Investigation of abrasive + erosive wear behaviour of surface hardening methods applied to AISI 1050 steel

N.Y. Sari a,*, M. Yilmaz b

a Department of Mechanical Engineering, Kocaeli University, 41040 Kocaeli, Turkey
b Department of Metallurgy and Materials Engineering, Kocaeli University, 41040 Kocaeli, Turkey

Received 24 May 2004; accepted 16 November 2004
Available online 25 December 2005

Abstract

In the present technology, machine parts which work at the industry area such as agriculture, mining and cement are subjected to wear. The wear resistance of these parts is improved by conventional heat treatments or surface heat treatments, which only improved the property surface and sub-surface of materials.

In this study, samples of AISI 1050 steel are subjected to induction hardening and thermochemical treatments such as boronising, nitriding and thermal spraying which involves flame spraying, flame spraying plus melting, high velocity oxyfuel (HVOF) plus melting apart from the conventional heat treatment, which is oil quenching.

At the end of wear tests, it is observed that the amount of wear in base metal decreased with the oil quenching but on the contrary to that the wear resistance was not improved with induction hardening and the other thermochemical surface treatments.

However, the amount of wear in base metal was significantly decreased with thermal spraying methods. Even the additionally applied remelting treatment after spraying reduced to more smaller amounts. So, the applied remelting treatment after spraying plays much more important role in reducing wear. At wear surfaces of thermal spraying samples, the regional surface damages with slight traces of abrasive wear are seen.

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Keywords: Abrasive wear; Erosive wear; Plasma nitriding; Thermal spraying; Flame spraying; High velocity oxyfuel (HVOF)

1. Introduction

Friction and wear behaviour of materials largely depend upon surface material, mechanical properties, physical structure and chemical composition of surfaces and surface topographies. Thermo-chemical and thermo-mechanical processes are heavily used for increasing the abrasive wear resistance of materials [1–3]. When comparing these two groups of methods, particularly in thermo-mechanical processes, the coating material selected as well as the process parameters must be considered as an important factor. Therefore, when comparing these two methods, the main criteria shall be the chemical composition of the surface layer and the surface adhesion of this layer. These two main criteria usually determine the wear conditions in which these methods can be preferred. For example, impact load and heavy load conditions restrict the use of thermo-mechanical processes. Although many methods may be selected in thermo-chemical surface treatments, we see that in this group plasma nitriding method is used extensively and gives very good results [4–6]. In these applications, the best process parameters must be determined in advance [6].

Coating material is naturally the most important parameter in thermo-mechanical processes, which are
used to improve the abrasive wear properties of the surface [7–10]. Both ceramic [7,10] and metal ceramic composites can be used as coating materials [8,9]. These coatings are usually powder blends made of different materials and the component ratios in this blend are highly important [7–10]. For example, in a research by Niemi et al. [7], wear resistance of ceramic coatings such as Al$_2$O$_3$, Al$_2$O$_3$ + 3% TiO$_2$, Al$_2$O$_3$ + 40% TiO$_2$, TiO$_2$ and Al$_2$O$_3$ + 40% ZrO$_2$ was produced using methods of atmospheric plasma spraying and detenation gun spraying over a low carbon steel material has been tested by dry sand rubber wheel test and particle erosion test and it was found that wear resistance of coatings made by both methods improved by adding a small amount (3%) of TiO$_2$ and reduced by adding 40% TiO$_2$.

Success of thermo-mechanical methods against abrasive resistance depends on method parameters and, if powder material has been used, on powder properties. In a research by Vuoristo et al. [11], WC and Cr$_7$C$_2$ powders were used to test the abrasive wear resistance of coatings made by detenation gun spraying and it was found that coatings made by powder containing small carbide size had the highest wear resistance when a proper gas composition was used. Also, a study by Dallaire, Legoux and Levert [8] investigated the abrasive wear resistance of AISI 304 stainless steel coatings and stainless steel coatings containing TiB$_2$ particles using electric arc spraying method, where argon or air was used as atomised gas and wear resistance of coatings was found to be 2–4 times more than stainless steel matrix depending on the quantity, size and hardness of sprayed particles.

