Proceedings of the Estonian Academy of Sciences,
2016, **65**, 2, 90–96
doi: 10.3176/proc.2016.2.03
Available online at www.eap.ee/proceedings

MATERIALS ENGINEERING

Optimization of reinforcement content of powder metallurgy hardfacings in abrasive wear conditions

Taavi Simson[a*], Priit Kulu[a], Andrei Surženkov[a], Riho Tarbe[a], Mart Viljus[b], Marek Tarraste[a], and Dmitri Goljandin[a]

[a] Department of Materials Engineering, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia
[b] Centre for Materials Research, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia

Received 30 June 2015, revised 14 October 2015, accepted 15 October 2015, available online 22 February 2016

Abstract. The article studies the effect of the hardmetal reinforcement content (80, 60, 40, and 20 wt%) on powder metallurgy (PM) hardfacings with the FeCrSiB matrix, produced by vacuum pressureless liquid-phase sintering. Research focus was on the microstructure, macro- and microhardness, as well as wear resistance of hardfacings under abrasive rubber wheel wear and abrasive–erosive wear tests. The results of the wear tests are compared to the wear of reference materials: steel Hardox 400, composite wear plate CDP 112 (Castolin Eutectic® Ltd.), and hardmetal VK15. A positive correlation was found between the microstructure and microhardness of the hardfacings and their wear resistance. Optimal hardmetal content in the PM hardfacings for different types of wear conditions is recommended.

Key words: hardfacing, powder metallurgy, abrasive wear, microstructure, hardmetal reinforcement.

1. INTRODUCTION

Composite hardmetal reinforced hardfacings have been proven to provide an efficient protection for machine parts and mechanical construction elements under different abrasive wear conditions [1–5]. Hardfacings with coarser hardmetal reinforcement have been found particularly effective [6]. In addition, hardmetal reinforced hardfacings have been reported to be very flexible in processing: they can be manufactured by plasma spraying [7], high velocity oxy-fuel spraying [8], plasma transferred arc welding [9,10], laser cladding [11,12], and electrospark deposition [13]. Hardfacings with a coarse (>1 mm) reinforcement can be manufactured by applying various casting technologies [14,15] and powder metallurgy [6]. The mechanical properties of the obtained composite structures and their wear resistance can be highly dependent on the hardmetal content [16,17].

However, no comprehensive studies into variations of hardmetal reinforcement content in the composite hardfacings have been reported yet. Furthermore, no results concerning the reinforcement content in the hardfacings with coarse hardmetal have been published. Therefore, the present study analyses composite hardfacings with coarse hardmetal reinforcement (1–2.5 mm), varying in the range from 20 to 80 wt%. A positive correlation between the hardmetal content and the wear resistance of the composite hardfacings at different abrasive wear conditions was found.

Focus is also on the relations between the reinforcement content and the microstructure as well as the hardness (macro- and microhardness) and porosity of hardfacings. Recommendations are given for the use of the studied hardfacings.

* Corresponding author, taavi.simson@ttu.ee

2. EXPERIMENTAL

2.1. Feedstock materials and manufacturing of hardfacings

A Fe-based self-fluxing alloy (SFA) and disintegrator milled recycled WC–Co hardmetal powder were chosen as the feedstock materials for the manufacture of the studied hardfacings (see Table 1). Hardmetal particle size was from 1.0 to 2.5 mm. Powder mixtures with 20, 40, 60, and 80 wt% hardmetal content were prepared.

The layer of powder mixtures on steel S235 (wt%: 0.17 C, 1.40 Mn, 0.55 Cu, 0.025 P, 0.025 S, 0.012 N, bal Fe) was subjected to sintering in vacuum at 1373 K for 30 min. These process parameters have been found to be optimal on the grounds of previous experiments [5]. As a result, the self-fluxing alloy powder particles melted down, while the hardmetal particles remained unmelted. During cooling and solidification, a hardfacing with a self-fluxing alloy matrix and hardmetal reinforcement was formed.

2.2. Characterization of hardfacings

The microstructure of the obtained hardfacings was analysed under a scanning electron microscope (SEM). A possible dissolution of the reinforcement in the matrix was studied by means of energy dispersive spectrography (EDS).

