THE EROSION OF FUNCTIONALLY GRADED COATINGS UNDER FLUIDISED BED CONDITIONS

G. R. Heath[1] P.A. Kammer[1] M.M. Stack[2] and M. Rehberg[2]
[1]Eutectic+Castolin Group, Research & Technology Center, C.P.360, CH-1001 Lausanne, Switzerland.
[2]Corrosion and Protection Centre, UMIST, P.O. Box 88,Manchester,M60 1QD.UK

Abstract

Although there have been recent studies on the erosion and wear of bulk metal matrix composites, there has been little wear work on the related group of materials, functionally graded materials (FGMs), particularly as coatings. Because such materials provide a gradation in properties such as hardness and thermal expansion coefficient between the coating and the substrate, it is thought that they may have potential in aggressive environments such high temperature energy conversion processes (resisting spallation and erosion).

In a low velocity fluidized bed erosion, environment the effects of erodent particle size and bed temperature on the erosion rate through the section of a functionally graded coating was studied. The coating consisted of a varying fraction of WC particles (0- 42 vol. %) in a Ni-Cr-based self-fluxing matrix. The FGM coating was successfully developed via a new, low-cost industrial route based on flame spraying. The erodent particle size varied from 200 μm to 600μm, testing was at 25 °C and 600 °C, and the impact angle was 90°. The erosion rate was at a minimum at an intermediate vol. % WC and increases with increasing temperature.

1. INTRODUCTION

In elevated temperature erosion, high wastage rates of bulk, wrought alloys have been reported in many environments which include coal and oil conversion. In some cases, the formation of a protective oxide scale can inhibit erosion; in other cases, it can enhance it [1-2]. Control of the exposure conditions in order to favour the formation of a "protective" oxide can be difficult; in such cases, the use of a hard coating may be the only possible route to minimising erosion.

Coatings offer some potential in reducing erosion in such conditions because of the ability to combine hard particles with a matrix possessing good oxidation resistance. One problem is spalling due to differences in properties between substrate and coating (hardness, modulus, thermal expansion coefficient, etc.). Functionally Graded Materials (FGMs) offer an advantage in their gradient of properties, i.e. vol. % of hard particles. A material's erosion rate depends on a wide variety of parameters (properties of the particle, target, temperature and the environment, etc.). The effects of such parameters are not well understood for bulk composites or composite coatings and are more complex with a material which is gradually changing. In this case, as material is eroded, a new different microstructure continually presents itself to the erodent.

Since there is little literature available on the erosion of FGM materials, the results for the erosion and wear of related materials such as metal matrix composites (MMCs) can be reviewed. One of the most interesting results is concerned with the effect of particle size for different volume fractions of reinforcement fibre. The relative wear resistances of such materials was shown to be a maximum at intermediate volume fractions for alumina fibres in an aluminium matrix [3]. When the particle size was decreased from 60 μm to 20 μm, this maximum in the wear resistance was not observed. In this case, the wear rate decreased with increasing volume fraction of alumina fibres.

Although the results on the effect of temperature for Fe-Cr bulk, wrought alloys in erosion conditions have been well documented [1-2], for FGM materials and MMCs, these effects have not been widely investigated to date. The purpose of this study was to investigate the combined effects of erodent size, temperature and volume fraction of WC particles in an FGM coating on its erosion behaviour in low velocity, fluidised bed conditions.

2. EXPERIMENTAL DETAILS

2.1 Erosion Wear Apparatus

The erosion-corrosion apparatus, described elsewhere [1], consisted of a fluidised bed of erodent particles, a heating system and a specimen holder (cross piece on a rotating axle). The specimens and axle can rotate at a range of angular velocities vertically through the bed of particles.

