COMPARISON OF CONTINUOUS AND PULSE LASER MODES USING A CO_2 LASER TO DEVELOP SURFACE MMCS IN TITANIUM ALLOYS

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SUMMARY: The formation of surface Ti/SiC and Ti//ZrC MMCs on a laser nitrided Ti-6Al-4V alloy using either a continuous or a pulse laser were investigated and compared. It was found that the microstructure, the MMC hardness profiles and the abrasive wear resistance of the MMC layer produced, were strongly influenced by the laser mode, as well as the beam power and the specimen velocity. The limitations of the pulse laser for the conditions explored and the advantages of the continuous laser, particularly in respect of the resultant abrasive wear resistance , are discussed.

KEYWORDS: surface nitrided-MMC, CO_2 laser, continuous and pulse modes, titanium alloy, melt profiles, hardness and wear resistance.

INTRODUCTION

The use of the titanium alloys for applications which require good wear resistance has been restricted, despite their attractive strength to weight ratios, due to their poor tribological properties. Laser processing of titanium alloys has been investigated extensively with the aim of improving the surface properties. The two important techniques used in this process are gaseous alloying, such as nitriding [1-7], and hard particle incorporation, such as formation of a surface MMC layer [8-10]. Previously, using a CW CO_2 CL5 laser, ceramic particles were successfully incorporated and produced high wear resistant MMC surfaces [9]. The surface hardness of a Ti/SiC surface MMC associated with nitriding reached Hv1200, and the abrasive wear resistance was over 20 times that of the base alloy [9].The formation of a surface MMC produced by a pulse laser has rarely been discussed in the literature. As low power pulse lasers are the most widely used lasers in industry and a pulse laser power offers a higher efficiency in terms of energy than a continuous laser [11], the investigation of the formation of a surface MMC associated with a low power pulse laser is important for a wider application of this technique. The present work compares continuous and pulse laser modes in the formation of an MMC layer on a titanium parent alloy using a CO_2 laser. The laser processing conditions were optimised for the specific pulse laser available for the present work, to produce a surface MMC on a nitrided Ti-6Al-4V alloy. The results were used to compare with those reported previously using a continuous laser [9]. The microstructures were analysed, the hardness and abrasive wear resistance determined.

EXPERIMENTAL WORK

A 1 kW pulse CO_2 laser at AEA Technology, Culham, UK was used for the processing. The beam on-time was set at 3 ms, the off-time , 1 ms and the average power of the beam 739 W. SiC (7μm) or ZrC (45μm) particles were used as the reinforcement in the surface of a Ti-6Al-4V alloy. 10 mm thick plates were prepared as the base alloy specimens. The hard particles were preplaced as a slurry on the surface of the specimens prior to the laser processing [9]. Pure argon, 20% N with 80% Ar or 40% N with 60% Ar were used as the environmental gases. The beam was stationary and the specimens moved on a worktable that was controllable using a programmed microcomputer. The specimen speed was 1.67 mms^{-1} to produce a laser track of 3 mm in width. 7 tracks were overlapped and the aim-at overlapping fraction was 50%.

The profiles of the MMC layer and the melt pool formed were examined using optical microscopy. The microhardness is given as a function of the distance below the surface, and the abrasive wear resistance was determined using a pin-on disc facility with a load of 4.9N,a disc velocity of $0.24ms^{-1}$.600 grit SiC paper was the abrasive and this was changed every 25m of testing [9] The surface roughness was measured using a Talysurf 5 System where the metre cut-off (0.8 mm) is the instrumental equivalent of the metrology sampling length.

RESULTS AND ANALYSIS

Microstructures

When a relatively low power laser is used, a small beam is required to provide a high energy density to produce a surface MMC of >0.5mm thickness on the titanium alloy. Therefore in the processing, the beam was initially set to the focal point ,to provide a sufficient power to melt the surface . A typical microstructure produced by the focused beam is shown in Fig.1. It can be seen that the small , high density energy source produced a melt pool that is deep but narrow at the centre and shallow in other regions of the melt pool. The whole melt pool looks like a combination of two melt pools: a deep melt that can be found in the laser keyhole welding process [11], and a parabolic shape of melt that can often be seen in laser surface processing [1-10]. A high tendency to porosity exists in the deep region of the melt pool and also to cracking, particularly in the region of intersection of the two melts and along the wall of the keyhole. This is due to the conditions of the high energy pulse beam used. In the processing, when the surface is melted by the beam and the temperature of the liquid reaches the boiling temperature of the liquid or higher, the vapour pressure build-up in the area will produce a cavity, and therefore the focussed energy of the beam will result in a deep penetration, which eventually develops a keyhole.The ceramic particles dissolved in the top region of the melt pool and their high concentration had a higher solidification temperature than other regions. Therefore the top region in the