Vickers macrohardness was measured on the surface of the hardfacings to estimate the hardness of the composite, and the microhardness at the cross-sections of the hardfacings was measured to find the hardness of the matrix and the reinforcement separately. The loads applied were 298 N (30 kgf) and 0.49 N (0.05 kgf), respectively. In each case, ten measurements were performed and average hardness values were calculated.

Table 1. Composition of hardfacings

Designation	Composition, wt%
H1	20 WC–Co[a], 80 FeCrSiB[b]
H2	40 WC–Co[a], 60 FeCrSiB[b]
H3	60 WC–Co[a], 40 FeCrSiB[b]
H4	80 WC–Co[a], 20 FeCrSiB[b]
VK15	85 WC, 15 Co
CDP 112	35 WC, 65 NiCrSiB
Hardox 400	Steel[c]

[a] Experimental, WC–(12–20)Co.
[b] 6 AB from Höganäs AB, with +15 – 53 μm particle size; 13.7 Cr, 2.7 Si, 3.4 B, 6.0 Ni, 2.1 C, bal Fe.
[c] 0.32 C, 0.70 Si, 1.60 Mn, 0.025 P, 0.010 S, 1.40 Cr, 0.60 Mo, 0.004 B, bal Fe.

Table 2. Parameters of abrasive wear tests

Type of wear test	Velocity, m/s	Quantity of abrading material, kg
Abrasive rubber wheel wear (ARWW)	2.4	3.75
Abrasive–erosive wear (AEW), impact angle 30° and 90°	80	6

2.3. Abrasive wear testing

Two different wear testing methods were used to characterize the wear resistance of the hardfacings: abrasive rubber wheel wear (ARWW) test according to the standard ASTM G65 and abrasive–erosive wear (AEW) test according to the standard GOST 23.201-78. Abrasive quartz sand with the particle size of 0.1–0.3 mm was used.

The parameters of the abrasive wear tests are shown in Table 2. For each test, three specimens from each type were tested. Their weight loss was measured. On the basis of the results, volumetric wear rate (loss of volume per 1 kg of abrading material in mm^3/kg) was calculated. The relative wear resistance ε was calculated as the ratio of the volumetric wear rates of the reference material Hardox 400 (hardness 425 ± 25 HV30) to the wear rates of the hardfacings. Results were compared to the WC–15Co hardmetal (1150 ± 50 HV30) and the Gastolin Eutectic CDP 112 wearplate (hardness 550 ± 50 HV30). Wear scars were studied under SEM to investigate the wear mechanisms.

3. RESULTS AND DISCUSSION

3.1. Microstructure and hardness of hardfacings

All the hardfacings studied exhibited pores and cracks in the matrix, whereas these defects became more remarkable with the increase of the hardmetal content (Fig. 1). Two types of pores were distinguished: (i) near-spherical or near-oval in shape 10–15 μm in size, scattered in the matrix, except for the hardfacing with 20 wt% WC–Co, and (ii) pores of irregular shape, situated in the proximity of the reinforcement. With the increase of the reinforcement content, the proportion and size of the latter were growing, the size reaching up to 450 μm. Near-spherical pores most probably appeared as a consequence of gas and/or moisture, entrapped between the particles of the feedstock powder, which was not removed during the vacuumizing process [18]. Large pores of irregular shape can be defined as shrinkage pores, formed during the solidification of the melt due to the different values of the coefficients of

