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# STUDY OF WEAR AND EROSION BEHAVIOR OF DETONATION SPRAYED BOILER STEELS

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**Abstract-Wear and Erosion are the most common occurrences in various power generating industries such as fossil fuel power plants, thermal power plants and various components such as boilers, gas turbines in aircraft etc. Since wear is the loss of material from a component due to mechanical interaction with another component so wear is one of the major causes of failure of high temperature equipment specially boilers. Erosion is the process of surface wearing in which material is removed from the surface by the action of solid particles impinging on it, so erosion along with wear have the potential to cause huge losses both direct and indirect in power generation and hence can affect the functioning and efficiency of a thermal unit. Hence one way to stop the damaging effects of wear and erosion is to thermally coat the material. Present work is focused on studying the wear and erosion behavior of T91 and T22 boiler steels by coating via Detonation gun spray coating process. Three types of coatings which were used to impart wear and erosion resistance to steels according to weight percentage were $Al_2O_3$, $Al_2O_3$ +$TiO_2$ (40%), $Al_20_3$+$TiO_2$ (3%). Both T91 and T22 boiler steels, coated and uncoated were subjected to wear on Pin-on-disk wear testing machine and for erosion testing steels were exposed to a high temperature erosion testing machine. Wear testing of samples was done on loads of 2kg and 4 kg with speed of 650 rpm for each load. Erosion testing was done at $90^0$ impact angle by using alumina as erodent material. Among the results for wear testing it was observed both the uncoated substrates showed higher wear rate as compared to their coatings; T22 showed higher wear rate as compared to T91; at both 2kg and 4kg loads $Al_2O_3$+40$TiO_2$ coating possessed least weight loss for both substrates and for all 3 coatings; $Al_2O_3$ coating possessed highest weight loss for both substrates. During high temperature erosion testing at $90^0$ impingement angle, uncoated substrate T22 possessed higher erosion rate as compared to uncoated T91substrate; $Al_2O_3$+40$TiO_2$ coating possessed least erosion rate among both substrates; $Al_2O_3$ coating possessed highest erosion rate among both substrates.**
**Keywords: Wear, Erosion, Thermal Spray, Detonation Gun Spray Coating, Scanning Electron Microscope.**

## 1. INTRODUCTION

Since the attainability of high temperatures has been an important factor in the growth of civilization for many countries [1]. So in various high technology fields, materials have to face severe conditions of temperature, pressure, corrosive and erosive environment which can change the physical properties of materials [2]. Hence material loss at high temperatures is a major issue in various high technology industries. Areas where erosion and corrosion resist their use or limit their life are boilers, fossil fuel power plants, gas turbines in aircraft and heating elements for high temperature furnaces [1].
Erosion and wear in boilers and related components have the potential to cause huge losses both direct and indirect in power generation and hence can undermine the functioning and efficiency of a thermal unit. In order to develop a suitable protective system an understanding of the system for protection from erosion, wear and other thermal unit hampering factors is essential for maximizing the utilization of such components. Material protection from wear and erosion by the use of coatings for separating material from the environment is gaining momentum these days for applications in surface engineering.

### *1.1 Erosion*

Erosion is the process of surface wearing in which material is removed from the solid surface by the action of solid particles impinging on it. This type of wear is common in many industrial devices including boilers, turbine blades, pressure vessels etc. Erosion is the most important cause for boiler tube failure. The combustion of products of coal contains fly ash particles, which impinge on the boiler tubes and erode them. Generally one-fifth of the ash produced in the boiler unit is deposited on the boiler walls, economizers, air-heaters and super-heater tubes in coal fired thermal power plants. This deposited ash is then discharged as slag during the soot blowing process. The rest of the ash is sent via steam of the gas leaving the boiler. These ash particles strike with boiler steel components and hence result in extensive surface erosion and hence wearing up of boiler tubes accompanies erosion. Such erosion along with the processes of blocking and corrosion shorten the service life of boiler components. Once this happens, the power station unit has to be closed in order to change the damaged components [3].

