Development and Performance of New Hard and Wear-Resistant Engineering Materials

E. Pagounis and V.K. Lindroos

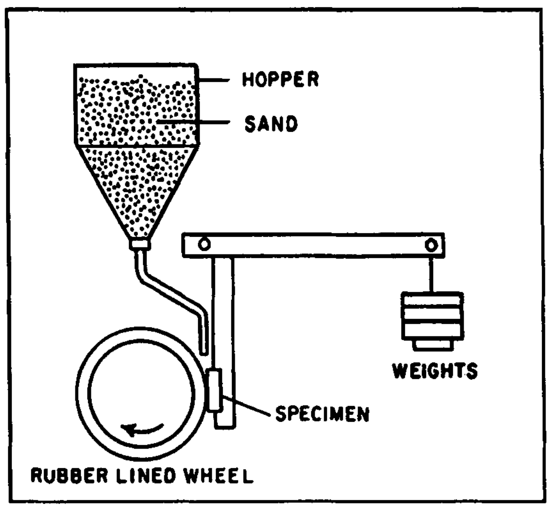
Wear is a major problem in many industrial applications, and the development of wear-resistant materials is therefore both a technical and an economic advantage. Iron-base composites bring new possibilities into the production of wear-resistant materials because of their high hardness and sufficient fracture toughness. They are suitable replacements for the conventional WC/Co cermets owing to their lower fabrication cost, better machinability, weldability, and corrosion resistance. In this study, hot-work steel/Cr_3C_2 composites and reference wear-resistant materials were produced by hot isostatic pressing. It was found that the matrix powder size used during processing did not affect the resultant wear properties of the composite. On the other hand, the impact toughness increased when fine matrix powders were used. The increasing reinforcement volume fraction increased significantly the hardness and wear resistance of the composite; however, the impact resistance decreased. The newly proposed hot-work steel/30 vol% Cr_3C_2 composite demonstrated a better combination of properties than some of the most abrasion-resistant materials available today.

Keywords Cr_3C_2 reinforcement, hot isostatic pressing, iron-base composites, wear-resistant materials

1. Introduction

The current dissipation of energy and the waste of valuable raw material due to wear are important economic factors. The cost of abrasion, for instance, has been estimated as ranging from 1 to 4% of the gross national product of an industrialized nation (Ref 1). Therefore, the development of advanced wear-resistant materials has been the target of much investigation and research work. Wear is a major problem particularly in the process and chemical industry as well as in mining and earth-moving operations. Among the wear-resistant materials available today, cermets (e.g., tungsten carbides, WC/Co) offer the best performance. They have established a strong position as structural parts combining the high hardness of the ceramic phase with the ductility of the metallic phase (Ref 2). However, the high cost of these materials together with the shortage of tungsten and cobalt restricts their wider utilization in practical engineering applications.

The more inexpensive and readily available iron alloys offer some highly wear-resistant grades, such as the high-speed steels (HSS) (Ref 3), chromium-molybdenum white cast irons (Ref 4), and some highly alloyed tool steels (Ref 5). The increased wear resistance of these alloys is attributed to the presence of a high amount of in situ carbides. On the other hand, the addition of ceramic particulates into iron alloys to produce composite materials has gathered increased scientific and industrial interest (Ref 6-10). Iron-base composites offer high hardness, which reduces the depth of penetration of abrasive grits, and sufficient fracture toughness, which prevents brittle fracture. In addition, they can be heat treated and they show good machinability (in the annealed condition) and weldability. The matrix of iron-base composites can be a tool steel or a stainless steel (in cases where corrosion resistance is also desired). The particulate reinforcements are oxides (Al_2O_3, ZrO_2), carbides (TiC, Cr_3C_2, VC, NbC), or nitrides (TiN). A great advantage of the composite nature of these materials is that their composition can be formulated (e.g., by using different combinations of matrix and reinforcement) for use in many different engineering applications. The purpose of this paper is



Rubber wheel:	**rubber lined steel wheel, 310 mm in diameter**
Rotating speed:	**147 r / min**
Load:	**60 N**
Type of abrasive:	**quartz sand, particle size 0,1 - 0,6 mm**
Abrasive flow rate:	**350 - 400 g / min**
Test time:	**10 min**
Distance covered:	**1432 m**
Sample size:	**7 mm X 22 mm X 50 mm**

Fig. 1 Schematic representation and operation parameters of the rubber wheel abrasion tester

E. Pagounis and **V.K. Lindroos,** Helsinki University of Technology, Laboratory of Physical Metallurgy and Materials Science, P.O. Box 6200, 02015 HUT, Finland.

to present new aspects in the development of wear-resistant iron-base composites and to assess their performance in comparison to commercially available hard materials.

2. Materials and Experimental Procedures

2.1 *Materials*

Gas-atomized hot-work tool steel powder was selected for the matrix material of the examined composites. Its composition was (in wt%) 0.35C-4.9Cr-1.6Mo-0.6V-Fe(bal), and it is similar to the AISI grade H11. This tool steel possesses high toughness and moderate wear resistance, even at elevated temperatures. The powder was supplied in the size distribution of <250 μm and subsequently sieved to obtain the desired powder sizes. The particulate reinforcement was dense sintered Cr_3C_2 (H.C. Starck, Düsseldorf, Germany) with the size of 5 to 25 μm. In order to study the influence of the matrix powder size on the mechanical properties, 12 hot-work steel/Cr_3C_2 composites were produced (referred to as heats), which are summarized in Table 1.

Table 1 Produced hot-work steel/Cr_3C_2 composites

Heat	Cr_3C_2, vol%	Matrix powder size, μm
11	5	<32
12	8	<32
13	10	<32
21	5	32-75
22	8	32-75
23	10	32-75
31	5	<75
32	8	<75
33	10	<75
41	5	Unsieved
42	8	Unsieved
43	10	Unsieved

In addition, hot-work tool-steel-matrix composites containing 20 and 30 vol% Cr_3C_2 (matrix powder size <75 μm), as well as some conventional/commercial powder metallurgical (P/M) wear-resistant materials were produced. The type and chemical composition of these materials are presented in Table 2.