melt pool would solidify before the lower part of the melt. This results in a high tendency to porosity in
the bottom of the keyhole due to the contraction of liquid without extra liquid filling into this region. A residual stress field that provoked a high cracking tendency in the top region and along the keyhole was also produced.

Normally, it is desirable to avoid the development of a keyhole melt pool during the formation of a surface MMC to ensure that it is pore and crack free. During the experiments, the laser system was reset and a defocused distance (DF) of 1, 2, 3 or
4 mm below the focus point was used for the processing.

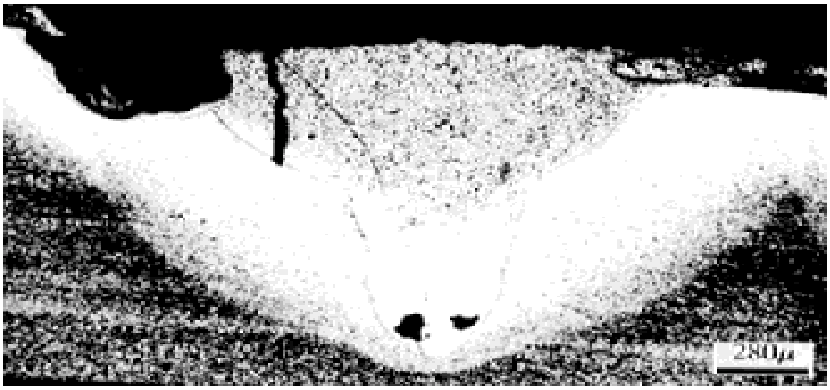


Fig.1 A micrograph from the hard particle (SiC) preplaced Ti64 specimen processed using a 739W pulse laser focus beam. The dark area at the top is mounting compound.

Fig.2 A micrograph of the specimen preplaced with SiC, pulse laser, 739W, stationary beam under a pure argon gas.

The beam with 4 mm DF did not produce a sufficient melt pool, and those with 1, 2 and 3 mm DFs, developed similar microstructures. The microstructures in the first few tracks produced by the beam with a 3 mm DF in the SiC preplaced specimen under Ar, 20%N and 40%N are shown in Figs.2, 3 and 4 respectively. It can be seen from these micrographs that the keyhole melt pool was still present, the cracking tendency reduced, but porosity still existed in the bottom of the keyholes. This, on the one hand, indicates that a keyhole must be avoided for a pore and crack free surface MMC. On the other hand, it is suggested that it is impossible to use the present 1kW CO_2 pulse laser to produce as high a quality surface MMCs on the Ti alloys as the 5kW continuous laser. Fig.5 shows the typical surface MMC layer produced by a 2.8kW continuous laser power. It is clear that the surface MMC layer in Fig.5 is uniformly thick, and porosity and crack free. Agglomerated SiC is seen at the extremities of the modified surface and within the melt pool.

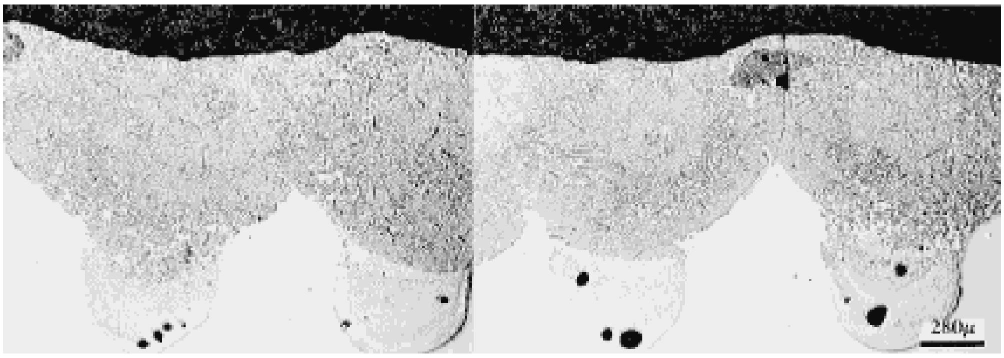


Fig.3 A micrograph of the specimen preplaced with SiC, pulse laser, 739W, stationary beam under a 20%N+80%Ar gas.