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*1.2 Wear*

Wear can be defined as the sideways displacement of a material from its surface by the action of another surface. Wear is the interaction between surfaces and is usually the removal and deformation of a material surface as a result of mechanical action of the opposite surfaces against each other [4].

*1.3 Controlling wear and erosion*

Materials used for high temperature applications need to be protected from wear, erosion and other forms of high temperature degradations such as erosion-corrosion. Although there are several counter measures to combat these high temperature problems, but thermal spraying is one of the promising and industrial viable solutions to such problems. Thermal spraying is a group of coating processes in which finely-divided metallic or non-metallic materials are deposited in a molten or semi molten condition to form a coating. The coating material may be in the form of a powder, ceramic-rod, wire or molten materials. This work includes coating of substrate steels by Detontion gun spray coating process which is a thermal spray coating process.

A detonation gun (D-gun) is a device that is used to deposit a variety of materials and ceramic coatings at supersonic speeds on the work material by controlled detonation of oxygen and acetylene. It is used in the thermal spraying process for providing hard, wear resistant and dense-microstructure coatings

**2. CHARACTERISATION AND DEPOSITION OF COATINGS**

*2.1 Selection and Preparation of Substrate Materials*

Substrate materials selected were ASTM-SA213-T22 (T22) designated as procured from Guru Gobind Singh Super Thermal Power Plant, Ropar (India) and T91 steel from Cheema Boilers Limited, Ban Majra, Kurali (India).For preparation of substrate steels T91 and T22 steels were cut as:

- For Erosion testing: The steel samples were cut to form approximately 20x15x5 mm size specimens.
- For Wear testing: The steel samples were cut to form approximately 20x7x5 mm size specimens.

The specimens were polished and grit blasted by $Al_2O_3$ (Grit 60) before the deposition of the coatings. The specimens were prepared manually and all care was taken to avoid any structural changes in the specimens.

*2.2 Coating Powders*

Detonation spray coating was done at SVX Powder M Surface Engg. Pvt. Ltd. Greater Noida, Uttar Pradesh, India. Three types of coating powder compositions deposited on the given steels T91 and T22 by the Detonation gun are given in Table 3.2.

Table 2.1 Coating Powders used

| **Substrate Steel** | **Coating powders (by weight percentage)** | | |
|---|---|---|---|
| T22 | $Al_2O_3$ | $Al_2O_3$(60) +$TiO_2$(40) | $Al_2O_3$(97) +$TiO_2$(3) |
| T91 | $Al_2O_3$ | $Al_2O_3$(60) +$TiO_2$(40) | $Al_2O_3$(97) +$TiO_2$(3) |

*2.3 Wear Testing*

Wear tests were performed on the pin specimens that had flat surfaces in the contact regions. The pin was held stationary against the counter face of a rotating disc made of En-32 steel at 100 mm track diameter. The pin was loaded against the disc through a dead weight loading system. En-32 steel is a plain carbon steel; case hardened 62 to 65 HRC as provided with the pin-on-disc machine

*2.4 High Temperature Erosion Testing*

Erosion testing was carried out using a solid particle erosion test rig TR-471-M10 Air Jet Erosion Tester (Ducom Instruments Private Limited, Bangalore, India) located at Baba Banda Singh Bahadur Engineering College, Fatehgarh Sahib as shown in figure 3.2. The high temperature erosion testing was performed on uncoated and coated substrate steel at impingement angle i.e. 90°. Dry compressed air was mixed with the erodent particles, which were fed at a constant rate from hopper via erodent feeding system in the mixing chamber and then the mixture was accelerated by passing it through a converging nozzle made of “Inconel” material of “4 mm” diameter. These accelerated particles impacted the specimen kept in the furnace unit consisting of specimen heater and air heater.