There were three heating zones in the apparatus to ensure control of the incoming air to the bed, the bed/erodent itself and the chamber. During operation, air was pumped through a spiral line in the pre-heater, which subsequently flowed through and fluidised the particles before passing into the coolers and cyclones. The specimens were rectangular (thickness 4mm, width 6mm and length 10mm with the coating on the outer surface) and were secured flush to the surface of the cross piece to give an impact angle of 90° between the particles and the main coating face. The bed erodent was alumina (average particle diameters 200 μm and 600 μm). Due to degradation, the erodent was replaced at regular intervals. The experimental run was 20 hrs. and the velocity between the specimens and particles was 4 $m.s^{-1}$. Following the tests, the specimens were cooled to room temperature, degreased in acetone, and thickness loss measurements were made using a digital micrometer, with a precision of 1 μm.

2.2 Materials + Processing of FGMs

The FGM coating consisted of WC particles (150 μm average diameter) in a proprietary Ni-Cr-B-Si matrix. The coating was successfully developed in the E+C Research Center via the proprietary Eutalloy RW thermal spray technique, detailed elsewhere [4]. Prepared powders of matrix and WC were mixed in a range of differing ratios (0, 25, 50, 75 wt. % WC) and sprayed and fused as a series of layers. The fusion step has the unique advantage of providing good localised mixing at the layer interfaces. Fewer individual layers are required and gradation and interlayer bonding are excellent. In addition to the FGM coating, separate individual layers of composite where deposited with the following fixed vol. % WC (0, 9, 19, 34) which represented different position through the FGM layer cross-section. A Scanning Electron Micrograph (SEM) of the cross-section of the functionally graded coating is shown in (fig.1).

Fig. 1. Scanning Electron Micrograph of Functionally Graded Material Coating (WC particles in Ni-Cr-B-Si matrix).

Microhardness measurements (Hv_{10}) carried out through the cross-section of the FGM coating showed that the values varied between 540 and 1500 (table 2). The hardness of the alumina erodent was 1800.

Position in Layer vol. % WC	0	9	19	34
Hardness (Hv_{10})	540	860	1170	1500

Table 2. Hardness (Hv_{10}) throughout FGM layer vs position.

3. RESULTS

2.2 Effect of particle size and temperature on the erosion rate throughout FGM coating

The results for erosion with 200 μm diameter erodent (fig.3) showed that the erosion rate (thickness loss after 20 hrs) was at minimum at 9% vol.% WC grains. For the erosion with 600 μm diameter erodent there was a significant difference between the erosion rates of the matrix layer (0% WC) for the different erodent sizes.

The erosion rate was 300 % greater when exposed to the larger erodent. Surprisingly, there was little difference between the erosion rates for the two erodent sizes at 9% and 19% vol. % WC, but at the highest vol. % WC (34%) the trend reverted to that observed for the matrix material (0% WC), where the erosion rate was greater for the larger erodent sizes.

The effect of temperature was investigated using the 200 μm erodent, at 25°C and 550°C (fig.4).