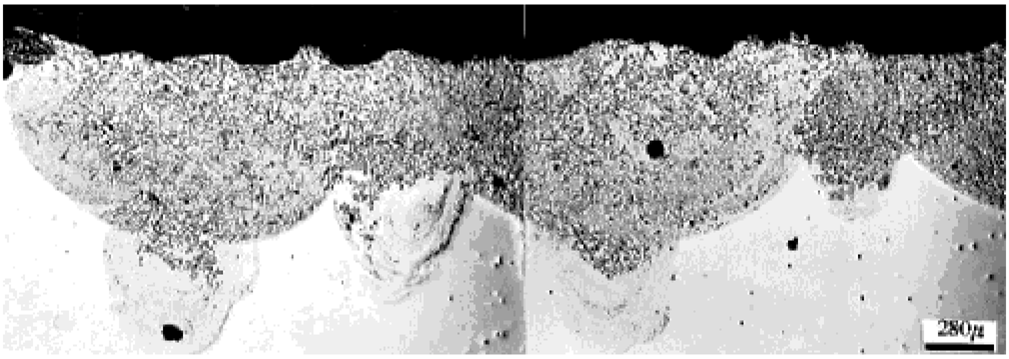


Fig.4 A micrograph of the specimen preplaced with SiC, pulse laser, 739W, stationary beam under a 40% N + 60% Ar gas.

This should be attributed to a different laser energy absorption for the specimen when a keyhole melt pool produced, compared with that without a keyhole. As reported by Ion, Shercliff and Ashby [12], the energy absorption for a laser melting or cladding process would be 0.3-0.5, depending upon the laser and the materials used in the process, but that for a keyhole welding process , the energy absorption could reach 0.8. The part of laser energy reflected in a keyhole has a much higher probability of being absorbed again than that from a flat surface. This is also supported by the observation that when a keyhole formed, the melt pool is much deeper as in Figs.2, 3 and 4 than that in Fig.5. Thus the specific laser and processing conditions used in the present work produced a large volume of liquid only when a keyhole was developed in the material due to the high energy absorption associated with the keyhole. When the keyhole did not occur, the energy developed was insufficient to melt the surface, which is essential for the formation of a surface MMC.

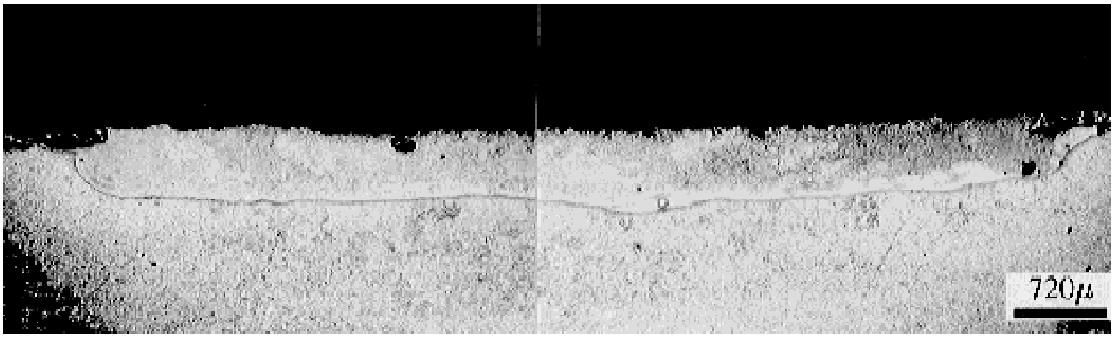


Fig.5 A micrograph of the specimen preplaced with SiC, continuous laser, 2.8 kW, spinning beam under a 40%N+60%Ar gas.