Table 2 Type and chemical composition of examined materials

Type of material	Chemical composition of matrix, wt %	Reinforcement
HSS	1.3C-4.2Cr-5.0Mo-3.1V-6.3W-Fe(bal)	...
HSS/10 vol% TiC	1.3C-4.2Cr-5.0Mo-3.1V-6.3W-Fe(bal)	TiC
White iron	2C-26Cr-Fe(bal)	...
White iron/10 vol% TiC	2C-26Cr-Fe(bal)	TiC
White iron/10 vol% Cr_3C_2	2C-26Cr-Fe(bal)	Cr_3C_2
Mn steel	1.3C-2.1Cr-0.4V-11.4Mn-Fe (bal)	...
Mn steel/10 vol% TiC	1.3C-2.1Cr-0.4V-11.4Mn-Fe (bal)	TiC
Stellite 12(a)	1.5C-29.5Cr-8W-1.2Si-<2 Fe, Ni-Co(bal)	...
Stellite 12/10 vol% Al_2O_3	1.5C-29.5Cr-8W-1.2Si-<2Fe, Ni-Co(bal)	Al_2O_3

(a) Stellite is a trademark of Stoody Deloro Stellite, Inc., CA, USA.

Finally, commercially supplied chromium-molybdenum white cast iron and Ferro-Titanit-Nikro 128 (31.5 vol% TiC + nickel martensitic matrix; trademark of Thyssen AG, Germany) were used as reference materials for comparison of the mechanical properties.

Table 3 Heat treating cycles for the processed materials

Material	Austenitizing	Subsequent treatment
Hot-work tool steel	1030 °C, 20 min, air cooling	540 °C, 1 h + 2 × (500 °C, 1 h)
HSS	1180 °C, 10 min, PAC(a)	3 × (550 °C, 2 h)
White iron	1160 °C, 1 h, air cooling	510 °C, 2 h
Mn steel	1100 °C, 1 h, PAC	...
Stellite 12	1230 °C, 1 h, air cooling	...

(a) PAC, Pressure air cooling.

2.2 *Processing*

The materials examined in the present study were processed using typical powder metallurgical routes and hot isostatic pressing (HIP) (Ref 8-11). Powder metallurgy is an attractive processing route for iron-base composites because a uniform reinforcement distribution can be achieved. Furthermore, deleterious interface processes (e.g., interdiffusion, chemical reactions) and extensive grain growth are avoided by using a solid-state procedure. Successful HIPing cycles (i.e., fully densified materials) were achieved with processing parameters 1180 °C temperature, 100 MPa pressure, and 3 h holding time. After processing, the materials were heat treated inside the HIPing capsule to avoid decarburization. The heat treating cycles for the composites were identical to those of the corresponding unreinforced alloys, which are summarized in Table 3.

2.3 *Materials Characterization and Testing*

The produced materials were characterized by means of optical microscopy (OM) and scanning electron microscopy (SEM). Because the purpose of the work was to develop wear-resistant parts, the abrasion wear resistance and the impact toughness of the examined materials were measured.

The three-body abrasion wear loss of the materials was measured with rubber wheel abrasion test equipment, based on the ASTM G 65-91 standard procedure. Details of the procedure are given in Fig. 1 and Ref 8. The Charpy impact energies were measured with a pendulum (noninstrumented) impact testing machine, a standard Losenhausenwerk tester (Dusseldorfer Maschinenbau AG, Germany). The samples used for testing measured $5 \times 10 \times 55$ mm^3 and were unnotched. Because the machining of the specimens was performed after heat treatment, some stresses were obviously introduced into the materials, and therefore the reported impact energy values should be taken as the lower limits for each formulation. The average of two to four measurements was taken as the impact energy of the material. Impact test measurements, instead of the more widely used fracture toughness tests for composite materials, were performed in order to measure the fracture resistance, because they are often more representative of the deformation rates in real applications where toughness is an important material parameter (Ref 9, 12).

3. Results

3.1 *Microstructures*

Figure 2 presents optical micrographs of the microstructure of conventional wear-resistant materials and of steel-matrix composites. As can be seen in Fig. 2(a) and (b), the microstructure of P/M high-speed steel and white iron consists of a high amount of fine (<10 μm) primary and secondary carbides in a martensitic matrix. The carbides in the high-speed steel are likely to be VC, WC, Mo_2C, and Cr_7C_3, while in white iron they are $(Fe,Cr)_7C_3$. Their hardness is up to 2500 HV and their volume fraction up to 26%. The presence of the carbides makes these materials extremely hard and wear resistant. Figure 2(c) shows the microstructure of a white iron/10 vol% TiC composite, where the ceramic reinforcements are present in addition to the matrix carbides. On the other hand, in the hot-work steel/Cr_3C_2 composite, no matrix carbides are visible and the microstructure consists of Cr_3C_2 micronetworks in a martensitic matrix (Fig. 2d). These micronetworks were created through diffusion processes between touching ceramic particles during HIPing (Ref 13), which resulted in particle coarsening.