In the published literature, there are limited data dealing with the abrasive plus erosive wear characteristics of powder sprayed coatings and thermo-chemical treatments. This study presents the results of abrasive plus erosive wear test carried out on powder sprayed coatings and thermo-chemical treatments.

2. Experimental procedures

The material used in the experiments is AISI 1050 and its chemical composition is given in Table 1. The wear area of test samples is the part with 7 mm diameter and 30 mm length.

Test materials were subjected to improvement treatment as well as surface treatments such as induction hardening, plasma nitriding, boronising, and thermal spraying. During application of surface treatment, method types and process parameters were taken as variables. Treatments applied to test material and process characteristics are given in Table 2. For coating with flame spraying, a Metco Thermo Spray Type 5P-II was used. Operating parameters of flame spraying are defined as spraying distance: 150 mm; spraying rate: 20 lb/h; flow rates of oxygen: 34 psi; flow rates of acetylene: 34 psi. For coating with high velocity oxyfuel (HVOF) spraying, a JP-500 HP/HVOF was used. Operating parameters of HVOF are defined as spraying distance: 350 mm; spraying rate: 13 lb/h; nozzle length: 200 mm; flow rates of oxygen: 140 psi; flow rates of nitrogen: 50 psi; combustion pressure: 130 psi; fuel: kerosene.

The test samples were subjected to wear tests in the abrasive wear test equipment as can be seen in Fig. 1. Wear test equipment was designed in order to simulate wear situation in mining and earthmoving equipments. Test installation includes a container which is filled with flint stone, as abrasive particle, having a Knoop hardness value of 820. Abrasive particles were crushed with jaw crusher before being used in tests and their grain size distribution was determined using sieve analysis. Particles used in tests have an average diameter of 7.370 ± 5.645 mm. Sample used in the test equipment, abrasive particles and the atmosphere are the base components of the tribological system. There is no interfacial element in the tribological system because of the loss of wear debris in abrasive particles and no moisture except atmosphere. So, the system is in the state of dry friction. At the wear test machine, which has a rotating and mixturing working principle, the samples fixtured to the centre of planet gears were rotated around either shaft and its own axis in abrasive particles. So, all surfaces of samples were subjected to wear with this motion principle. On the other hand, the test periods were decreased by increasing the friction way. The fixturing position of the samples to the planet gear system and the motion orbits of the samples are seen in Figs. 1 and 2, respectively.

Wear rates of the samples which revolve around themselves and around the main shaft among the abrasive particles in the container were determined using weight loss. Before testing, samples were dried by cleaning in alcohol in an ultrasonic cleaner and weighed using Shimadzu-Libror EB-330H electronic scale with 330 g
capacity and 0.1 mg precision. Before samples were weighed at the end of a certain period of wear test to determine the weight loss, they were cleaned for 10 min in alcohol in ultrasonic cleaner so that they were freed of all abrasive particles or other foreign substances such as dust, dirt, etc.

Wear period of each sample was determined as 10 h. Weight loss measurements were done at 1 h intervals. During wear tests, process parameters such as size and type of abrasive particles, speed of samples and depth of samples within the abrasive particles have been selected constant for each sample. Operating parameters are defined as specimen velocity: 1.35 m/s; shaft revolution in wear test machine: 150 rpm; total distance travelled by every specimen at the end of 10 h: 5.364 km; working depth: 55 mm. Totally, 40 h is needed to wear the four specimens for a period of 10 h where only one treatment has been applied. Since it is possible to wear two specimens at the same time in the wear test machine, the operating period is halved, thereby saving time. Abrasive particles have been replaced after periods of 40 h in consideration of the fact that their abrasive capability reduces due to the interaction among themselves.

