be shown, combining inter-particle distance and equivalent diameter as independent variables delivers the best fitting model, with $R^2 = 99\%$. The correlation of carbide inter-particle distance (L_{IPD}) and mean carbide diameter (D) with abrasive wear rate, respectively, is shown on **Figure 15**. The inter-particle distance affects much more the wear rate than the carbide diameter.

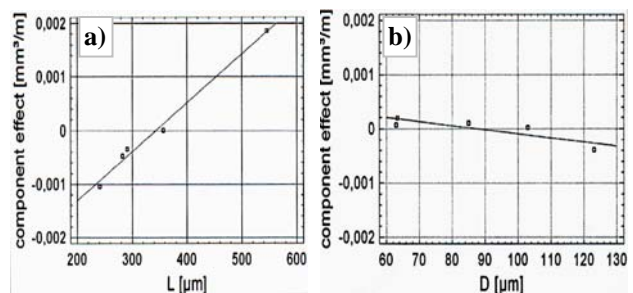


Figure 15. Microstructure parameters affecting the wear rate of the tested Ni-based matrix systems – a) inter-particle distance L_{IPD} ; b) mean carbide diameter D

6. CONCLUSION AND OUTLOOK

Characterisation of materials subject to abrasion/erosion processes conditions must be based on adequate experimental methods. Such methods make use of various special tribometers some of them are commercially available. The tests have to be accompanied by materialographic analyses. "Classical" methods should be complemented by advanced modelling techniques and mathematical tools that enable correlation of wear properties and characteristic material properties for wear protection materials. The latter will be studied extensively by novel investigation tools providing both mechanical and structural material data.

ACKNOWLEDGEMENT

Development and/or installation of the test equipment at AC²T research GmbH as well as research work were partly funded from the Austrian Kplus program (a governmental funding initiative for precompetitive research for and with the industry).

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