3.2 *Mechanical Tests*

The results of the wear tests, hardness measurements (Rockwell C), and impact tests are summarized in Table 4. The effect of the matrix powder size on the abrasion wear loss of the hot-

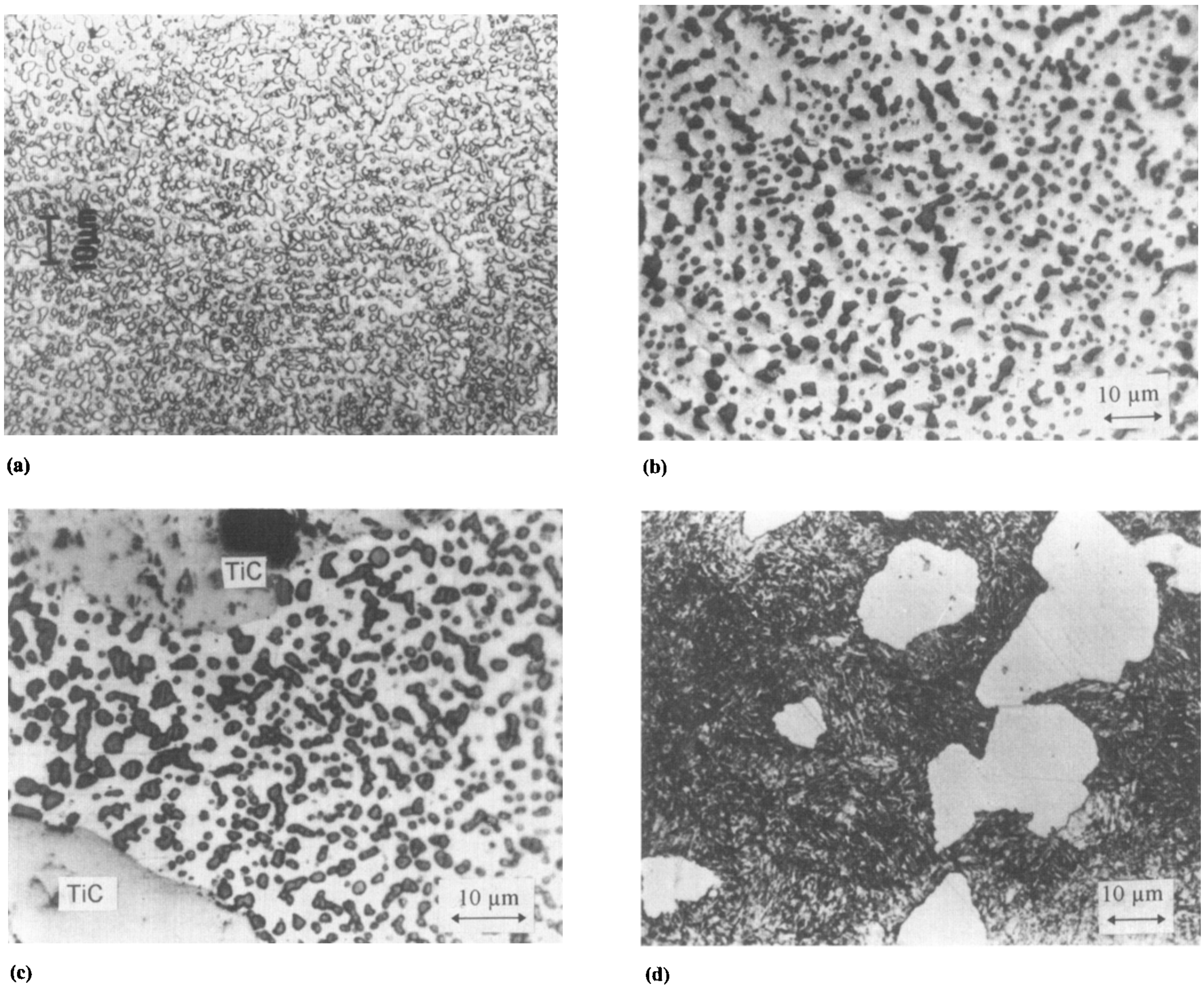


Fig. 2 Typical microstructures of P/M processed materials (OM). (a) High-speed steel, 2% nital etching. (b) White iron, NH_4OH electrolytic etching. (c) White iron/10 vol% TiC composite, NH_4OH electrolytic etching. (d) Hot-work steel/10 vol% Cr_3C_2 composite, Villela's reagent

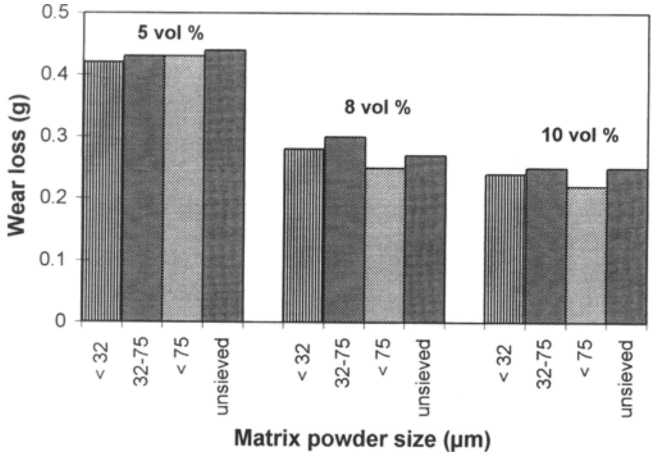


Fig. 3 Effect of the matrix powder size on the abrasion wear loss of hot-work steel/Cr_3C_2 composites containing 5, 8, and 10 vol% reinforcements

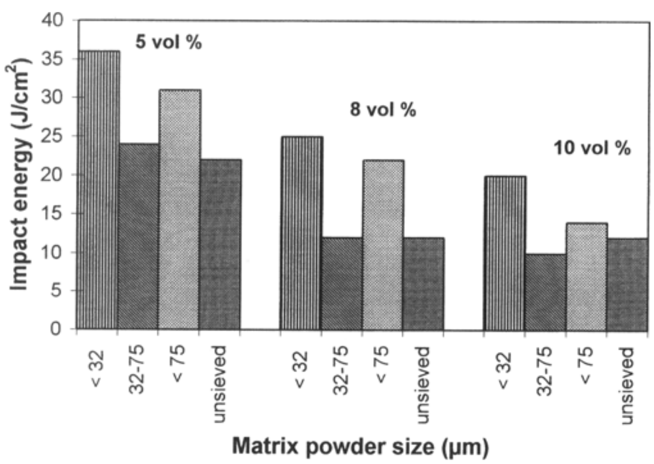


Fig. 4 Effect of the matrix powder size on the impact toughness of hot-work steel/Cr_3C_2 composites containing 5, 8, and 10 vol% reinforcements

work steel/Cr_3C_2 composites is shown in Fig. 3. It is seen that the matrix particle size does not significantly affect the wear resistance of P/M-processed composites, when the amount and type of reinforcements are held constant. The small deviations in wear losses are simply within the experimental error. These results demonstrate that the use of fine matrix powder during processing, with the associated cost-consuming sieving procedure, may not necessarily improve the wear properties of the composite. On the contrary, the matrix powder size has a great influence on the impact toughness of the composites (Fig. 4). Composites processed using fine powder possess the highest impact toughness for every reinforcement volume fraction. In addition, the composites with matrix powder size of less than 75 µm have good impact energy values, while the removal of the very fine matrix powder decreases the impact resistance.