Table 2
Properties of the treatments that have been applied to test materials

<table>
<thead>
<tr>
<th>Method</th>
<th>Type of method</th>
<th>Test code</th>
<th>Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>No treatment</td>
<td>–</td>
<td>N</td>
<td>It is the base metal and is not treated</td>
</tr>
<tr>
<td>Oil quenching</td>
<td>–</td>
<td>OQ</td>
<td>Heating for 30 min at 850 °C and quenching in oil</td>
</tr>
<tr>
<td>Induction hardening</td>
<td>–</td>
<td>IH</td>
<td>Induction hardening</td>
</tr>
<tr>
<td>Boronising</td>
<td>–</td>
<td>B</td>
<td>Boronising for 6 h at 950 °C in solid B, in electrical resistance furnace</td>
</tr>
<tr>
<td>Nitriding</td>
<td>Salt bath nitriding</td>
<td>SBN</td>
<td>Nitriding for 3.5 h at 565 ± 5 °C in 35% CNO, 0.89–1% CN, 15–7% CO</td>
</tr>
<tr>
<td></td>
<td>Gas nitriding</td>
<td>GN6, GN12</td>
<td>Gas nitriding for 6–12 h at 540 °C in 50% NH₃–50% N₂</td>
</tr>
<tr>
<td></td>
<td>Plasma nitriding</td>
<td>IN1/2, IN1, IN4</td>
<td>Ion nitriding for 1/2, 1 and 4 h at 500 °C in 70% H₂–30% N₂</td>
</tr>
<tr>
<td></td>
<td>Plasma nitriding</td>
<td>IN12, IN24 IN48</td>
<td>Ion nitriding for 12, 24 and 48 h at 480 °C in NH₃ and cooling under vacuum</td>
</tr>
<tr>
<td>Thermal spraying</td>
<td>Flame spraying</td>
<td>FS1, FS2</td>
<td>Coating with Ni–Cr–B–Si and WC–Ni–Cr–B–Si based powder</td>
</tr>
<tr>
<td></td>
<td>Flame spraying + melting</td>
<td>FSM</td>
<td>Coating with Cr–Ni–B–Si-based powder</td>
</tr>
<tr>
<td></td>
<td>HVOF + melting</td>
<td>HVOF12, HVOF24</td>
<td>Coating with 35% WC + 65% (Cr–Ni–B–Si) based powder</td>
</tr>
</tbody>
</table>

Fig. 1. Abrasive wear test equipment.
Cross-section of samples has been metallographically prepared in order to determine the microstructure that exists in the test samples, which have been subjected to various methods and to do hardness scanning from the outer surface to the centre at the end of surface treatments. After such preparation, the samples have first been examined under optic microscope. Hardness measurements of all samples have been done using Zwick make Vickers microhardness equipment. In order to ensure low thickness of the white layer that forms during surface treatments like nitriding and to precisely scan the hardness values between outer surface and centre, hardness measurements have been done using 10 gr test loads except for the samples which have been subjected to thermal spraying. In samples which have been subjected to thermal spraying, 20 gr test loads have been used considering the fact that the coating layer is thick enough.

At the end of the 10-h wear test, surface topography of each worn test sample has been examined under JEOL JSM 6400 scanning electron microscope and photographs have been taken of the worn surfaces of samples.

On the other hand, in spray coating, diffusion of coating material elements which is very important in terms of surface adhesion has been examined under scanning electron microscope using EDX analysis extending from the surface to inside.

3. Results and discussion

Weight losses which are the total wear at the 10th h for the each test samples divided by the unit surface area, expressed in mg/mm$^2$, are given in Fig. 3. As can be seen in Fig. 3, oil quenched (OQ) samples and samples coated with thermal spraying (FS1, FS2, FSM, HVOFM) have worn less than the base metal. Particularly, those samples that have been subjected to HVOF plus melting (HVOFM) have worn much less than the base metal. On the contrary, samples subjected to thermo-chemical surface treatment (B, GN6, GN12, SBN, IN1/2, IN1, IN4, IN12, IN24, IN48) and the sample which has been induction hardened have worn more than the base metal.