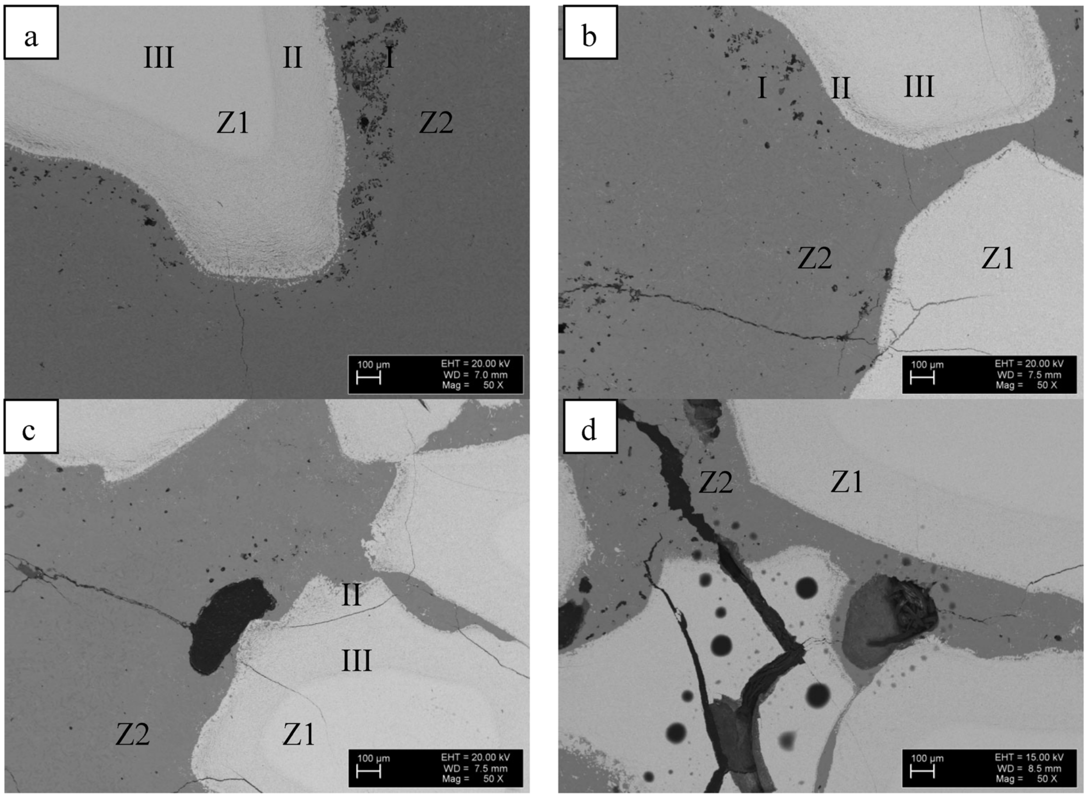

Fig. 1. Microstructure of the studied hardfacings: (a) 80 wt% FeCrSiB + 20 wt% WC–Co; (b) 60 wt% FeCrSiB + 40 wt% WC–Co; (c) 40 wt% FeCrSiB + 60 wt% WC–Co; (d) 20 wt% FeCrSiB + 80 wt% WC–Co. Z1 – hardmetal particle, Z2 – FeCrSiB matrix. I – dissolution–reprecipitation zone, II – interdiffusion zone, III – core zone.

thermal expansion of the matrix and the reinforcement. This raises the internal stresses at the reinforcement–matrix interface, which finally disrupt the matrix that has a lower tensile strength than the reinforcement, leading to the formation of shrinkage pores. The internal stresses and content of the shrinkage porosity will grow with the growth of the reinforcement content, which was confirmed by the microstructure observations. Intensifying cracking of the hardfacings at a higher WC–Co content can also be observed visually.

The EDS analysis showed that three zones could be distinguished in the formed structures: a 10–50 μm thick dissolution–reprecipitation zone I, contacting directly with the matrix; followed by a 200–300 μm thick interdiffusion zone II and the core zone III (Fig. 1). Zone I is composed of the grains of the primary WC, which became loose during the sintering process due to the cobalt binder dissolution, embedded in the reprecipitated iron, chromium, and tungsten carbides. In zone II, the cobalt binder was partially replaced by iron and, on a smaller scale, by chromium and nickel due to the interdiffusion between the reinforcement and the matrix, whereas the iron content decreased slightly with the increase of the WC–Co proportion in the hardfacing. In zone III, the initial hardmetal structure was preserved.

Presence of tungsten and cobalt in the FeCrSiB matrix was observed. The content of both elements increased with the increase of the reinforcement content.

The average microhardness value of the reinforcement was generally at the same level as the microhardness of the feedstock hardmetal powder (Table 3) varies mostly due to the different binder content in the reinforcing particles. The microhardness of the matrix tended to decrease slightly with the increase of the WC–Co percentage in the hardfacings.