The increasing reinforcement volume fraction increases the hardness and decreases the abrasion wear loss of the hot-work steel/Cr_3C_2 composites (Fig. 5). A 70% reduction in the wear loss and a 12% increase in the Rockwell C hardness of the base hot-work steel material is achieved after incorporating only 5

Table 4 Mechanical test results

Material	Wear loss, g	Hardness, HRC	Impact energy, J/cm²
11	0.42	62	36
12	0.28	64	25
13	0.24	64	20
21	0.43	62	24
22	0.30	61	12
23	0.25	63	10
31	0.43	62	31
32	0.25	63	22
33	0.22	63	14
41	0.44	61	22
42	0.27	61	12
43	0.25	62	12
Hot-work steel	1.46	55	145
Hot-work steel/20 vol% Cr_3C_2	0.14	66	9
Hot-work steel/30 vol% Cr_3C_2	0.06	68	7
HSS	0.69	62	22
HSS/10 vol% TiC	0.19	61	4
White iron	1.19	56	9
White iron/10 vol% TiC	0.16	59	7
White iron/10 vol% Cr_3C_2	0.11	57	4
Mn steel	1.35	35	Not fractured
Mn steel/10 vol% TiC	0.79	37	55
Stellite 12	1.29	51	29
Stellite 12/10 vol% Al_2O_3	0.78	53	11
Ferro-Titanit-Nikro 128	0.40	61	19
Cr-Mo white cast iron	0.18	62	2

vol% ceramic reinforcements. On the other hand, the impact toughness of the composites decreases with the increasing reinforcement volume fraction (Fig. 6). The decrease is more evident at the lower Cr_3C_2 contents and tends to taper off at higher contents.

The wear resistance of the newly developed hot-work steel/Cr_3C_2 composites and of the other examined materials is schematically illustrated in Fig. 7. The composite containing 10 vol% Cr_3C_2 has a similar weight loss in the abrasion wear test with the conventional chromium-molybdenum white cast iron, Ferro-Titanit, and the high-speed steel and white-iron-matrix composites. However, when the Cr_3C_2 content increases to 30 vol%, the performance of the hot-work steel/Cr_3C_2 composite in the abrasion-wear test is superior to that of the best-performing conventional wear-resistant material. In addition, it is interesting to observe the great reductions in wear loss of the composites compared to that of their unreinforced alloys. The reduction is more evident in the white iron and hot-work-steel-matrix composites.

The ratio of impact energy to abrasion wear loss of a material is in many cases more critical during the practical engineering design. Therefore, this ratio for the materials examined in the present study is presented in Fig. 8. In this figure, the superiority of the hot-work steel/30 vol% Cr_3C_2 composite compared to the other wear-resistant materials is evident.

3.3 *Scanning Electron Microscope Observations*

Figure 9 presents SEM micrographs of the worn surfaces of the Stellite 12 material and the hot-work steel/30 vol% Cr_3C_2

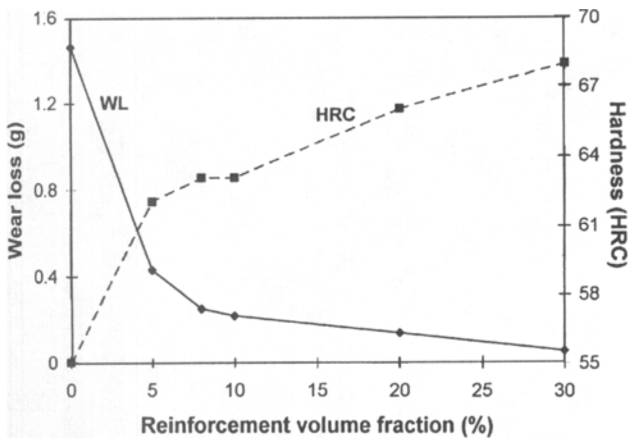


Fig. 5 Influence of the reinforcement volume fraction on the abrasion wear loss (WL) and hardness (HRC) of hot-work steel/Cr_3C_2 composites

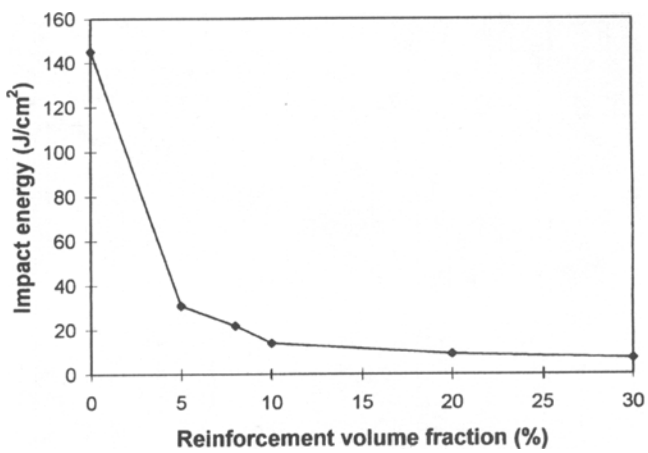


Fig. 6 Influence of the reinforcement volume fraction on the impact toughness of hot-work steel/Cr_3C_2 composites