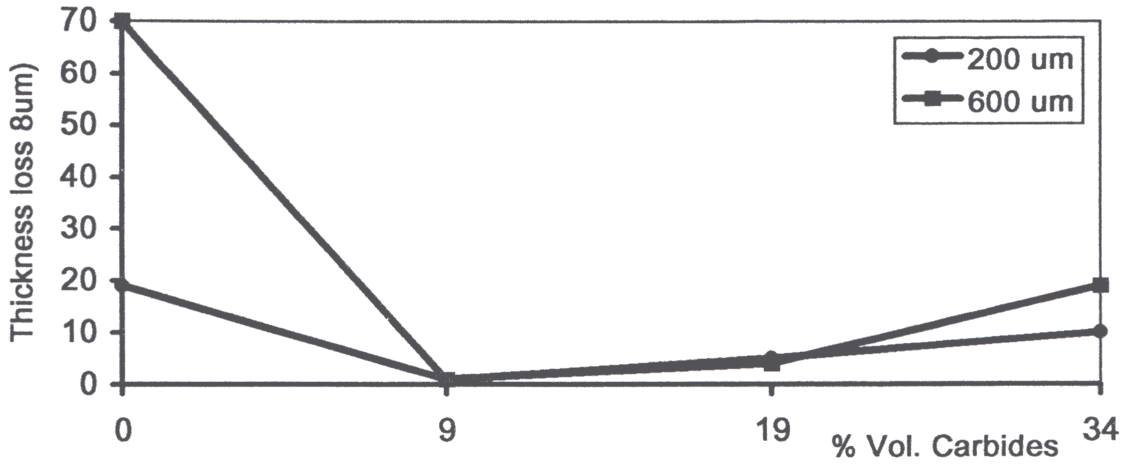

Fig. 3. Effect of particle size on the erosion rate for various vol. % WC at 25 °C.

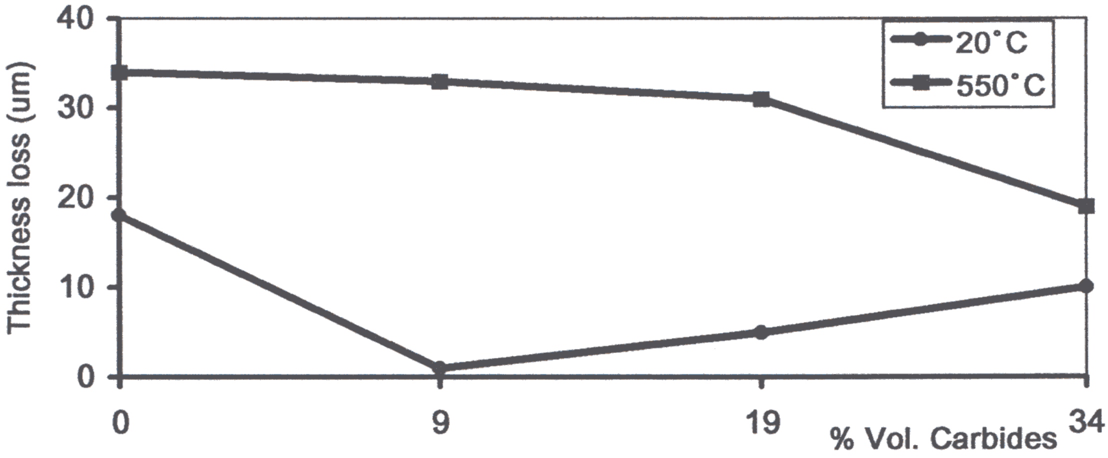

Fig. 4. Effect of temperature on the erosion rate for various vol. % WC for 200 μm erodent.

The results showed that the erosion rate at 550 °C was relatively independent of WC up to 9 vol. % WC, when it decreased with further increases in vol. % WC. Analysis of the results showed that the effect of temperature was more significant at intermediate vol. % WC. The effect of temperature was at a maximum at 9% WC content. Such results indicated that the increase in erosion rate with increasing temperature for the various layers was non uniform.

SEM of the eroded surfaces showed that there was little difference between the surface morphologies of the pure matrix material (0% WC) at 25°C and at 550°C after erosion with 200 μm erodent. However, once WC grains were present and exposed to the larger erodent at elevated temperatures, there was some evidence of chipping of the WC particles (9 vol. % WC). For the layers containing higher vol. % WC, there was evidence of deformation of the WC grains on the surface at the higher temperatures erosion with the 600 μm erodent.

4. DISCUSSION

The results have shown that the erosion rate with the two erodent sizes, 200 μm and 600 μm alumina, was at a minimum at intermediate vol. % WC within the FGM coating. Such results were not unexpected as a similar pattern had been observed for the erosion of metal matrix composites for a range of erodent sizes. In a recent study on the erosion of FGM materials in slurry environments [5], it was found that the material with the lowest vol. % WC grains (19%) exhibited the best erosion-corrosion performance. Other results on the slurry erosion of metal matrix composites [6] showed that the velocity dependence changed as a function of impact angle and vol. % reinforcement. However, the reasons for such behaviour are not well established. In addition, the clear difference for the effects of particle size for 0 and 34 vol. % WC compared with the insignificant differences at intermediate vol. % WC (9 and 19) were surprising.

