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# Wear resistance and mechanisms of composite hardfacings at abrasive impact erosion wear

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# Wear resistance and mechanisms of composite hardfacings at abrasive impact erosion wear

**A Surzhenkov, M Viljus, T Simson, R Tarbe, M Saarna and F Casesnoves**

Department of Mechanical and Industrial Engineering, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia

andrei.surzenkov@ttu.ee

**Abstract.** Tungsten carbide based hardmetal containing sprayed and melted composite hardfacings are prospective for protection against abrasive wear. For selection of abrasive wear resistant hardfacings under intensive impact wear conditions, both mechanical properties (hardness, fracture toughness, etc.) and abrasive wear conditions (type of abrasive, impact velocity, etc.) should be considered.
This study focuses on the wear (wear rate and mechanisms) of thick metal-matrix composite hardfacings with hardmetal (WC-Co) reinforcement produced by powder metallurgy technology. The influence of the hardmetal reinforcement type on the wear resistance at different abrasive impact erosion wear (AIEW) conditions was studied. An optimal reinforcement for various wear conditions is described. Based on wear mechanism studies, a mathematical model for wear prediction was drafted.

## 1. Introduction

Abrasive impact erosion wear (AIEW) of materials depends on their mechanical properties and on wear parameters. The dominating mechanisms at AIEW may generally be predicted on the grounds of the material / abrasive hardness ratio ($H_m/H_a$) and the impact angle (0...90º). Depending on the first ratio, these mechanisms are [1,2]:

– $H_m < H_a$: microcutting or plastic deformation with surface fatigue;
– $H_m \approx H_a$: deformation with microcutting and/or surface fatigue;
– $H_m > H_a$: deformation with surface fatigue and direct fracture.

Toughness of a material is another important mechanical characteristic that determines the behavior of a material at impact erosion. Depending on fracture toughness, the following mechanisms of wear may occur [3,4]:

– in brittle materials (low $K_{1c}$): plastic deformation with surface fatigue and great probability of direct fracture;

– in ductile materials (high $K_{1c}$): deformation with microcutting and/or surface fatigue [3,4].

Thick metal matrix composite (MMC) hardfacings are recommended for extreme abrasive wear conditions (i.e., high abrasivity, hardness and impact velocity of abrasive particles) due to their optimal hardness-toughness ratio. In this case, different wear mechanisms may simultaneously exist.

Such hardfacings may be produced, for example, by casting, plasma transferred arc (PTA) welding and submerged arc welding (SAW), vacuum sintering (VS), spray-fusion (SF), and high velocity spraying (HVS) [5–10].

The concept of plastic deformation and brittle fracture and a combined model of erosion were proposed to calculate the wear of composite structure materials [11]. A relatively soft metal matrix allows for use of the energetic theory of wear with the mean hardness and dimensionless specific energy parameter $\tau_o/e_s$. In the wear calculations of hardphase, the models of plastic deformation and brittle fracture using hardness distribution and fracture probability must be taken into consideration [2,11].

The calculated and the experimental results showed that the wear rates of the Ni-based matrix composite coating with a relatively low hardness ($H_m < H_a$) have very good coincidence [12].

In the analysis of the abrasive wear resistance of HVOF-spayed, PTA-welded and PM hardfacings in different wear conditions (abrasion at rubber wheel, impact erosion) in [13], potential application areas of selected composite hardfacings were proposed.

Wear of matrix material at impact erosion is contributed from erosion by microcutting [1,2]. As not all impacts lead to the formation of a clean machined chip that is removed, at multiple impacts within the plastic strain field of the previous impacts, it may be possible for material to be removed. In [14] that kind of wear is classified as fatigue wear for only two overhapping impacts.

The aim of the present research was (a) to study wear resistance and wear mechanisms of surface damage of thick MMC hardfacings at different AIEW modes (oblique and normal impact), and (b) to propose criteria for selection of hardfacings for the above-mentioned conditions based on the mechanical properties (hardness-toughness ratio) and microstructure (reinforcement content, size and shape).