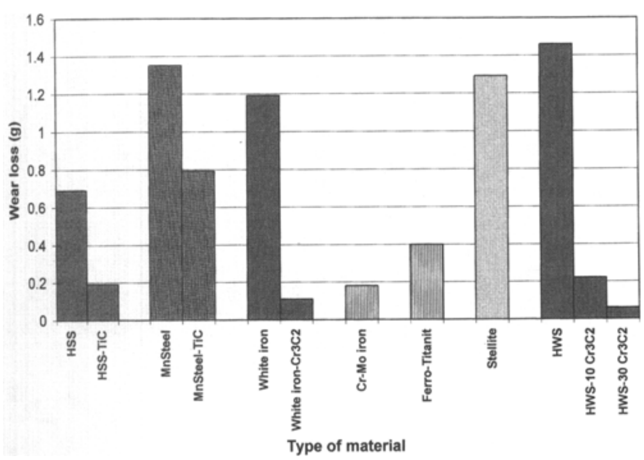


Fig. 7 Abrasion wear loss of examined wear-resistant materials and hot-work-steel (HWS) matrix composites

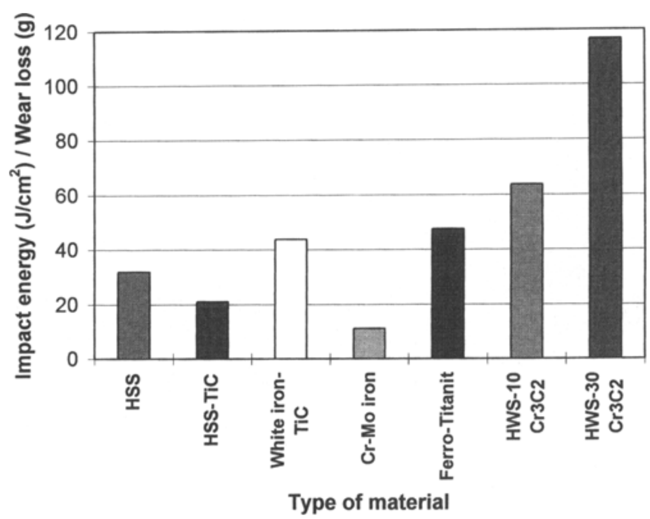


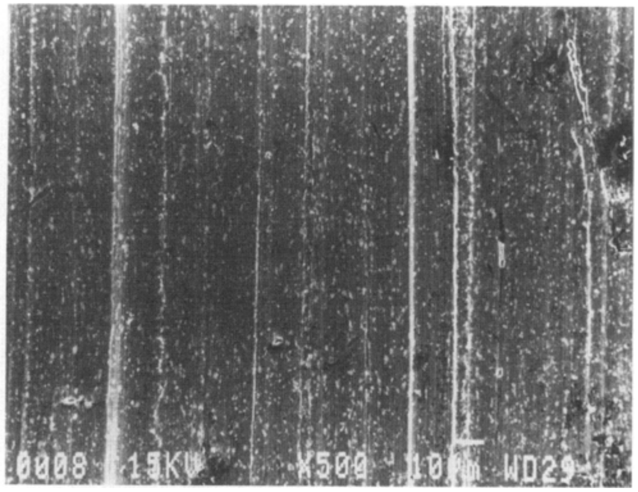
Fig. 8 Ratio of impact energy to abrasion wear loss for the new hot-work-steel (HWS) matrix composites and some conventional/commercial wear-resistant materials

composite. In Stellite 12, extensive grooving and cutting of the material by the quartz abrasives is observed (Fig. 9a), which caused a high wear weight loss. Examination of the worn surface of the hot-work steel/30 vol% Cr_3C_2 composite (Fig. 9b) revealed that the three-dimensional ceramic network remained on the surface after the wear test. This indicates a strong bonding with the matrix. No deep grooves created by the sliding action of the quartz abrasives were observed, and this is due to the small interparticle spacing of the composite. Therefore, the relatively large quartz particles were not able to penetrate the composite sufficiently because of their lower hardness compared to the Cr_3C_2 phase. Some grooving of the matrix should be attributed to sharp angles on the abrasive particles, which may have penetrated the softer martensitic matrix. On these grooves the mechanism of wear was changed from ploughing of the matrix to microfracture of the material that was removed to the sides.

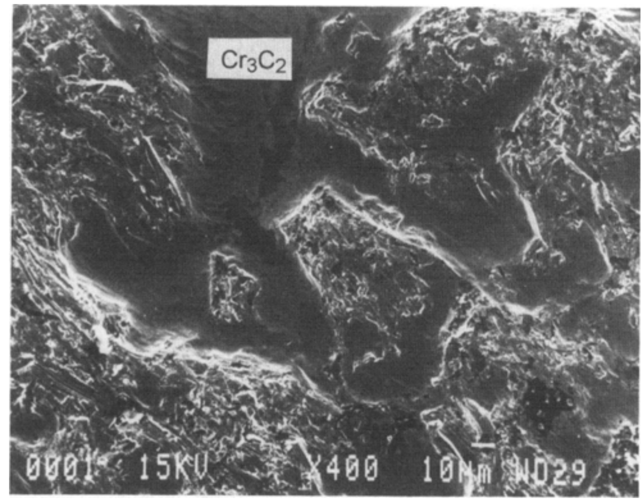
Examination of fracture surfaces demonstrated that a ductile fracture mode took place in Stellite 12, while in the hot-work steel/Cr_3C_2 composite the fracture mode revealed less ductility and more cleavage features (Fig. 10). The higher magnification fractographs (Fig. 10b and d) show that the dimples in Stellite 12 were larger than those in the composite. Furthermore, no matrix/reinforcement interfacial decohesion was observed in the composite (e.g., Fig. 10d) and the fracture path proceeded through the Cr_3C_2 particles.