The distinctive pattern of erosion resistance with increasing vol. % WC may be explained in terms of the combined effects of ratio of erodent to target hardness and the relative erosion resistance of brittle and ductile materials at normal impact. Fig. 5 shows the ratio of the erodent to target hardness as a function of vol. % WC content.

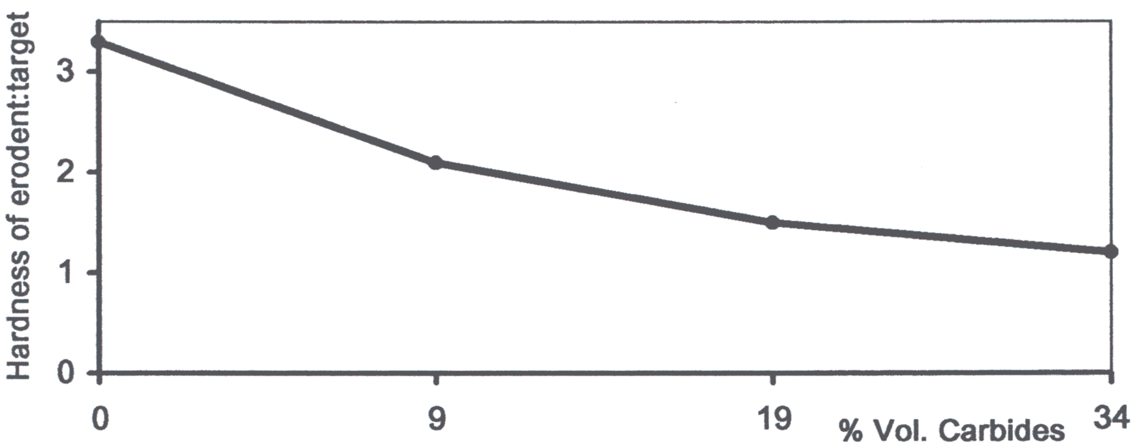

Fig. 5. Variation of erodent to target hardness ratio as a function of vol. % WC.

The ratio decreases from 3.3 to 1.4 as the vol. % WC increases from 0 to 34%. It is generally agreed that when the ratio of the erodent/target hardness is greater than 1.5, the erosion of the target is independent of the erodent hardness [7]. However, when the ratio is less than 1.5, the erosion rate becomes dependent on the erodent hardness, and when less than 1, the erodent rather than the target is eroded.

Such a decrease in erodent/target hardness ratio with increasing vol. % WC would suggest that the erosion rate would be relatively independent of erodent/target hardness ratio at low vol. % WC, and would commence to decrease as the erodent hardness approached that of the target. However, this decrease only occurs for the results above, as the vol. % WC varies from 9% to 19%. On the other hand, the erosion of brittle materials is observed to be a maximum and that of ductile materials, a minimum, at impact angles of 90° [8,9].

Although this relationship can reverse depending on the erosion conditions (i.e. particle shape [10], velocity [11], it is observed that for the erosion with angular particles, brittle materials exhibit highest erosion rates at 90° [8,10]). This would suggest that the erosion rate at 90° should show an increase with increased "brittleness" of the target, represented by increasing vol. % WC. Thus, on the basis of this alternative argument, we should see an increase in erosion rate with increasing vol. % WC. The fact that neither of the above explain the observed behaviour might suggest that the results are due to a combination of both phenomena (fig. 6): the effect of the erodent/target hardness ratio and the relationship between the erosion of ductile and brittle materials at 90°, with the former predominating at lower vol. % WC and the latter predominating at high vol. % WC.