*Table 2.2 Erosion test conditions*

| | |
|---|---|
| Erodent material | Alumina (Irregular shape) |
| Erodent Specifications | Alumina (size50 microns) |

| | |
|---|---|
| Particle velocity (m/s) | 32 |
| Erodent feed rate (g/min) | 6.8 |
| Impact angle (°) degree | 90 |
| Test temperature ($^0$C) | Sample Temperature 400°C Air Temperature 450°C |
| Nozzle diameter (mm) | 4 |
| Test time (Hours) | 3 |

*2.5 Objectives*

Wear and high temperature erosion can be reduced by the use of coatings. So, the objectives of the present work are as follows:

- To deposit oxide coatings of $Al_2O_3$, $Al_2O_3$ +$TiO_2$ (60%+40%), $Al_20_3$+$TiO_2$ (97%+3%) on T91 and T22 steels using detonation gun spray coating process.
- To study the wear behavior of uncoated T91 and T22 steels at different loads.
- To study the wear behavior of Detonation gun spray coatings namely $Al_2O_3$, $Al_2O_3$ +$TiO_2$ (60%+40%), $Al_20_3$+$TiO_2$ (97%+3%) on T91 and T22 steels at different loads.
- To study and compare the high temperature erosion behavior of uncoated specimen with the coated specimen at $90^0$ impact angle.
- To study the wear mechanisms of the specimens by SEM analysis.

## 3. RESULTS AND DISCUSSIONS

*3.1 Wear Testing*

T91 and T22 steels were investigated for wear testing on complete pin on disc wear test set up. The wear rate of the uncoated and coated steels was carried out at two loads i.e. 2kg and 4kg and at disc speed of 650 rpm. Test was conducted using disc track diameter 80mm. For each sample five readings were taken and the time interval for each reading was 2 minutes.

*3.1 At 2kg load*

Weight loss for uncoated and coated T91 and T22 samples along with graphs after one complete cycle at 2kg load is shown below in Table 3.1 and Table 3.2 below.

Table 3.1 Weight loss of T91substrate after each cycle (in g/$mm^2$) at 2kg load

| **Speed- 650 rpm** | **Load (2kg)** | | | |
|---|---|---|---|---|
| | **T91** | | | |
| **Time (Min)** | **Uncoated** | **$Al_2O_3$+ 3$TiO_2$** | **$Al_2O_3$+ 40$TiO_2$** | **$Al_2O_3$** |
| 2 | 0.0009 | 0.0002 | 0.0003 | 0.0017 |
| 4 | 0.0010 | 0.0004 | 0.0004 | 0.0009 |
| 6 | 0.0025 | 0.0005 | 0.0002 | 0.0015 |
| 8 | 0.0013 | 0.0002 | 0.0003 | 0.0011 |
| 10 | 0.0009 | 0.0006 | 0.0004 | 0.0006 |

From Figure 3.1 it can be observed that T91 steel having coating $Al_2O_3$ had least resistance to wear in comparison to other coatings. But $Al_2O_3$+40$TiO_2$ is most resistant to wear.

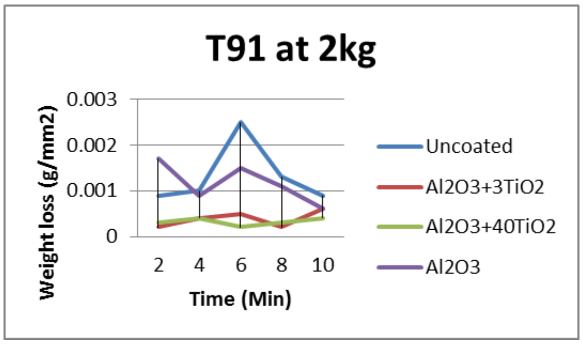


Figure 3.1: Wear rate for uncoated and coated T91 steel at 2kg load and speed 650 rpm