As it can be seen in Figs.2 to 4, a high nitrogen content in the environmental gas resulted in a deeper and larger melt pool. This is due to a higher laser energy absorption in nitrogen than in argon [11], and also to exothermic heat from the formation of titanium nitrides during nitriding [13]. This was also observed in the specimens preplaced with ZrC particles. Fig.6 shows a micrograph of the specimen preplaced with ZrC and processed under Ar, while Fig.7 shows the situation for the specimen processed under 20%N.

Higher magnification micrographs are shown in Figs.8 and 9 for the specimens preplaced with SiC and ZrC and processed under 20%N respectively. There are no visible, originally preplaced solid particles which are remaining in the MMC layer, but some dendritic structures. Unlike the nitride dendrites in a Ti nitriding process, which grow from the surface in a direction nearly perpendicular to the surface [1-7], the dendrites in Figs.8 and 9 showed no preferential directions. The SiC preplaced specimen showed more and longer dendrites in its surface than the ZrC specimen , which contains more isolated particles. These particles are unlike the original ZrC particles in the preplaced slurry ,that have a mesh size of 45μm.

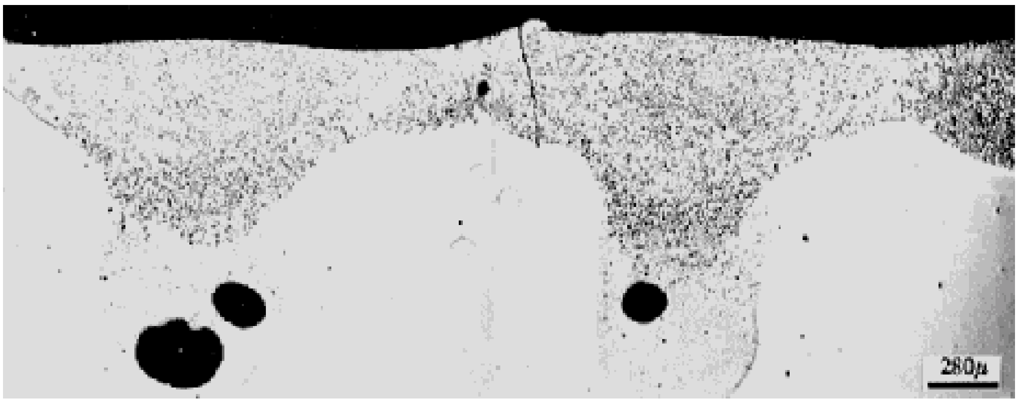


Fig.6 A micrograph from the specimen preplaced with ZrC, pulse laser, 739W, stationary beam under a pure argon gas.

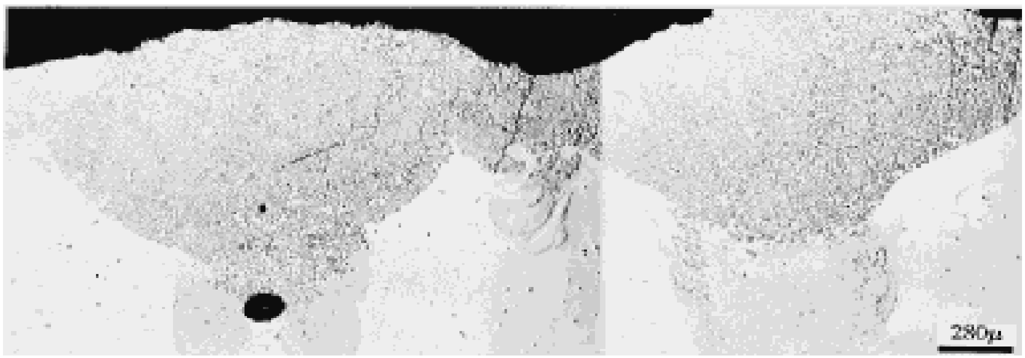


Fig.7 A micrograph from the specimen preplaced with ZrC, pulse laser, 739W, stationary beam under a 20%N+80%Ar gas.