4. Discussion

In the development of P/M particulate composites, the size of the metal and ceramic powders used during processing is of key importance. Particularly the size of the matrix powder influences to a great extent the reinforcement distribution as well as the interparticle spacing of the composite. However, this critical effect has not received attention until recently. In the present study, the influence of the matrix powder size on the composite performance has been considered.

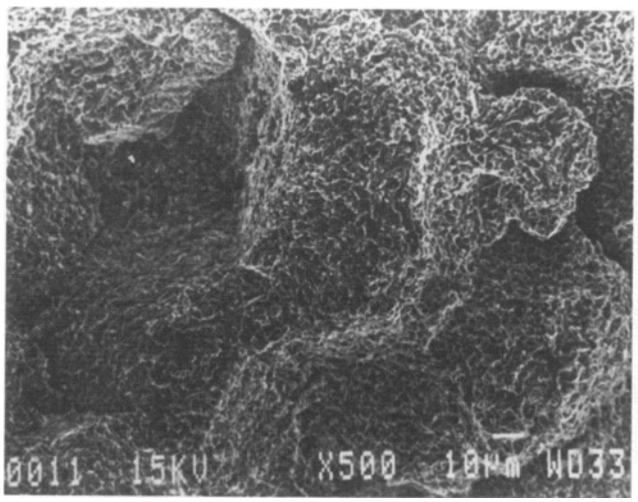


(a)

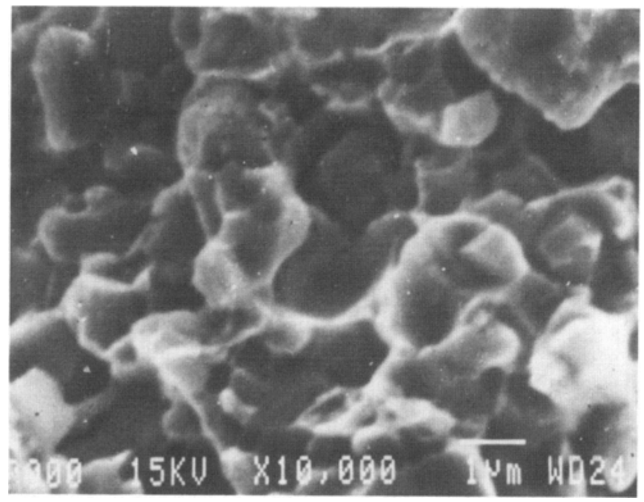


(b)

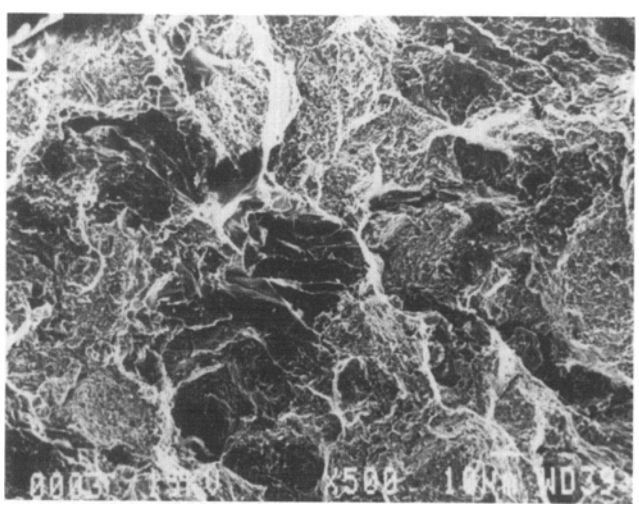
Fig. 9 SEM micrographs of the worn surface of (a) Stellite 12 and (b) hot-work steel/30 vol% Cr_3C_2 composite



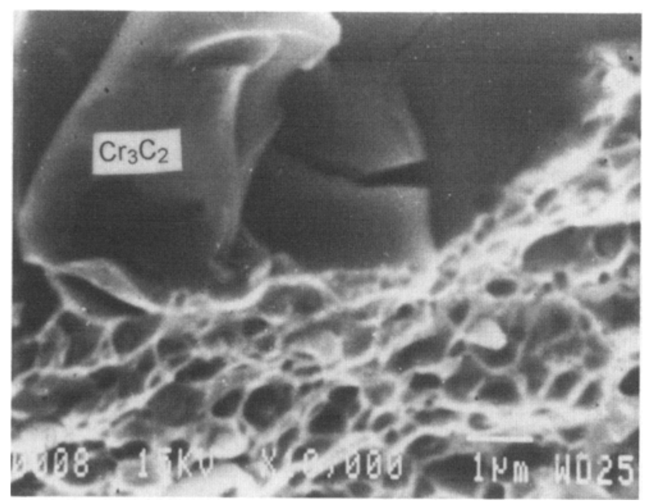
(a)



(b)



(c)



(d)

Fig. 10 SEM fractographs of impact specimens of (a) Stellite 12 (low magnification), (b) Stellite 12 (high magnification), (c) hot-work steel/Cr_3C_2 composite (low magnification), and (d) hot-work steel/Cr_3C_2 composite (high magnification)

In the hot-work steel/Cr_3C_2 composite it was found that the matrix powder size does not significantly affect the wear properties. Composites processed using unsieved (i.e., coarse) matrix powder possessed similar wear-resistance properties with composites processed using fine-sieved powders. Therefore, expensive and time-consuming sieving procedures are not necessary when the wear resistance of the composites is a concern. Furthermore, this result indicates that the reinforcement distribution is not a critical factor for the wear performance of iron-base composites. Similar results have been reported when the reinforcement powder size was varied while the matrix powder size was held constant (Ref 13). In that study, the uneven reinforcement distribution achieved using ultrafine ceramic powder did not result in the deterioration of the wear properties of the composite. On the other hand, the use of finer abrasive particles during the wear test, which can more easily penetrate the composite matrix, may alter the preceding conclusions.