Table 3. Hardnesss of the studied hardfacings

Designation	Macrohardness HV30	Microhardness HV0.05	
		Matrix	Reinforcement
H1	1166 ± 261	793 ± 107	1648 ± 205
H2	1141 ± 289	730 ± 89	1406 ± 124
H3	1281 ± 436	717 ± 159	1361 ± 133
H4	1444 ± 96	721 ± 84	1781 ± 265
CDP 112	548 ± 50	524 ± 111	1730 ± 318

3.2. Abrasive rubber wheel wear

The results of the ARWW test are given in Table 4 and Figs 2 and 3. It can be observed that the higher the hardmetal reinforcement content, the higher is the resistance to the ARWW. However, H4 is an exception, i.e. it contains more reinforcement than H3 but showed a higher wear. This can be explained by the very high porosity of the H4 hardfacing, which causes the reinforcement getting loose easier and therefore contributes to the higher wear.

Comparison of hardfacings H1, H2, H3, and H4 (Fig. 2) revealed no great differences in wear resistance. Comparison of the hardfacings to the reference materials showed that they had 15–20 times higher wear resistance than Hardox 400 and about 2.5 times higher wear resistance than the commercial wear plate CDP 112 (Table 4).

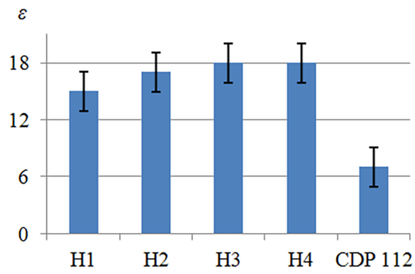

Fig. 2. Relative wear resistance ε of hardfacings at the ARWW test (reference material Hardox 400).

Table 4. ARWW test results

Designation	Density ρ, g/cm^3	Wear rate, mm^3/kg
H1	8.9	1.32
H2	10.3	1.17
H3	11.8	1.11
H4	13.2	1.14
VK15	14.5	0.19
Hardox 400	7.85	19.91
CDP 112	10.9	3.15

Figure 3 illustrates also the wear scars and wear mechanism of the hardfacings after the ARWW test. Hardfacings H1 and H2 are rather smooth, but H3 and H4 exhibit high porosity and surface roughness. As can be seen, H4 has more abrasive material between hardmetal particles than other hardfacings. This possibly affects the wear results and the actual wear may be higher.

3.3. Abrasive-erosive wear

The results of the AEW test are given in Table 5 and Figs 4 and 5. The obtained hardfacings were found to have much lower wear resistance in the AEW than in the ARWW test.