Surface Roughness

As the aim of this project was to produce high wear resistant surfaces on real components, the surface roughness of the specimens processed by a laser is an important parameter. The specimens processed by a pulse laser in the present work showed much rougher surfaces than those produced by a continuous laser. The roughness was also found to be affected by the nitrogen concentration in the environmental gas. For example, the average roughness (Ra) value along the laser track was 154, 187 and 345 μm on the surface processed using a pulse laser under argon, 20%N+80%Ar and 40%N+60%Ar gases respectively, and that for the specimens processed using a continuous laser was 1.52 μm under Ar and 9.7 μm under 40%N+%60Ar. This is believed to result from the difference in the temperature fields due to the difference in the size and the energy intensity of the beams used. As the surface tension of most liquids has $d\sigma/dT < 0$, the liquid at a higher temperature is dragged towards the liquid that has a lower temperature, and therefore has a lower surface tension than that at a lower temperature ,to maintain the stress balance in the melt pool [14]. A small, but high energy beam produces a high temperature gradient in the liquid surface which resulted in a rough surface. This is why laser processing seems always to produce , to a greater or lesser extent , a rough surface. Thus, a nitrogen concentration in the environment may affect the roughness through increasing the value of $d\sigma/dT$ when $d\sigma/dT < 0$.

Microhardness

The average values of three measurements from different tracks in the same cross section were used to assess the hardness. The hardness profiles, as a function of the distance below the surface, are shown in Fig.10. It can be seen that in general, for the same the processing conditions with identical preplaced particles, those specimens processed using a higher nitrogen concentration produce a higher hardness, and the specimens preplaced with SiCp have a higher hardness than those with ZrC ,. This result is in agreement with our previous work using a continuous laser [9], where the

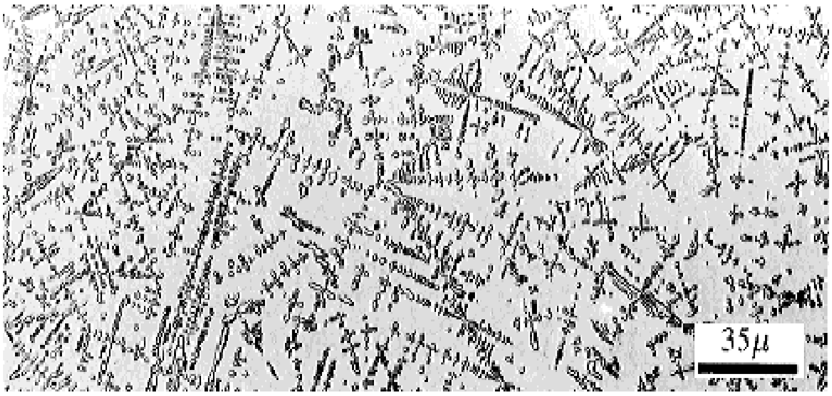


Fig.8 A higher magnification micrograph obtained of the specimen preplaced with SiC, pulse laser, 739W, stationary beam under a 20%N+80%Ar gas.

Fig.9 A higher magnification micrograph of the specimen preplaced with ZrC, pulse laser, 739W, stationary beam under a 20%N+80%Ar gas.

specimen preplaced with SiCp showed the highest hardness among those preplaced with SiCp, SiCp+Ti64p, ZrCp or ZrNp all using a 40%N gas, Fig.11. Both Figs.10 and 11 show that the hardness in the MMC layer is fairly uniform although it gradually decreases with the distance below the surface, except the specimen preplaced with SiCp processed by a continuous laser, whose hardness in the top region of the MMC layer is very high and drops sharply with an increase in the distance below the surface. The reason for this is still not clear. The hardness values for both the pulse and the continuous laser are located in a similar range (500 to 700 HV).

A higher hardness in the SiC specimens than that in the ZrC specimens is consistent with the microstructures discussed before. The SiC specimens contain a larger volume of dendritic particles in the MMC layer and it is believed to be the dendritic phase that made a great contribution to the hardness. As the above specimens were processed under a nitrogen environment, the compounds formed in these specimens are more complex.