## 2. Experimental

*2.1 Materials*

Metal matrix composite hardfacings were produced by powder metallurgy (PM) technology using vacuum liquid-phase sintering. For matrix iron based self-fluxing alloy powder Höganās 6AB with composition, wt.%: 13.72 Cr, 2.67 Si, 0.32 Mn, 2.07 C, 0.02 S, 3.40 B, 6.04 Ni, bal. Fe was used. As a reinforcement, WC-15Co hardmetal powder produced by mechanical milling using a disintegrator milling system [15], with a particle size of 1.0–2.5 mm (coarse), 0.16–0.315 mm (fine) and their mixture (50% coarse + 50% fine) was used. The amount of 50% (optimal) was determined in our previous studies [8].

Table 1 shows the composition and hardness and Figure 1 – the microstructures of the studied hardfacings. As a reference material, Hardox 400 steel was used.

**Table 1.** Designation, composition and hardness of studied hardfacings.

| Designation | Reinforcement | | Hardness [16] | |
|---|---|---|---|---|
| | Particle size, mm | Content, vol.% | HV30 | HV1[a] |
| P1 | – | 0 | 870 ±30 | 1035 ±70 |
| C5 | Coarse angular (C) 1.0–2.5 | 50 | 1260±435 | 1005±40/1855±65 |
| F5 | Fine angular (F) 0.160–0.315 | 50 | 830±160 | 900±90/1445±135 |
| M5 | Mixture 50C + 50F | 50 | 1715±295 | 815±65/1480±125 |
| H400 | Reference steel Hardox 400 | – | 425±25 | – |

[a] metal matrix/hard phase

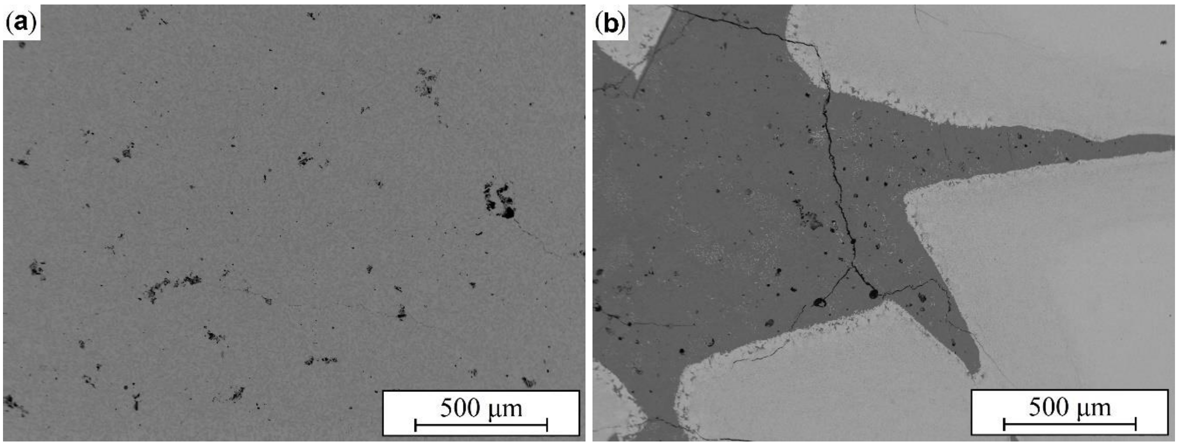


**Figure 1.** Microstructures of the studied hardfacings: a – P1 (unreinforced), b – C5 (50 vol.% WC-Co angular reinforcement) [16].

*2.2 Abrasive wear studies*

Abrasive impact erosion wear (AIEW) tests were used to determine the wear resistance of the hardfacings. At the low-energy wear test, granite and quartz sand of fraction 0.2–0.3 mm and centrifugal type tester CAK were used; at the high-energy wear test, granite gravel of fraction 3.0–5.6 mm and a disintegrator type tester DESI (Figure 3) were used.

The schemes and parameters of AIEW are given in Tables 2 and 3.

Based on the weight loss of abraded hardfacings, the volumetric wear rate (loss of volume per 1 kg of abrading material) in $mm^3/kg$ was determined.

The relative wear resistance ε was calculated as the ratio of volumetric wear rates of the reference material (Hardox 400) to the wear rate of the studied hardfacing.

Mechanisms of the impact erosion wear were studied using a scanning electron microscope (SEM) EVO MA-15 (Carl Zeiss, Germany).

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**Table 2.** Abrasive impact erosion wear (AIEW) modes.