Table 3.2: Weight loss of T22 substrate after each cycle (in g/mm$^2$) at 2kg load

| Speed- 650 rpm | Load (2kg) T22 | | | |
|---|---|---|---|---|
| Time (Min) | Uncoated | $Al_2O_3$+ $3TiO_2$ | $Al_2O_3$+ $40TiO_2$ | $Al_2O_3$ |
| 2 | 0.0011 | 0.0006 | 0.0009 | 0.0006 |
| 4 | 0.0025 | 0.0004 | 0.0003 | 0.0008 |
| 6 | 0.0020 | 0.0008 | 0.0002 | 0.0004 |
| 8 | 0.0032 | 0.0004 | 0.0004 | 0.0010 |
| 10 | 0.0017 | 0.0006 | 0.0003 | 0.0007 |

From figure 3.2 it can be seen that T22 steel having coating $Al_2O_3$+$40TiO_2$ was most resistant to wear rate in comparison to other coatings. $Al_2O_3$ had maximum wear rate among all the coatings.

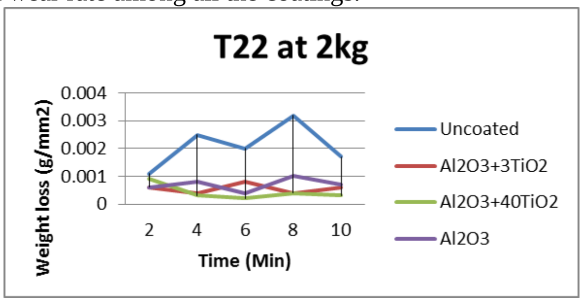


Figure 3.2: Wear rate for uncoated and coated T22 steel at 2kg load and speed 650 rpm

*3.2 At 4kg load*

Weight loss for uncoated and coated T91 and T22 samples after one complete cycle at 4kg load along with graphs is shown below in Table 3.3 and Table 3.4. The weight loss at load of 4kg and speed of 650rpm has been clearly depicted. The time interval for each reading was 2 minutes.

Table 3.3: Weight loss for T91 substrate after each cycle (in g/mm$^2$) at 4kg load

| **Speed-650 rpm** | **Load (4kg) T91** | | | |
|---|---|---|---|---|
| **Time (Min)** | **Uncoated** | **$Al_2O_3$+ $3TiO_2$** | **$Al_2O_3$+ $40TiO_2$** | **$Al_2O_3$** |
| 2 | 0.0027 | 0.0018 | 0.0022 | 0.0023 |
| 4 | 0.0020 | 0.0015 | 0.0017 | 0.0017 |
| 6 | 0.0024 | 0.0013 | 0.0015 | 0.0018 |
| 8 | 0.0016 | 0.0009 | 0.0011 | 0.0019 |
| 10 | 0.0021 | 0.0016 | 0.0012 | 0.0010 |

The graph for comparison of the weight loss at 4kg load and 650 rpm for uncoated and coated T91 steels after wear testing has been represented in Figure 3.3. The trend in Figure 3.3 shows that uncoated T91 steel conceived higher weight loss than the coated T91 steel. T91 steel having coating Al2O3+40TiO2 was most resistant to wear rate in comparison to other coatings.

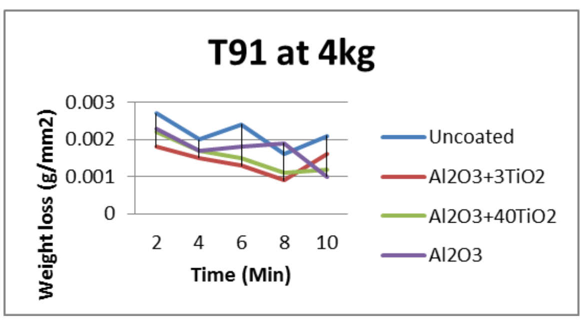


Figure 3.3: Wear rate for uncoated and coated T91 steel at 4kg load and speed 650 rpm

Table for T22 steel at 4kg load is given below. The weight loss at load of 4kg and speed of 650rpm has been clearly depicted. The time interval for each reading was 2 minutes.