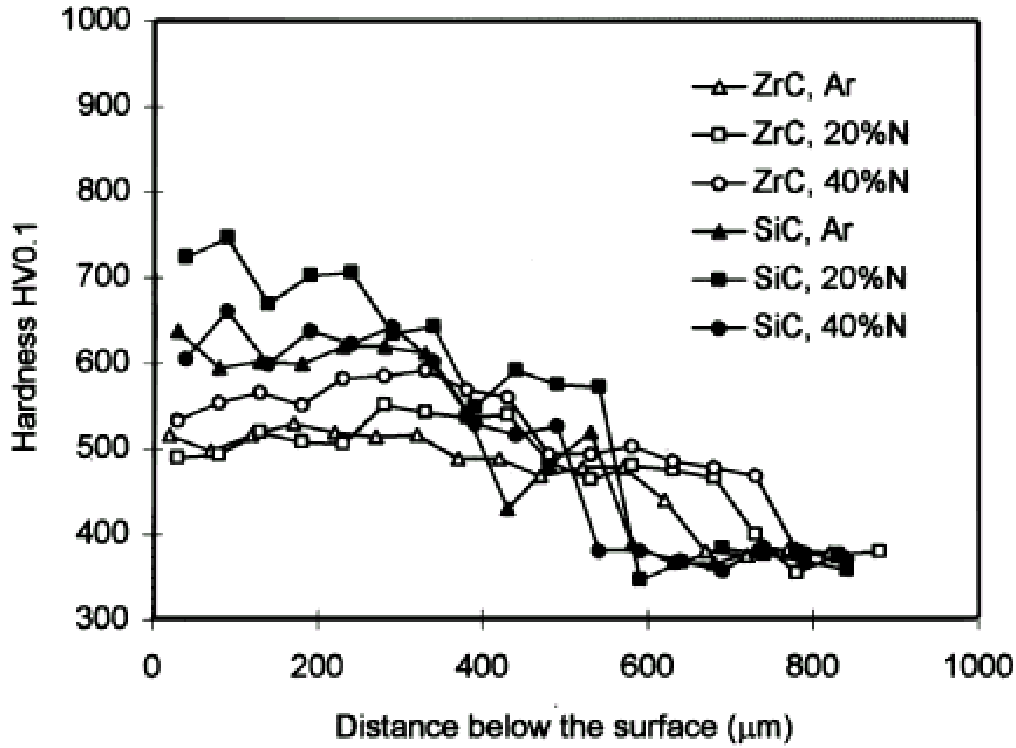


Fig.10 The hardness as a function of the distance below the surface in the specimens preplaced with particles and processed using a pulse laser.

Abrasive Wear Resistance

This was determined in an identical manner to that described previously [9,15].Fig12 compares the data from continuous CO_2 laser nitrided specimens (S) [15] and the preplaced plus 40%N (S) [9] ,with data from the corresponding pulsed laser nitrided specimens (P)discussed above, together with an untreated specimen. In the current work, testing has been extended beyond 2 Km. From Fig12, it is apparent that all the nitrided specimens have superior abrasive wear resistance to the untreated specimen, that the ZrC+ 40%N is independent of the laser mode and that SiC+40%N processed using a continuous laser has an excellent resistance. Fig 11 shows that this
treatment produced a high surface hardness, but without the cracking invariably present with nitrogen concentrations of 80% or greater, which are necessary to give this level of hardness, in the absence of SiC incorporation. Porosity at the base of the melt pool, has no apparent adverse effect on the abrasive wear resistance.

CONCLUSIONS

1- Using a CO_2 laser in the pulse mode to generate 739W beam power, processing Ti-6Al-4V alloy using preplaced powder of 45µm average size particles of Zr and SiC with Ar, 20%N+80%Ar or 40%N+60% Ar produced a keyhole melt pool for the range of focal lengths,1 to 4 mm, used in this work.
2- Microstructural observations showed that the modified surfaces contained pores and cracks , with rough surfaces being created.
3- It is apparent that all the nitrided specimens have superior abrasive wear resistance to the untreated specimen, that the 40%N+ ZrC is independent of laser mode and that SiC+40%N processed using a continuous CO_2 laser has an excellent resistance.