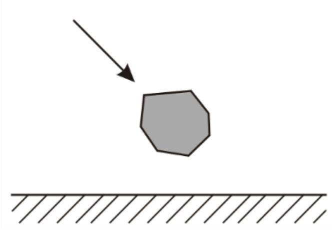
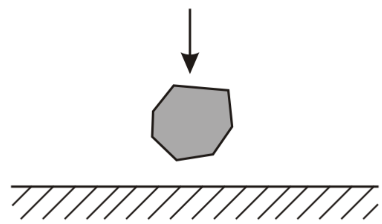
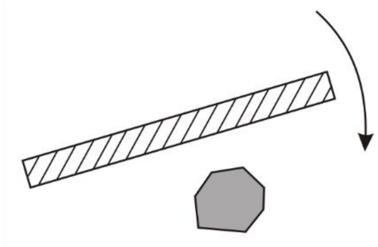
| | Oblique impact erosion wear<br>0º > α < 90º | Normal impact erosion wear<br>α = 90º |
|---|---|---|
| Low energy |  | Abrasive 0.2–0.3 mm<br><br>Kinetic energy $E_k$ at v = 40 m/s $3.0\times10^{-5}$ J<br>at v = 80 m/s $1.2\times10^{-4}$ J |
| High energy | — | Abrasive 3.0–5.6 mm<br><br>Kinetic energy $E_k$ at v = 40 m/s $1.4\times10^{-2}$ J<br>at v = 80 m/s $5.6\times10^{-1}$ J |

**Table 3.** Abrasive impact erosion wear (AIEW) parameters (a).

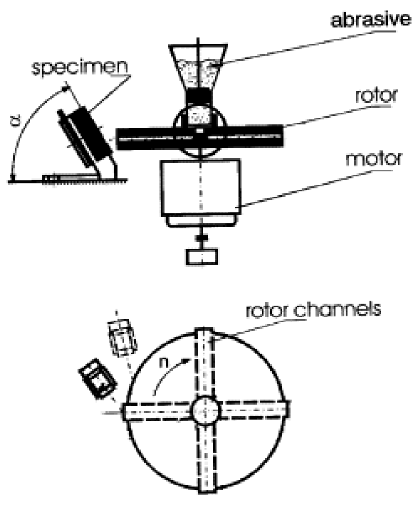
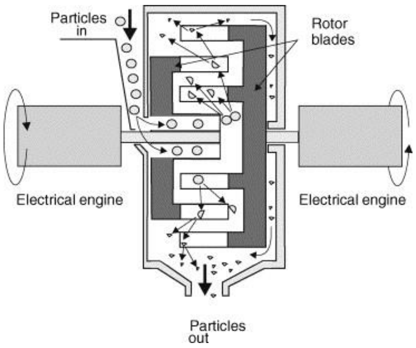
| Scheme of wear tester | Wear test parameters |
|---|---|
| <br>**Figure 2.** AIEW tester CAK. | Quartz sand 0.2–0.3 mm, 1000–1100 HV<br>Granite sand 0.2–0.3 mm, 900–950 HV<br>Impact angle α = 30º and 90º<br>Impact velocity v = 40 m/s and 80 m/s<br>Quantity of abrasive Q = 6 kg |

**Table 3 (continues).** Abrasive impact erosion (AIEW) parameters (b).

| Scheme of wear tester | Wear test parameters |
|---|---|
|   **Figure 3.** AIEW tester DESI. | Granite gravel 3.0–5.6 mm; 900–950 HV<br>Impact angle α ≈ 90º<br>Impact velocity v = 40 m/s and 80 m/s<br>Quantity of abrasive Q = 15 kg |

## 3. Results and discussion

### *3.1 Wear resistance of hardfacings at AIEW*

*3.1.1 Influence of abrasive hardness.* Results of low-energy AIEW are given in Table 4 and Figure 4. As it follows from Figure 4, the wear resistance of hardfacings is better with a softer abrasive – granite (abrasive hardness is comparable with matrix hardness); relative wear resistance exceeds that of steel Hardox 400 by about 3 times. With a harder abrasive – quartz sand ($H_a$≈1.2 $H_m$), the wear resistance of the studied hardfacings is low; relative wear resistance is at the same level or below that in comparison with Hardox 400.