Table 3.4: Weight loss for T22 substrate after each cycle (in g/mm$^2$) at 4kg load

| **Speed-650 rpm** | **Load (4kg)** | | | |
|---|---|---|---|---|
| | **T22** | | | |
| **Time (Min)** | **Uncoated** | **$Al_2O_3$+ $3TiO_2$** | **$Al_2O_3$+ $40TiO_2$** | **$Al_2O_3$** |
| 2 | 0.0044 | 0.0007 | 0.0004 | 0.0018 |
| 4 | 0.0034 | 0.0006 | 0.0002 | 0.0007 |
| 6 | 0.0030 | 0.0008 | 0.0005 | 0.0006 |
| 8 | 0.0020 | 0.0004 | 0.0003 | 0.0004 |
| 10 | 0.0032 | 0.0003 | 0.0005 | 0.0005 |

From Figure 3.4 it's seen that uncoated T22 steel conceived higher weight loss than the coated T22 steel. This can be observed that T22 steel having $Al_2O_3$ coating was least resistant to wear rate in comparison to other coatings.

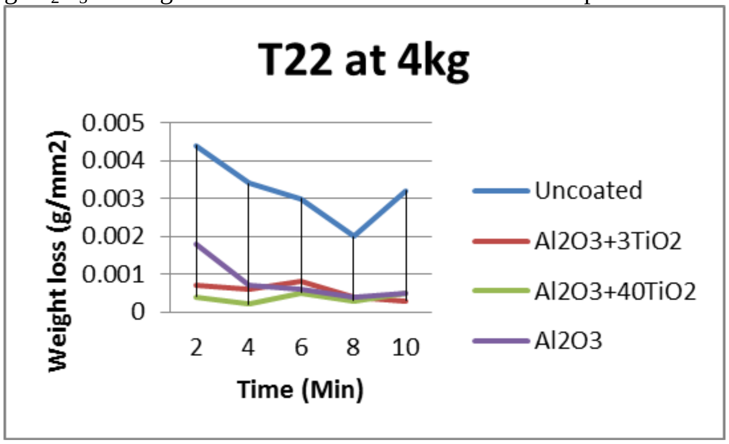


Figure 3.4: Wear rate for uncoated and coated T22 steel at 4kg load and speed 650 rpm

*3.1.1 SEM Analysis of wear tested samples*

SEM analysis of the uncoated and coated substrate steels for wear testing has been carried out on Sophisticated Analytical Instruments Laboratories, Punjabi University, Patiala (Punjab)

Figure 4.5 shows the micrograph of $Al_20_3$ coated T22 steel after wear testing, it can be seen that surface after wear testing shows the presence of particle pull out and large cavities are showing material removal. The blackish area at the sides of specimen represents deformation of material in the form of cavities. Hence $Al_2O_3$ shows high wear among coatings.

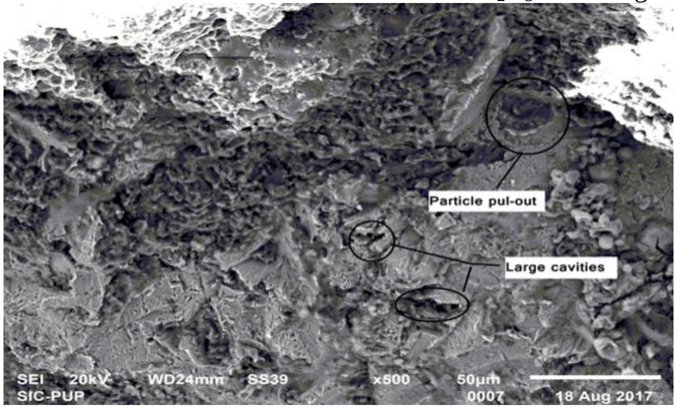


Figure 3.5: SEM micrograph of $Al_2O_3$ coated T22 steel after wear testing

Micrograph of $Al_2O_3$+$3TiO_2$ coated T22 steel after wear testing is shown in figure 4.6. From the SEM micrograph, presence of large cavities shows the deformation of material during wear testing. Some blackish areas also show deformations in form of small cavities, hence it shows less material removal as compared to $Al_2O_3$ coating.