The increasing reinforcement volume fraction increases significantly the hardness and wear resistance of the hot-work steel/Cr_3C_2 composites. It is interesting to observe in Fig. 5 that the abrasion wear loss of the composite decreases continuously even with 30 vol% ceramic reinforcements. This contrasts with the results reported for white iron/TiC composites (Ref 8), where a minimum in the wear loss occurred at 20 vol% reinforcements. In those composites the wear resistance increased until spalling of the reinforcements during the wear test started. It seems that the absence of a significant amount of in situ matrix carbides in the hot-work steel matrix (Fig. 2d) permits the addition of an increased reinforcement content without spalling occurring. Furthermore, the three-dimensional Cr_3C_2 micronetworks produced are better embedded within the composite matrix. On the other hand, the increase in the hardness of the hot-work-steel-matrix composite after incorporating a low amount of ceramic reinforcements (<10 vol%) is considerably higher than that reported for other iron-base composite systems (Ref 10, 14).

A dependence between the hardness and the abrasion wear loss of the composite was observed when the reinforcement volume fraction increased (Fig. 5). The wear loss decreased with the increasing hardness. Similar results have been reported for white iron/TiC composites (Ref 8) and chromium-molybdenum white cast irons (Ref 4), when the amount of hard phase (TiC and Cr_7C_3, respectively) increased. However, this observation cannot be generalized, and the hardness is, usually, not a suitable indicator of the abrasion wear resistance of multiphase or composite materials, as Fig. 11 demonstrates. Materials with similar hardness values possess significant differences in the wear loss, and vice versa. It seems therefore that factors such as the material microstructure (e.g., retained austenite, hardness of martensite), amount and type of second phases, internal stresses, and so forth, may have a more significant impact on the wear resistance than the overall hardness. Similar results have been reported for a white iron/10 vol% TiC composite, the microstructure of which was varied by different heat treatment procedures (Ref 9).

The impact toughness of the composite shows a great dependence on the matrix powder size (Fig. 4). It increases significantly when fine powder is used during composite processing. Obviously, the fine matrix powder results in better

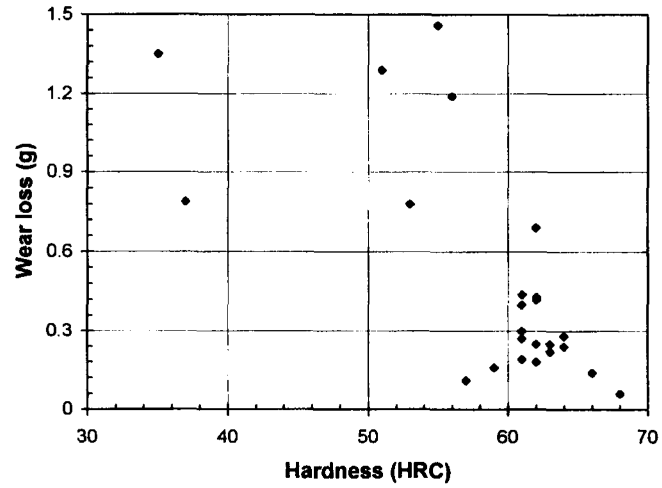


Fig. 11 Abrasion wear loss versus hardness for the materials examined in the present study (data taken from Table 4)

mixing with the ceramic particles and, therefore, in a more homogeneous reinforcement distribution. On the other hand, the use of coarse matrix powder causes severe agglomeration of the fine Cr_3C_2 particles, for example, at the junctions of coarse matrix particles (Ref 15). Reinforcement clusters reduce the impact resistance of the composites, because they serve as sites of high triaxial stresses owing to the elastic misfit between metal and ceramic (Ref 13, 16). Finally, the increasing reinforcement volume fraction decreases the impact toughness of the hot-work steel/Cr_3C_2 composites (Fig. 6). The decrease is more evident at the lower volume fractions, which is consistent with previous observations of aluminum matrix composites (Ref 17, 18).

Some of the most widely used wear-resistant alloys have been selected as reference materials for comparison with the newly developed hot-work steel/Cr_3C_2 composites. The high-speed steels have a high wear resistance because of the presence of MC and M_6C carbides (M = V, W, Mo, Cr, Fe) within the martensitic matrix. White iron, chromium-molybdenum white cast iron, and Stellite 12 contain mainly M_7C_3 carbides (M = Cr, Fe) while Ferro-Titanit contains TiC. Finally, the wear resistance of austenitic manganese steels originates from their exceptional work-hardening behavior (Ref 19). From the results presented in Fig. 7 it seems that the MC carbides in the high-speed steel, the coarse three-dimensional M_7C_3 carbide networks in the chromium-molybdenum cast iron, and the TiC in the Ferro-Titanit are effectively increasing the wear resistance. On the other hand, the fine $(Fe,Cr)_7C_3$ carbides in the P/M white iron as well as the Cr_7C_3 and W_6C carbides in Stellite 12 do not seem to protect the materials as effectively. This is because MC-type carbides show higher mechanical properties and better cohesion with the matrix (Ref 20).

However, great reductions in the wear losses are achieved by incorporating ceramic reinforcements in the iron alloys, which is consistent with the authors' previous work (Ref 8-10). The added ceramic particles seem to protect the materials more effectively than the in situ matrix carbides. As can be seen in Fig. 9, in the hot-work steel/30 vol% Cr_3C_2 composite the ceramic network remains on the surface and protects the matrix during the wear test. On the other hand, in Stellite 12 the Cr_7C_3

and W_6C carbides are easily pulled out by the sliding action of the quartz abrasives, and extensive cutting and grooving of the material results in high wear loss.

The newly developed hot-work steel/30 vol% Cr_3C_2 composite does not only possess excellent wear resistance but also an adequate impact strength. This is very important because wear-resistant parts are frequently operating in conditions where some toughness is also required. The limited ductility of this composite, indicated by the fine dimples observed on the fracture surface (Fig. 10d), as well as the good metal/ceramic interfacial bonding contribute to the increase of the fracture resistance. Therefore, the newly proposed wear-resistant composite possesses the best combination of properties in comparison to some of the most widely used hard materials (Fig. 8).