**Table 4.** Wear rate (mm$^3$/kg) of hardfacings at low-energy AIEW.

| Designation | Granite sand HV 900–950 | Quartz sand HV 1000–1100 |
|---|---|---|
| P1 | 12.0 | 26.9 |
| C5 | 11.7 | 30.2 |
| F5 | 30.2 | 90.3 |
| M5 | 21.9 | 76.3 |
| H400 | 37.0 | 32.8 |

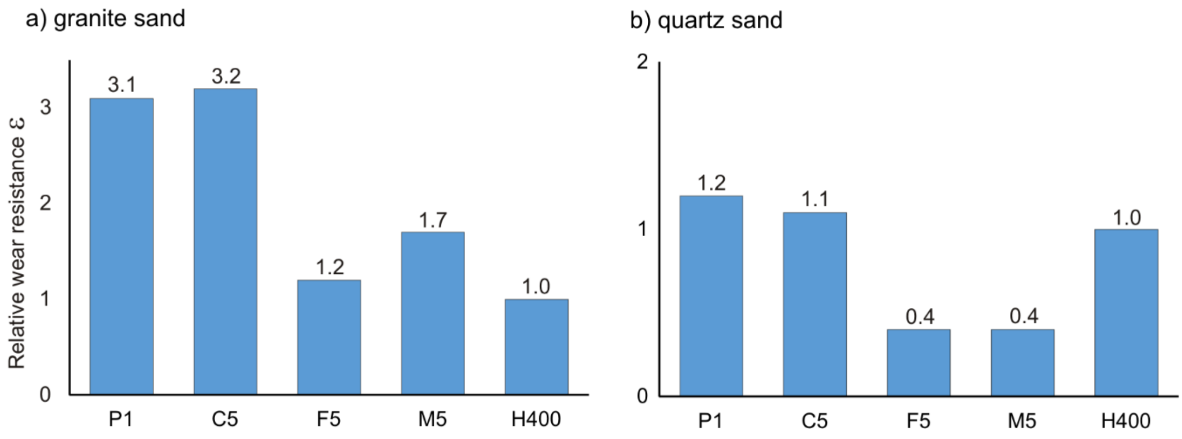



**Figure 4.** Relative wear resistance of hardfacings at low-energy AIEW with different abrasives (reference material – steel Hardox 400).

*3.1.2 Influence of impact angle at AIEW.* The results of wear resistance comparison of studied hardfacings at oblique impact (α = 30º) and at normal impact (α = 90º) show that the wear rate at straight impact is approximately 1.5 times higher (see Table 2). The relative wear resistance of the best hardfacing (C5) at α = 30º was 3.2 times higher, at normal impact (α ≈ 90º) it is only 1.9 times higher (Figure 5).

**Table 5.** Wear rates ($mm^3/kg$) of hardfacings at different impact angles at low-energy AIEW (abrasive – granite sand, impact velocity v = 80 m/s).

| Designation | Impact angle, α | |
|---|---|---|
| | α = 30° | α= 90° |
| P1 | 12.0 | 21.5 |
| C5 | 11.7 | 15.5 |
| F5 | 30.2 | 41.0 |
| M5 | 21.9 | 40.4 |
| Hardox 400 | 37.0 | 30.0 |

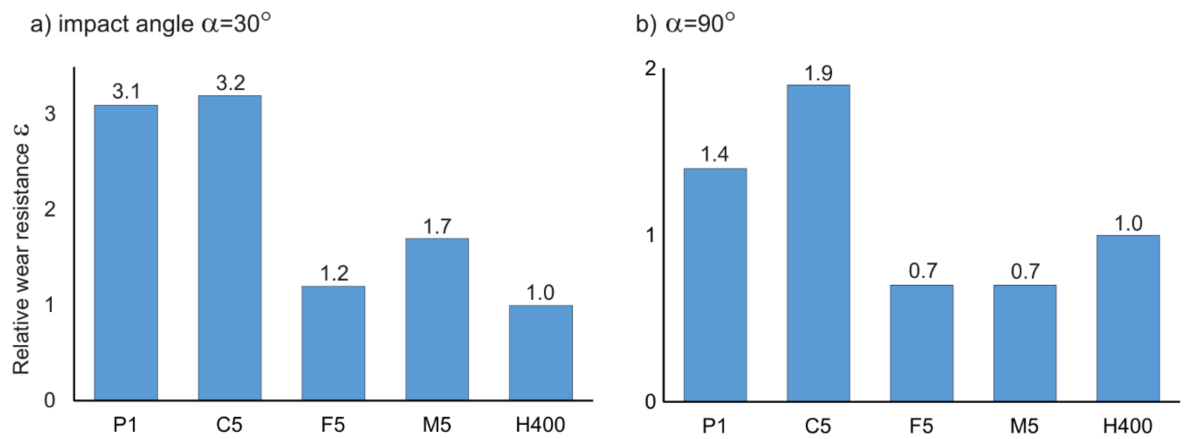



**Figure 5.** Relative wear resistance of hardfacings at low-energy AIEW under different impact angles (abrasive – granite sand, reference material – Hardox 400).