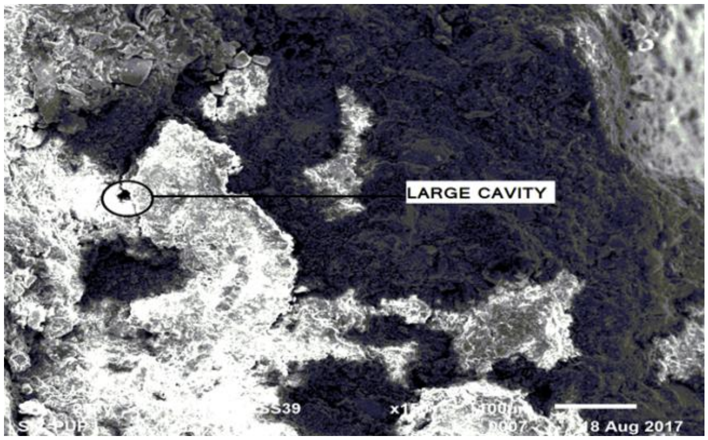

Figure 3.6: SEM micrograph of Al2O3+3TiO2 coated T22 steel after wear testing

Figure 4.7 shows the micrograph of $Al_2O_3$+40$TiO_2$ coated T22 steel after wear testing, here it can be clearly observed that this coating possess uniform and least wear loss than all other coatings with very small cavities and grooves.

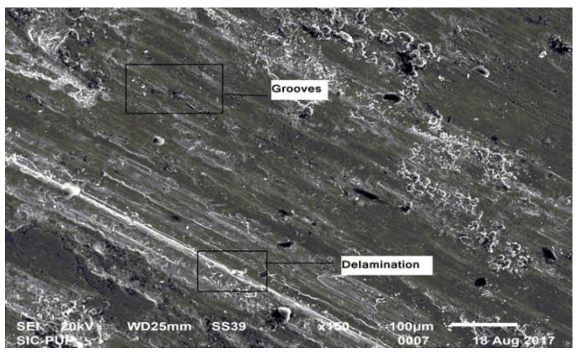

Figure 3.7: SEM micrograph of $Al_2O_3$+40$TiO_2$ coated T22 steel after wear testing

Micrograph of uncoated T91 steel after wear testing is shown in figure 4.8, it shows presence of large cavities shows the deformation of material during wear testing and there is highest wear rate in uncoated T91 steel, hence it shows highest material removal as compared to all coatings

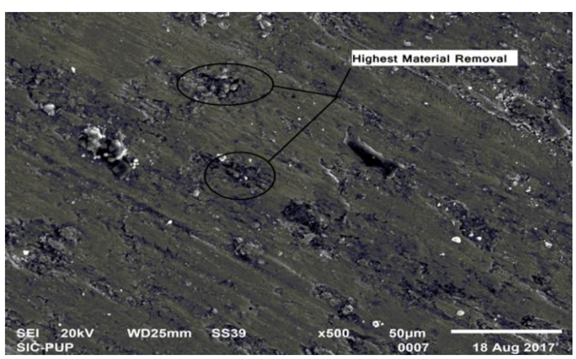

Figure 3.8: SEM micrograph of uncoated T91 steel after wear testing

*3.2 High Temperature Erosion Testing*

T91 and T22 steels were investigated for high temperature solid particle erosion testing. The erosion rate of the uncoated and coated steels was carried out at impingement angle of 90°. The erosion rate was measured on the high temperature solid particle erosion test rig on the basis of weight loss per unit area of the specimen. The test was conducted using $Al_2O_3$ as an erodent material. For each sample one reading was taken and the time interval for each sample was three hours. The results have also been compared with uncoated specimen.