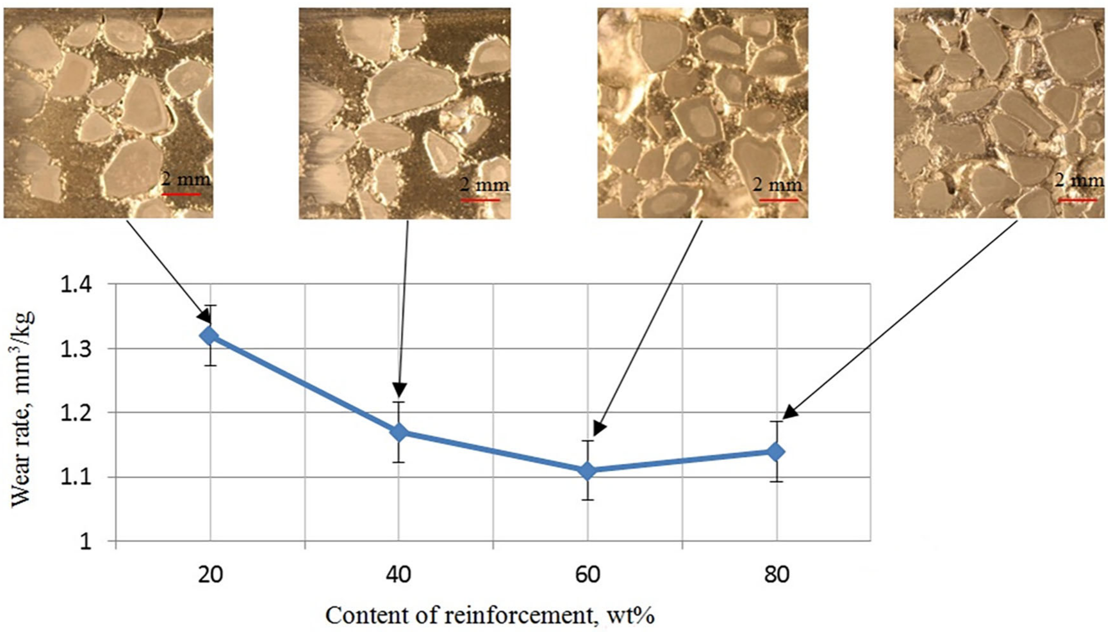

Fig. 3. Influence of the reinforcement content on hardfacings at the ARWW test and SEM images of worn surfaces.

Table 5. AEW test results

Designation	Wear rate, mm^3/kg	
	30°	90°
H1	13.9	53.6
H2	12.9	42.3
H3	15.0	34.2
H4	23.6	33.3
Hardox 400	40.4	26.2

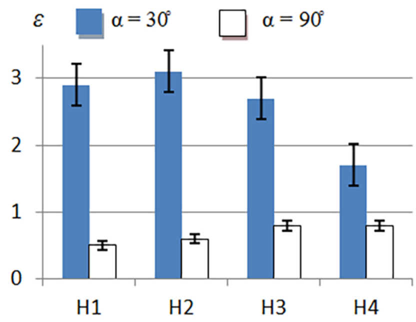

Fig. 4. Relative wear resistance ε of hardfacings at the AEW test. Reference material Hardox 400.

The relative wear resistance at the AEW test was higher (1.7–3.1 times) compared to Hardox 400 in the case of impact angles of 30 degrees and lower (0.5–0.8 times) at the impact angles of 90 degrees. The poor performance in erosive wear at normal impact is most probably due to the high porosity of the obtained hardfacings, especially in the case of H3 and H4. At the low impact angle the wear increases with the hardmetal content, at normal impact the wear decreases with the hardmetal content (Fig. 5).

At the impact angle of 30 degrees, the predominant wear mechanism was microcutting of the matrix, followed by the removal of loose hardmetal particles. An increase of the wear with the growth of the hardmetal content can be explained by the fact that the hardmetal has higher density (14.3 g/cm^3) than the FeCrSiB matrix (7.4 g/cm^3), therefore an enlarged loss of hardmetal particles will increase the weight loss of a tested hardfacing, which is reflected in the respective wear values.

At the impact angle of 90 degrees, surface fatigue of the matrix and, on a smaller scale, of the reinforcement, was the prevailing wear mechanism.

4. CONCLUSIONS

Based on the study of the influence of the hardmetal reinforcement content in composite hardfacings, the following conclusions were drawn:

(1) It was demonstrated that it is possible to produce hardfacings with a high hardmetal content (up to 80 wt%) using the powder metallurgy (sintering) technology.

(2) The study of the hardness and porosity of the obtained hardfacings showed that with the increasing hardmetal content in hardfacings the average macrohardess and porosity of the hardfacings increase.

(3) The influence of reinforcemnet content to wear properties was the following:

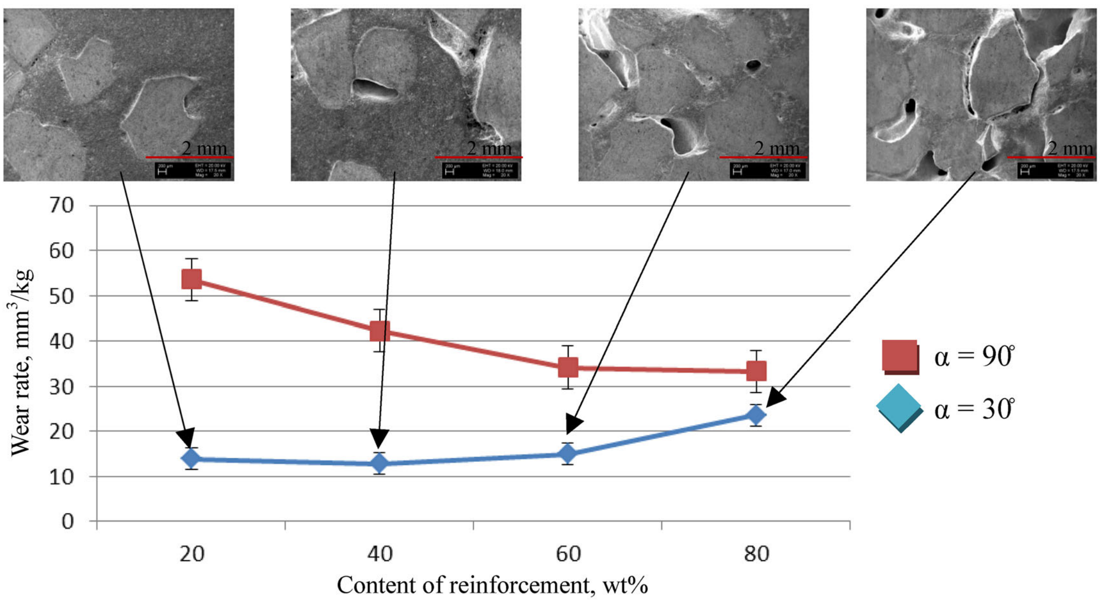

Fig. 5. Influence of reinforcement content on hardfacings at the AEW test and SEM images of worn surfaces.

- At abrasive rubber wheel wear (ARWW) test, hardfacings with a higher hardmetal content tended to have better wear resistance. It was shown that the hardmetal content of about 60 wt% was optimal: the obtained hardfacings were 18 times more wear resistant than Hardox 400 and 3 times more resistant than the CDP 112 wear plate.
- At abrasive–erosive wear (AEW) test, the wear resistance of hardfacings was lower than in ARWW conditions. At the impact angle of 30 degrees, the wear resistance decreased with the increase of the hardmetal content. This is due to the wear of the matrix as a result of which hardmetal particles begin to separate more easily. In contrast, at the impact angle of 90 degrees the wear resistance increased.
- At the AEW test at the impact angle of 90 degrees, the wear resistance of hardfacings was poorer than of the reference material.

ACKNOWLEDGEMENTS

This research was supported by Institutional research grant IUT19-29, the Archimedes project 'Wear Hard', and the European Social Fund's Doctoral Studies and Internationalisation Programme DoRa carried out by the Archimedes Foundation.