*3.1.3 Influence of abrasive particle velocity.* The results of wear rate comparison of studied hardfacings at 40 m/s and 80 m/s (Table 6 and Figure 6) show that the wear rate of reinforced hardfacings at higher velocities is 3–4 times higher when the wear of the reference steel Hardox 400 is 7–8 times higher.

Thus, at low velocity (in the range ε = 0.3–0.8), the relative wear resistance is lower to compare with Hardox 400; at high velocity, wear resistance of composite hardfacings is very low (in the range ε = 0.1–0.2). It can be explained by the differences in the wear mechanisms of hardened steel as compared with metal matrix composite hardfacings.

**Table 6.** Wear rates ($mm^3/kg$) at different velocities at low-energy AIEW (abrasive – granite sand, impact angle α = 90º).

| Designation | Velocity of abrasive particles, v | |
|---|---|---|
| | v = 40 m/s | v = 80 m/s |
| P1 | 10.0 | 21.5 |
| C5 | 4.8 | 15.5 |
| F5 | 13.8 | 41.0 |
| M5 | 5.6 | 40.4 |
| H400 | 3.8 | 30.0 |

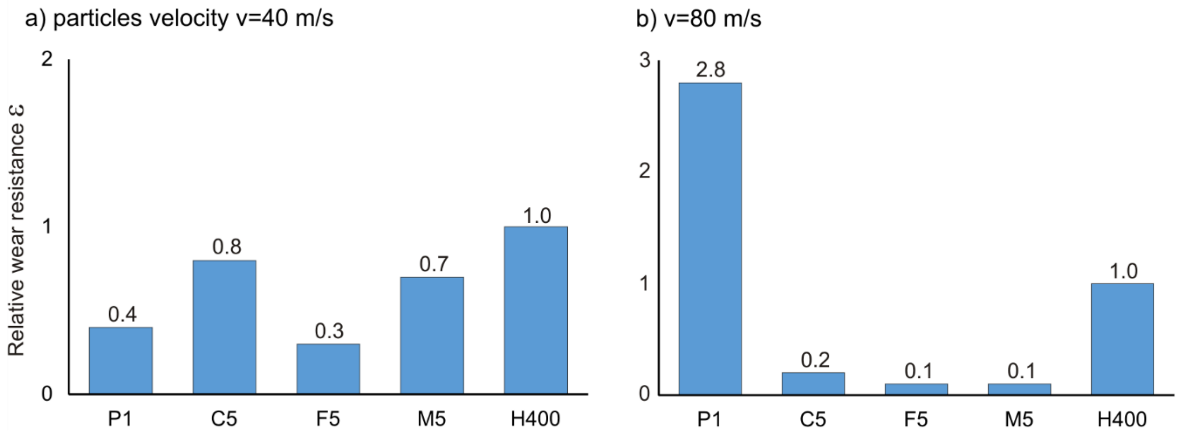



**Figure 6.** Relative wear resistance of hardfacings under different impact velocities (abrasive – granite sand, reference material – steel Hardox 400).

*3.1.4 Influence of impact energy of abrasive particles.* As the difference in studied impact energies is high (ratio of kinetic energies of high and low energy impact at v = 40 m/s is about 500 times), it influences the wear resistance significantly (see Table 7 and Figure 7). Wear rates of best hardfacing C5 differ about 23 times while the difference of the reference steel is only about 7 times.