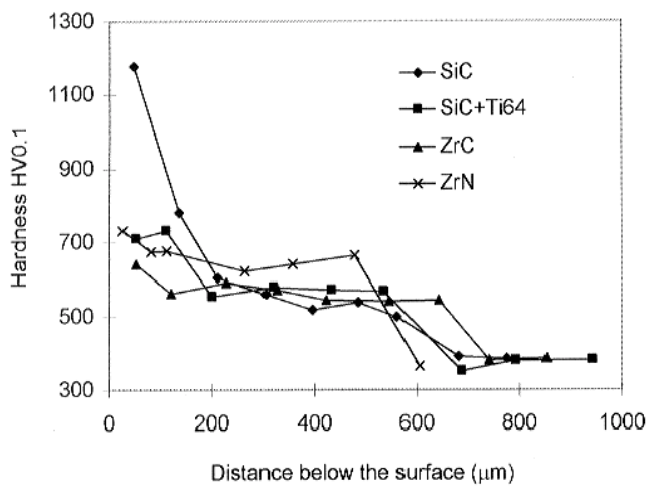
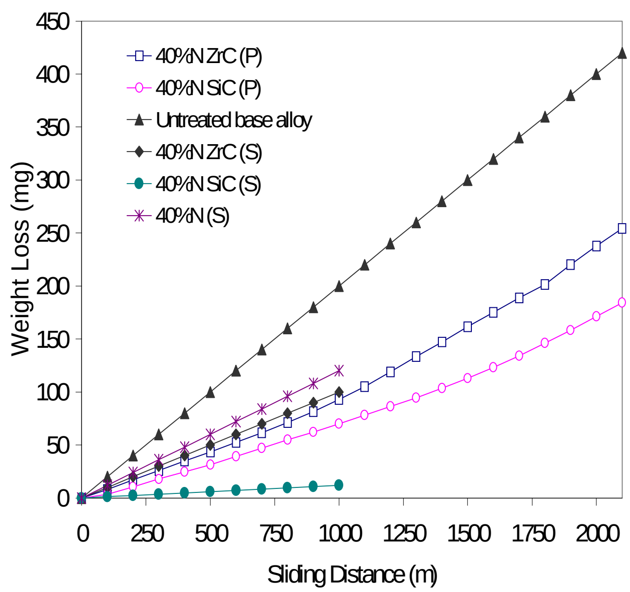


Fig.11 The hardness as a function of the distance below the surface in the specimens preplaced particles and processed with a continuous laser.

Fig 12. Abrasive wear resistance of pulse (P) and continuous (S) CO_2 laser nitrided Ti-6Al4V



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REFERENCES

1. A. Walker, J. Folkes, W. M. Steen and D. R. F. West, J. Surf. Eng., 1985, **1**, 23-29.

2. T. Bell, H. W. Bergmann, J. Lanagan, P. H. Morton and A. M. Staines, J. Surf. Eng. 1986, **2**, 133-143.

3. P. H. Morton, T. Bell, A. Weisheit, J. Kroll, B. L. Mordike and K. Sagoo, Surface Modification Technologies 5, T. S. Sudarshan, and J. F. Braza, The Institute of Materials, 1992, 593-609.

4. S. Mridha and T. N. Baker, Proc. Ad. Mater., 1994, **4**, 85-94.

5. S. Mridha and T. N. Baker, Mater. Sci. Eng., 1994, **A188**, 229-239.

6. A. B. Kloosterman and J. Th. M. De. Hosson, Scripta Metallurgica et Materialia, 1995, **33**, 567-573.

7. C. Hu, S. Mridha, H. S. Ubhi, A. W. Bowen and T. N. Baker, ‘Titanium ‘95: Science and the Technology’, P.A. Blenkinsop, W. J. Evans, and H. M. Flower, The Institute of Materials, London, UK, 1996, **3**, 2835-2842.

8. S. Mridha and T. N. Baker, Mat. Sci. Tech., 1996, **12**, 595-602.

9. C. Hu, H. Xin and T. N. Baker, Proc. 11-ICCM,: Metal Matrix Composites and Physical Properties. 1997, **III**, 80-89.

10. C. Hu, M. S. B. Selamat, H. S. Ubhi and T. N. Baker, Mater. Sci. Tech., 1998, **14**, 1045-1052.

11. W. H. Cubberly et al (eds), Metals Handbook (9th edition), ASM, Metals Park, OH, 1983, vol.6, pp. 659-660.

12. J. C. Ion, H. R. Shercliff and M. F. Ashby, Acta Metall. 1991, vol.40, 7, pp.1539-1551.

13. C. Hu and T. N. Baker , Mat. Sci. Eng. A.,!999, In The Press.

14. T. R. Anthony and H. E. Cline, J. Appl. Phy., 1977, **48** (9), pp.3888-3894.

15 C.Hu,H.Xin and T.N.Baker, *‘Titanium ‘95: Science and the Technology’*, P.A. Blenkinsop, W. J. Evans, and H. M. Flower, The Institute of Materials, London, UK, 1996, **3**, 99-104.