REFERENCES

1. Wang, P. Z., Qu, J. X., and Shao, A. S. Cemented carbide reinforced nickel-based alloy coating by laser cladding and the wear characteristics. *Mater. Design*, 1996, **17**(5), 289–296.
2. Smurov, J. Laser cladding and laser assisted direct manufacturing. *Surf. Coat. Tech.*, 2008, **202**(18), 4496–4502.
3. Kulu, P. and Zimakov, S. Wear resistance of thermal sprayed coatings on the base of recycled hardmetal. *Surf. Coat. Tech.*, 2000, **130**(1), 46–51.
4. Kulu, P. and Halling, J. Recycled hard metal-base wear-resistant composite coatings. *J. Therm. Spray Techn.*, 1998, **7**(2), 173–178.
5. Guo, C., Zhou, J., Chan, J., Zhow, J., Yu, Y., and Zhou, H. High temperature wear resistance of laser cladding NiCrBSi and NiCrBSi/WC-Ni composite coatings. *Wear*, 2011, **270**(7–8), 492–498.
6. Kulu, P., Surzhenkov, A., Tarbe, R., Viljus, M., Saarna, M., and Tarraste, M. Hardfacings for abrasive wear applications. In *Proceedings of the 28th International Conference on Surface Modification Technologies, Tampere, Finland, 16–18th of June, 2014*. Valardocs, 2014, 149–157.
7. Surzhenkov, A., Kulu, P., Tarbe, R., Mikli, V., Sarjas, H., and Latokartano, J. Wear resistance of laser remelted thermally sprayed coatings. *Estonian J. Eng.*, 2009, **19**, 318–328.
8. Sarjas, H., Goljandin, D., Kulu, P., Mikli, V., Surženkov, A., and Vuoristo, P. Wear resistant thermal sprayed composite coatings based on iron self-fluxing alloy and recycled cermet powders. *Mater. Sci. (Medžiagotyra)*, 2012, **18**(1), 34–39.
9. Zikin, A., Ilo, S., Kulu, P., Hussainova, I., Katsich, C., and Badisch, C. Plasma transferred ARC (PTA) hardfacing of recycled hardmetal reinforced nickel-matrix surface composite. *Mater. Sci. (Medžiagotyra)*, 2012, **18**(1), 12–17.
10. Kulu, P., Käerdi, H., Surženkov, A., Tarbe, R., Veinthal, R., Goljandin, D., and Zikin, A. Recycled hardmetal-based powder composite coatings: optimisation of composition, structure and properties. *Int. J. Mater. Prod. Tec.*, 2014, **49**(2–5), 180–202.
11. Paul, C. P., Alemohammad, H., Toyserkani, E., Khajepour, A., and Corbin, S. Cladding of WC-12Co on low carbon steel using a pulsed Nd:YAG laser. *Mater. Sci. Eng.*, 2007, **464**, 170–176.
12. Afzal, M., Ajmal, M., Nusair Khan, A., Hussain, A., and Akhter, R. Surface modification of air plasma spraying WC-12%Co cermet coating by laser melting technique. *Opt. Laser Technol.*, 2014, **56**, 202–206.
13. Wang, J., Meng, H., Yu, H., Fan, Z., and Sun, D. Surface hardening of Fe-based alloy powders by Nd:YAG laser cladding followed by electrospark deposition with WC-Co cemented carbide. *Rare Metals*, 2010, **29**(4), 380–384.
14. Rojacz, H., Varga, M., Kerber, H., and Winkelmann, H. Processing and wear of cast MMCs with cemented carbide scrap. *J. Mater. Process. Tech.*, 2011, **214**, 1285–1292.
15. Stepanchuk, A. N. Manufacturing of composite materials and coatings from self-fluxing alloys and hardmetal scrap. 2011. http://cla.kpi.ua/handle/123456789/5381 (accessed 28.05.2015).
16. Gu, D. and Shen, Y. Influence of reinforcement weight fraction on microstructure and properties of submicron WC-Co/Cu bulk MMCs prepared by direct laser sintering. *J. Alloy Comp.*, 2007, **431**(1–2), 112–120.
17. Kulu, P., Tarbe, R., Zikin, A., Sarjas, H., and Surženkov, A. Abrasive wear resistance of recycled hardmetal reinforced thick coating. *Key Eng. Mat.*, 2015, **527**, 185–190.
18. Kulu, P., Surženkov, A., Tarbe, R., and Simson, T. Abrasive impact wear resistance of hardfacings. In *Proceedings of the European Conference on Heat Treatment 2015 & 22nd IFHTSE Congress, Venice, Italy, 20–22 May 2015*. CD-ROM.

Kõvasulami sisalduse optimeerimine pulberpinnetes abrasiivkulumise tingimustes

Taavi Simson, Priit Kulu, Andrei Surženkov, Riho Tarbe, Mart Viljus,
Marek Tarraste ja Dmitri Goljandin

Artiklis on keskendutud kõvasulami sisalduse (20, 40, 60 ja 80 wt%) mõjule pulbermetallurgia meetodil valmistatud FeCrSiB maatriksiga paksudes kõvapinnetes. Artikli põhifookuses on pinnete mikrostruktuur, mikro- ja makrokõvadus ning kulumiskindlus kummiratta (ARWW) ja erosiooni (AEW) katses. Tulemusi on võrreldud referentsmaterjalidega: Hardox 400, kulumisplaat CDP 112 (Castolin Eutectic® Ltd.) ja kõvasulam VK15. On välja selgitatud seosed mikrostruktuuri, mikrokõvaduse ja kulumiskindluse vahel. On välja toodud optimaalne kõvasulami sisaldus erinevates kulumisolukordades.