**Table 7.** Wear rates ($mm^3/kg$) at different impact energies (abrasive – granite, v = 40 m/s, α = 90º).

| Designation | Low energy (sand) $E_k = 3.0\times10^{-4}$ J | High energy (gravel) $E_k = 1.4\times10^{-2}$ J |
|---|---|---|
| P1 | 10.0 | 9.3 |
| C5 | 4.8 | 108.6 |
| F5 | 13.8 | 215.2 |
| M5 | 5.6 | 348.6 |
| Hardox 400 | 3.8 | 26.1 |

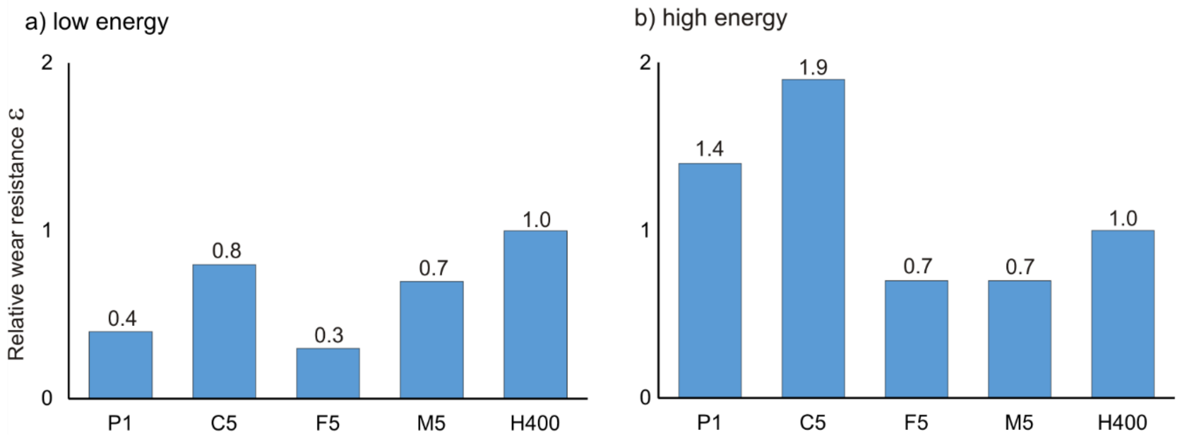



**Figure 7.** Relative wear resistance of hardfacings at low-energy and high-energy AIEW (abrasive – granite, reference material – steel Hardox 400).

*3.2 Mechanisms of AIEW*

As the unreinforced hardfacing (P1) and the hardfacing reinforced with the coarse hardmetal (C5) exhibited the lowest wear among the studied hardfacings, they were taken as the object for our analysis of wear mechanisms. Both under low-energy and under high-energy AIEW conditions, the general wear process took place in two stages: firstly, destruction of the matrix and secondly, loss of loose WC-Co particles (Figures 8 and 9). Because the wear of the matrix was much more intensive than the wear of the reinforcement, higher magnification pictures of the first are demonstrated separately.

Under the low-energy AIEW conditions, the wear of both the FeCrSiB matrix (both in unreinforced and composite hardfacing) and the WC-Co reinforcement occurred by the low-cycle fatigue mechanism (Figure 8) [2]. In the first case, it included the stages of work hardening by the impact particles, resulting in the formation and development of lateral cracks [17] and, finally, spalling of flat fragments. It is interesting to note that the wear of the FeCrSiB matrix was more extensive in the composite hardfacing, and in the proximity of the reinforcing particles (Figure 8 b,c), it became most remarkable. The most probable cause for that is the thermally induced tensile stresses at the matrix-reinforcement interface [8], which favor the removal of the material [18]. At reinforcement, the wear started with the extrusion of the binder and continued by the subsequent chipping of the exposed carbide particles, as described in [4] (not shown in Figures 8, 9).

Under high-energy AIEW conditions, the wear mechanism of the reinforcement was identical to that under the low-energy AIEW conditions. However, the wear mechanism of FeCrSiB alloy underwent some changes (Figure 9). In addition to lateral cracks, median ones [17] may be seen (Figure 9). Thus, the wear mechanism of the FeCrSiB matrix may be described as a combination of low-cycle surface fatigue and direct fracture. As at the low-energy AEIW, the wear of the FeCrSiB matrix was higher at the composite hardfacing (Figures 8 b,c) for the same reason.