Weight loss for uncoated and coated T91 and T22 samples after one complete cycle is shown below in Table 3.5.

Table 3.5: Weight loss after each cycle (in $g/mm^2$)

| **Specimens** | **T91 steel** | **T22 steel** |
|---|---|---|

| | At 90° impingement angle | At 90° impingement angle |
|---|---|---|
| Uncoated | 0.0055 | 0.0079 |
| $Al_2O_3$ | 0.0023 | 0.0041 |
| $Al_2O_3$+3$TiO_2$ | 0.0010 | 0.0015 |
| $Al_2O_3$+40$TiO_2$ | 0.0004 | 0.0008 |

*3.2.1 Comparison of high temperature erosion rate for coated and uncoated T91 and T22 steels at 90°*

The graph for comparison of the weight loss for uncoated and coated T91 and T22 steels after high temperature erosion at 90° impingement angle has been represented in figure 4.9. It can be clearly seen that T22 steel conceived higher weight loss than T91 steel in both coated and uncoated states. This clearly shows that T91 steel having $Al_2O_3$+ 40$TiO_2$ coating was most resistant to erosion rate in comparison to other coatings and T22 steel with Al2O3 coating possessed the highest wear rate

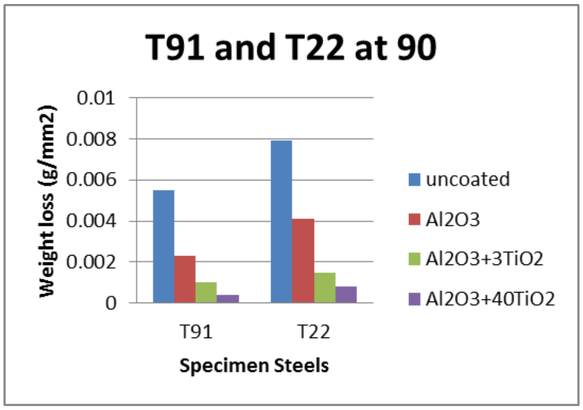


Figure 3.9: Comparison of erosion rate for coated and uncoated T91 and T22 steels at 90°

## 4. CONCLUSION

Conclusions from the present study have been summarized as given below:

- During wear testing of the two uncoated substrates, T22 possessed higher weight loss in comparison to T91 at both loads i.e. 2kg and 4kg and at speed of 650 rpm during wear testing.
- Both the uncoated substrates showed higher wear rate as compared to their coatings.
- During wear testing of T91 and T22 substrate coatings at same load of 2kg, Al2O3+40TiO2 coating possessed least weight loss in comparison to Al2O3+ 3TiO2 and Al2O3 coatings, which showed that Al2O3+40TiO2 possess the least wear rate.
- During wear testing of T91 and T22 substrate coatings at same load of 4kg, Al2O3 coating possessed highest weight loss in comparison to Al2O3+40TiO2 and Al2O3+ 3TiO2 coatings, which showed that Al2O3 possesses the highest wear rate.
- During high temperature erosion testing at impingement angle 90°, uncoated substrate T22 possessed higher weight loss as compared to uncoated T91, which showed that the erosion rate was higher for uncoated substrate T22.
- During high temperature erosion testing, for both T91 and T22 coated substrates, Al2O3 coating possessed highest weight loss in comparison to Al2O3+40TiO2 and Al2O3+ 3TiO2 coatings, which showed that Al2O3 possess the highest erosion rate.
- Al2O3+40TiO2 coating possess the lowest weight loss in comparison to other tested specimens at impingement angle 90° during erosion testing which showed that this coating possess the lowest erosion rate for both T91 and T22 steels.
- In case of erosion testing the two mechanisms which might be responsible for the removal of material are plastic deformation and ploughing.

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