5. Conclusions

The development of wear-resistant iron-base composites for industrial applications has been the target of the present study. Based on the experimental results and discussion, the following conclusions can be drawn:

- Hot-work steel/Cr_3C_2 composites have been successfully produced using P/M techniques and HIPing. It was found that the matrix powder size used during processing does not affect the wear performance of the composite. However, the impact toughness increased significantly when fine powders were used.
- The hardness and wear resistance of the composite increase with the increasing reinforcement volume fraction. A 70% reduction in the wear loss and a 12% increase in the Rockwell C hardness of the base hot-work steel material is achieved after incorporating only 5 vol% ceramic reinforcements. On the other hand, the impact toughness decreases.
- The newly developed hot-work steel/30 vol% Cr_3C_2 composite possesses the lowest wear loss and the best combination of properties among some of the most abrasion-resistant materials available today.

Acknowledgment

The present work is part of a large national materials program funded by the Technology Development Centre of Finland (TEKES) and Finnish industry. The authors would like to acknowledge this support, as well as the assistance of Y. Ezer, O. Mattila, J. Hellman, and P. Korpiala.

References

1. J.H. Tylczak, Abrasive Wear, *Friction, Lubrication, and Technology,* Vol 18, *ASM Handbook,* ASM International, 1992, p 184-190
2. P. Ettmayer and W. Lengauer, The Story of Cermets, *Powder Metall. Int.,* Vol 21 (No. 2), 1989, p 37-38
3. G. Hoyle, *High Speed Steels,* Butterworths, 1988
4. K.-H. Zum Gahr and D.V. Doane, Optimizing Fracture Toughness and Abrasion Resistance in White Cast Irons, *Metall. Trans. A,* Vol 11, 1980, p 613-620
5. W. Stasko, K.E. Pinnow, and W.B. Eisen, Development of Ultra-High Vanadium Wear Resistant Cold Work Tool Steels, *Advances in Powder Metallurgy & Particulate Materials,* Vol 5, Part 17, Metal Powder Industries Federation, 1996, p 179-188
6. J.M. Panchal, T. Vela, and T. Robisch, Ferro-TiC Metal Matrix Composites for High Performance Tooling and Engineering Applications, *Fabrication of Particulates Reinforced Metal Composites,* J. Masounave and F.G. Hamel, Ed., ASM International, 1990, p 245-260
7. E. Pagounis, E. Haimi, J. Pietikäinen, M. Talvitie, S. Vahvaselkä, and V.K. Lindroos, Effect of Thermal Expansion Coefficients on the Martensitic Transformation in a Steel Matrix Composite, *Scr. Mater.,* Vol 34, 1996, p 407-413
8. E. Pagounis, M. Talvitie, and V.K. Lindroos, Influence of Reinforcement Volume Fraction and Size on the Microstructure and Abrasion Wear Resistance of Hot Isostatic Pressed White Iron Matrix Composites, *Metall. Mater. Trans. A,* Vol 27, 1996, p 4171-4181
9. E. Pagounis, M. Talvitie, and V.K. Lindroos, Influence of Matrix Structure on the Abrasion Wear Resistance and Toughness of a Hot Isostatic Pressed White Iron Matrix Composite, *Metall. Mater. Trans. A,* Vol 27, 1996, p 4183-4191
10. E. Pagounis, M. Talvitie, and V.K. Lindroos, Influence of the Metal/Ceramic Interface on the Microstructure and Mechanical Properties of HIPed Iron-Based Composites, *Compos. Sci. Technol.,* Vol 56, 1996, p 1329-1337
11. H. Seilstorfer, Application Fields of the HIP-Technology, *Powder Metall. Int.,* Vol 16, 1984, p 268-271
12. C.M. Friend, Toughness in Metal Matrix Composites, *Mater. Sci. Technol.,* Vol 5, 1989, p 1-7
13. E. Pagounis, M. Talvitie, and V.K. Lindroos, Microstructure and Mechanical Properties of Hot Work Tool Steel Matrix Composites Produced by Hot Isostatic Pressing, *Powder Metall.,* Vol 40, 1997, p 55-61
14. J.D. Bolton and M. Youseffi, Fracture Toughness of Sintered Metal Matrix Composites Based upon High Speed Steels Enriched with Hard Ceramic Carbides, *Powder Metall.,* Vol 36, 1993, p 142-152
15. E. Pagounis, M. Talvitie, and V.K. Lindroos, Consolidation Behavior of a Particle Reinforced Metal Matrix Composite during HIPing, *Mater. Res. Bull.,* Vol 31, 1996, p 1277-1285
16. H.M. Ledbetter and M.W. Austin, Internal Strain (Stress) in an SiC-Al Particle-Reinforced Composite: An X-Ray Diffraction Study, *Mater. Sci. Eng.,* Vol 89, 1987, p 53-61
17. W.H. Hunt, Jr., T.M. Osman, and J.J. Lewandowski, Micro- and Macrostructural Factors in DRA Fracture Resistance, *J. Met.,* Vol 45 (No. 1), 1993, p 30-35
18. Y. Flom and R.J. Arsenault, Effect of Particle Size on Fracture Toughness of SiC-Al Composite Material, *Acta Metall.,* Vol 37, 1989, p 2413-2423
19. A. Göcke, I. Schmidt, and M. Wilhelm, Gouging and Sliding Abrasion of Austenitic Manganese Steels Reinforced by Hard Phases, *Wear,* Vol 119, 1987, p 313-327
20. M. Vardavoulias, C. Jouanny-Tresy, and M. Jeandin, Sliding-Wear Behaviour of Ceramic Particle-Reinforced High Speed Steel Obtained by Powder Metallurgy, *Wear,* Vol 165, 1993, p 141-149