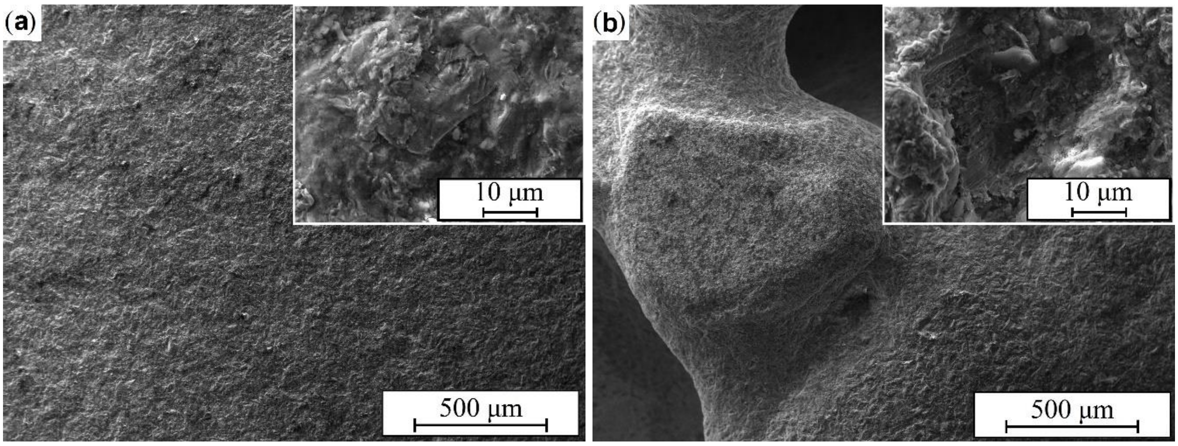



**Figure 8.** Worn surfaces of the hardfacings under low-energy AIEW conditions (v = 80 m/s): a – P1 (unreinforced), b – C5 (50 vol.% angular WC-Co reinforcement).

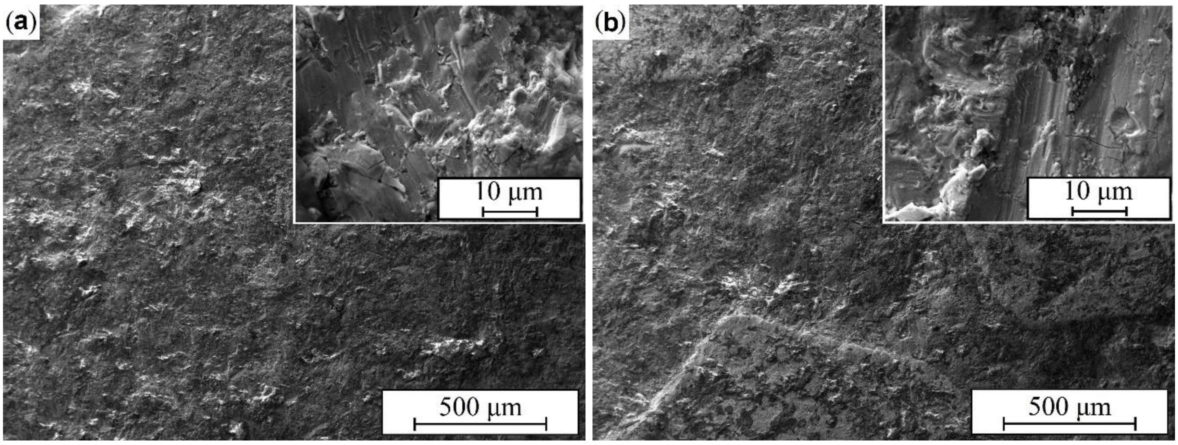



**Figure 9.** Worn surfaces of the hardfacings under high-energy AIEW conditions (v = 40 m/s): a – P1 (unreinforced), b – C5 (50 vol.% angular WC-Co reinforcement).

## 4. Conclusions

1. Wear rate of AIEW of studied composite WC-Co containing hardfacings depends first on the wear parameters (type and hardness of abrasive, velocity and kinetic energy of particles). Relative volumetric wear resistance of better hardfacings (coarse angular reinforcement, C5) exceeds that of the reference steel Hardox 400 about 3 times at low-energy AIEW with the abrasive – granite sand. At high velocity, AIEW relative wear resistance is low.
2. The dominating wear mechanism of both matrix and reinforcement at the low-energy AIEW was surface fatigue, at the high-energy AIEW – a combination of surface fatigue and direct fracture at the matrix and surface fatigue at the reinforcement.
3. The criteria for coating selection by composition and hardness-toughness ratio for hardmetals containing hardfacings are the following:

a) at oblique impact AIEW – maximal hardphase content and higher hardness of the composite;
b) at normal impact AIEW – lower hardphase content and hardness of metal matrix and higher toughness of hardphase.

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