Among the methods applied to reduce the amount of wear of base metal, the most effective one is using thermal spraying to form a coating layer. In reducing the wear rate of base metal, HVOF plus melting method is followed by flame spraying plus melting and flame spraying methods. Ni–Cr–B–Si powder (FS1) was the base election. Ni based coatings were mainly used in the chemical industry, petrol industry, glass mould industry and for valves, hot working punches, fan blades, mud purging elements in cement factories [12]. By adding WC to FS1 powder, a little decrease on the weight loss is obtained. Again, as can be seen in Fig. 3, the weight loss on the unit surface of the base metal is decreased by 59% and 61% with FS1 and FS2 powders, respectively. Wear resistance of the base metal is increased by 3.36% by adding 35% WC to coating powder. It is reported that the wear resistance of NiCrBSi coatings can be increased by adding WC hard phase [13]. Then, the weight loss was significantly decreased with the process of remelting after flame spraying using FS1 powder. The weight loss of the base metal is decreased by 69% with FSM. After having succeeded in all methods, the most significant decrease on the weight loss was obtained with the process of remelting after high velociti oxyfuel (HVOF) spraying using a mixture of WC and FS1 powders. The total weight loss on unit surface of base metal was 80% less in the sample, which was subjected to high velocity oxygen fuel spraying plus melting.

Fig. 3 shows that the worst results have been obtained in samples which were subjected to nitriding treatment (particularly plasma nitriding). It has been observed that coarse and hard abrasive particles have impacted sample surface, which is characteristic of wear test. Since the ceramic like layers forming on the surface under such conditions can easily crack upon impact, they shall have little abrasion resistance. We observe that a hard and brittle nitride layer called white layer forms on the surface of all samples after nitriding. The measurements show that white layer thickness is 10–12 μm in salt bath nitriding, 8–9 μm in gas nitriding for 6 and 12 h, 3–4 μm in plasma nitriding for 1/2, 1 and 4 h, 6–7 μm in plasma nitriding for 12, 24 and 48 h. Fig. 4(a) clearly shows the white layer that forms after nitriding treatment in salt bath.
Samples applied nitriding have significantly different wear resistances depending on the method and the method parameters. This situation is related to the hard layer that forms on the surface as well as the microstructure that develops on the surface as a function of the method and the method parameters. In this group, a comparison of samples applied long-period plasma nitriding and those applied short-period plasma nitriding reveals that coarse grains develop because of the long period of treatment and nitrogen diffuses under the surface in

Fig. 3. Weight losses and surface hardness on unit surface of test sample.

Fig. 4. Microstructure of samples that have been applied salt bath nitriding SBN (a), plasma nitriding IN48 (b) and gas nitriding GN (c).
large quantities to form very hard, brittle and coarse carbonitride deposits that make grain boundaries very weak against crack development (Fig. 4(b)). The same effect has been observed by samples applied gas and salt nitriding (Fig. 4(a) and (c)). Microcracking mechanism is caused to wear at these samples. The crack, which is started by the impact of abrasive particles to the white layer, passed through the already weakened grain boundaries and/or in the coarse grains to cause small pieces to break off. This can be seen in the surface examination by scanning electron microscope (Fig. 5). Therefore, the surface appearance is very rough after wear test. This roughness varies according to the method and the method parameters in proportion to coarseness of grain boundary deposits and grain size in microstructure (Fig. 6).

Fig. 3 shows that samples applied boronising have similar characteristics. In these samples, an non-etched, very hard and brittle boron layer having 70–90 $\mu$m thickness forms on the surface (Fig. 7). In these samples also microcracking mechanism is caused to wear. The crack is started by the impact of abrasive particles to the white layer. This is also observed in the surface examination done by scanning electron microscope (Fig. 8). Therefore, surface appearance is rather rough following the wear test (Fig. 6).

The method of surface hardening by induction does not have a significant effect on wear resistance. In this group of samples, oil quenched sample which has more surface hardness was observed to have significantly improved in terms of wear resistance due to increased hardness. Induction hardened sample, which was supposed to give the same result as oil quenched sample, had a higher wear rate probably due to the surface cracks that may have formed after the quenching treatment which has been applied during induction hardening process (Fig. 3).