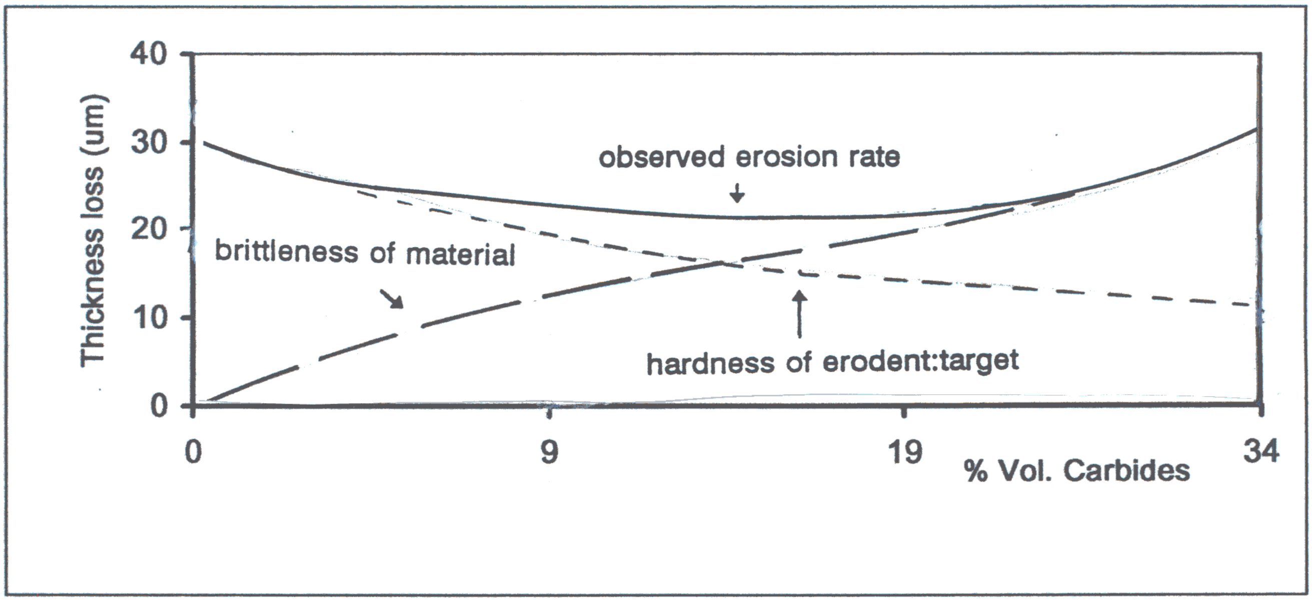

Fig. 6. Schematic diagram of the expected variation of erosion rate with vol. % WC based on the combined effects of reduction in erodent to target hardness ratio and the increase in the "brittleness" of the material as a function of increasing vol. % WC.

The increase in erosion rate with increasing erodent size in the layers containing the higher vol. % WC (19% and 34%) may be explained by these FGMs acting as brittle ceramics. It is well documented that erosion (mass loss per mass of impacting erodent particles) is relatively independent of erodent size (for erodents greater than 100 μm) for metals [12], but that this is not the case for ceramics [13].

The effect of temperature on the erosion of the various layers is significant, particularly at intermediate vol. % WC, (fig.4). Possible explanations can be related to erosion/temperature observations in bulk, wrought alloys where the erosion rate of

Fe-based alloys shows a maximum at intermediate temperatures [1,2] due to a mixture of oxidation and material softening effects. As WC is relatively stable in these respects, the matrix properties would dominate and explain why the temperature effect on the erosion should decrease as a function of increasing WC content. This behaviour may be analogous to that of reducing temperature in low velocity erosion-oxidation of bulk materials, where the erosion-oxidation rate is observed to be a maximum at intermediate temperatures. Further work needs to be carried out to clarify these trends.