As mentioned above, spray coated samples have the best wear resistance. In these samples, spray coating process was initially done using Ni–Cr–B–Si (FS1) powder. This powder blend was then mixed with WC to increase the wear resistance of coating material.
(FS2 powder). Samples which have been coated using flame spraying method with these two different powder combinations were observed to have approximately the same resistance (FS1 and FS2 samples in Fig. 3). When these samples were subjected to melting process with welding torch after flame spraying (FSM), wear resistance was observed to improve significantly. It is obvious that melting process has a significant contribution here. The best wear resistance was obtained when samples were first coated using HVOF method with these powder blends and then melted (HVOFM).

Following the wear test, surfaces of these samples were examined using scanning electron microscope and wear behaviour of samples which were not subjected to surface melting after spraying was found to be in the form of microcrack mechanism. Spray coating process causes the formation of a surface layer where molten particles are stacked one over the other in stages. If these stages do not completely penetrate into each other, the impact of abrasive particles forms cracks in these interfaces leading to small pieces breaking off (Fig. 9(a)). When WC powders which are added to the coating material powders in order to increase wear resistance remain on the surface between splat layers after spraying, they contribute to the development of cracks because of their hardness and brittleness (Fig. 9(b)).
Furthermore, these particles may have an increasing effect on wear by breaking off the matrix during wear test. It is known that tungsten carbide particles play an abrasive role, which greatly increases the wear rates of the counterbodies [14]. Therefore, it would be wise to apply a surface melting process in order to reinforce the matrix and the connection in the matrix. Since better penetration is achieved between splat layers when these samples were applied to surface melting after spraying, wear mechanism becomes micro ploughing mechanism (Fig. 9(c)). Consequently, the wear rate is reduced. The fact that samples coated with HVOF method instead of flame spraying give the best wear resistance may be the result of better surface adhesion and better penetration between splat layers due to the very high energy level of this method. Higher particle velocity during deposition provides several advantages such as lower porosity, higher bond strength and hardness in HVOF method [15]. The higher velocities and lower temperatures experienced by the powder particles result in less decomposition of the WC during spraying. Consequently, this results in higher quality, more wear-resistant coatings, with higher levels of retained WC and less porosity [16].

In these surface coatings, one of the important factors for surface adhesion is the diffusion of coating layer and the interfacial alloy elements. And naturally the factor with the highest effect on this diffusion is the energy applied to the surface during treatment. The energy applied to the surface depends on both the method and the melting process that follows spraying. In that sense, among the samples coated by spray coating, the ones having the lowest surface energy are FS1 and FS2 samples. These samples have been coated with flame spraying and in this method powder particles sprayed to the substrate material have low level of energy. EDX analysis of these samples using scanning electron microscope has not revealed a significant diffusion of any of the elements in coating layer towards substrate material (Fig. 10(a)). Spraying plus surface melting process in flame sprayed samples encourages diffusion and consequently significant amount of diffusion is observed in Cr whose atom diameter is very close to the atom diameter of iron (Fig. 10(b)).

4. Conclusions

a. When ceramic-like, hard and brittle layers form on the surface of a material which has been exposed to abrasive wear by abrasive particles, impact of these particles leads to microcrack mechanism, with a consequent increase in the rate of wear. This is observed in samples applied thermo-chemical processes such as nitriding and boronising, which cause formation of hard and brittle layers on the surface.

b. Wear resistance may be increased when the coating layers are made of composite-based materials instead of ceramic materials. Such combinations may be obtained by spray coating from among an unlimited number of options.

c. In the flame spraying process, the weight loss on the unit surface of the base metal is decreased by 59% and 61% with FS1 and FS2 powders, respectively. Moreover, the weight loss of the base metal is decreased by 69% and 80% with FSM and HVOFM, respectively.

d. Wear resistance of the base metal is increased by 3.36% by adding 35% WC to coating powder in flame spraying process.

e. Once a proper coating layer-powder combination has been selected, the secondary factor affecting the wear characteristic is the energy load on the coating particles on the material surface during and after spraying. Any increase in the level of this energy encourages diffusion between coating layer and surface, which leads to increased adhesion, and as the energy increases, the voids between the splat layers on the surface that lead to wear are
eliminated, giving way to better penetration. This is effectively achieved by applying surface melting process after spraying.

References