An interesting result on the erosion of MMCs is the relationship between the contact area that a erodent particle makes with the surface and the spacing between the hard grains. When the erodent contact radius is significantly lower than the distance between the grains, the erosion response is considered to be heterogeneous [14]. When the contact radius is much larger than the distance between the grains, then the response is said to be homogenous. In the latter case, the beneficial effects of the reinforcement grains are though to be much less than in the former case, but obviously this should depend on the precise conditions. A recent study of the erosion of an aluminium-reinforced stainless steel composite illustrates this behaviour [14]. It was shown that there was little difference between the erosion rate of the reinforced and unreinforced material after erosion at different impact angles at 90° and 15°. However, when the erodent size was reduced by a factor of 10, to 37 μm, there was a significant difference between the erosion rate of the composite and the steel, particularly at the lower impact angles. In this study, the diameter of the aluminium rods was 500 μm and the distance between the rods was 200 μm.

5. CONCLUSIONS

- A new, low cost, industrial route for utilising FGM technology as a high-temperature, erosion-resistant coating has been successfully developed.

- Study of the low velocity ($4 m.s^{-1}$) fluidised bed erosion of functionally graded coatings (WC particles in a Ni-Cr-B-Si matrix) has identified a minimum erosion rate at intermediate volume fraction of WC in the coating.

- There was no direct relationship between erosion rate and erodent size for the various volume fractions of WC grains. At intermediate vol. %, WC size effects were negligible.

- The erosion rate was observed to increase with increasing temperature for each of the vol. % WC studied. However, the effect of temperature was at a maximum at intermediate vol. % WC.

- The distinctive effects of erodent size and environment temperature for the various volume fractions of WC grains were related to erodent/target hardness ratios, the relative difference between erosion rates of brittle and ductile materials at 90° and the effect of high temperature oxidation on the erosion resistance of WC and Ni-Cr alloys.

6. REFERENCES

[1] Ninham, A.J., Hutchings, I.M., and Little, J.A.,« paper 554 » *Proc. Conf. CORROSION '89, NACE, Houston*, 1989,

[2] Stack, M.M., Stott, F.H., and Wood, G.C. « p1128 » *Mat. Sci. Tech.,* 7 1991.

[3] Hutchings, I.M., and Wang, A., Proc. Int. Nat. Conf. New. Mat. and their App., Univ. Warwick, Pub. Instit. Phys. Conf.Ser. 111, (1990), 91-100.

[4] Szieslo, U. « Korrosions und Verschleissschutz durch Flammspritzen » *VDI-Berichte*, Nr. 506, 1984.

[5] Borjadal, E., Bardel, E., Rogne, T., Eggen, T.G. *8th Int. Conf. Erosion by Liquid and Solid Impact, 1994.* Pub. Wear, (1995-in press).

[6] Masounave, J., Turenne, S., LeDore, C. and Gagnon, G. « p1255-1266 » *Proc. Failure Analysis-Theory and Practice, ECF7*, Budapest, 1990.

[7] Hutchings, I.M., « p393-428 » *Proc. Conf. Corrosion-Erosion of Coal-Conversion Systems Maters.* Berkley, 1979.

[8] Heath, G.R., Johnson, T.D., Parry, M.T., Wall, D.J. «p17-21» *British Ceramics Transactions Journal.* 1989.

[9] Finnie, I., Wolak, J. and Kabil, Y.K. « p682-700 » *J. Materials Sci..*,2, 1967.

[10] Cousens, A.K. and Hutchings, I.M. « paper 41 » *Proc. 6th Int. Conf. Erosion by Liquid and Solid Impact*, Pub. Cavendish Lab., Univ. of Cambridge, 1983.

[11] Hutchings, I.M. « A212-A221 » *J. Phys. D: Appl. Phys.*, 25, 1992.

[12] Tilly G.P., and Sage, W. Wear, « p447 » 16, 1970.

[13] Sargent, G.A., Mehrotra, P.K. and Conrad, H. « 28 » *Proc. 5th Int. Conf. on Erosion by Liquid Impact.* 1979.

[14] Turenne, S., LeDore, C., and Masounave, J., *Wear Resistamce of Metals and Alloys,* ASM Int., 1988.

[15] Morrison, C.T., Routbort, J.L., Scattergood, R.O., and R. Warren, « p345-350 » *Wear*, 160, 1993.