A Major Project – II

on

Tribological Study of HVOF Sprayed Tungsten Carbide Coated Stainless Steel

submitted in partial fulfilment to the degree

of

Master of Technology
in
Production Engineering

by

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(2K18/PIE/24)

under the supervision

of

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June, 2020

DECLARATION

I, **ALOK KUMAR, (2K18/PIE/24),** Department of Mechanical Engineering, Delhi Technological University, Delhi hereby declare that the major project - II entitled, "**Tribological Study of HVOF Sprayed Tungsten Carbide Coated Stainless Steel**" submitted by me in partial fulfilment of the requirement for the award of Master of Technology in Production Engineering from Delhi Technological University, Delhi is a record of authentic work carried out by me under supervision and guidance of **Dr. R.C. SINGH** (Professor)**,** Department of Mechanical Engineering, and **Dr. RANGANATH. M. SINGARI** (Professor)**,** Head, Department of Design, Delhi Technological University, Delhi. The matter embodied in this major project - II has not been submitted to any other University/Institute for the award of any degree or diploma. Literature bestowed in this project report is being provided with proper citing.

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CERTIFICATE

This is to certify that the declaration made by **Mr. ALOK KUMAR, (2K18/PIE/24),** Department of Mechanical Engineering, Delhi Technological University, Delhi is true to the best of our knowledge and belief.

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ABSTRACT

Corrosion and Wear, or combination of both, are the main causes of degradation of metals used in various industrial sector. Degradation of the metals can be slowed down by adding a layer of resistant coating on metal surface. This coating separates the base metal from a corrosive environment, reduces wear and improves the appearance of the metal. The workpiece after coating becomes a composite that have properties far better than the substrate alone. There are various coating techniques, HVOF is one of the most important and widely used process to protect the metals from wear, corrosion by providing hard and dense coatings. WC coating done by the high velocity oxy fuel (HVOF) spray method is the widely used method for providing a layer of corrosive resistance to a wide range of materials which are used in many different industries.

In this study, Tungsten carbide (WC-12CO) Coating, HVOF Spray method was studied in great detail. Tungsten Carbide coating was done on a SUS400 Stainless steel substrate using HVOF Spray Process. And, Experiment was done to analyse the various effect of different parameters namely, oxygen rate, propane (fuel) rate, powder rate, spray distance on hardness and surface roughness of a SUS 400 Stainless Steel substrate. Process optimization was done by using Taguchi and ANOVA methods. It was found that, achieving maximum hardness was greatly depended on propane (fuel) rate followed by powder rate, spray distance and oxygen rate. Hardness decreases with increasing fuel rate. And, achieving minimum surface roughness was greatly depended on spray distance followed by oxygen rate, propane (fuel) rate, powder rate. Surface Roughness increases with increasing spray distance.

Keywords - Tungsten Carbide, Corrosion, Chrome Plating, Wear Resistance, HVOF Spraying, Hardness, Surface Roughness.

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PROJECT REPORT STRUCTURE

Structure of this project:

CHAPTER 1: Tungsten Carbide Coating and HVOF Spraying Process were explained in this chapter along with their properties, advantages, disadvantages & factors affecting their properties.

CHAPTER 2: Various comprehensive studies related to Tungsten Carbide Coating and HVOF Spraying Process were given in the form of literature matrix along with the research gap.

CHAPTER 3: Setup assembly was given in this chapter.

CHAPTER 4: Procedure for conducting the experiment were given, Readings were obtained in this chapter and process optimization was done using Taguchi and ANOVA method. Results were calculated and analysed.

CHAPTER 5: Final conclusions and future scope of study were mentioned in this chapter.

CHAPTER – 1

INTRODUCTION

1.1 FRICTION AND WEAR

All engineering materials used in the industries were bound to fail over the passage of time. Their properties started degrading which results in their poor working efficiency. Friction and wear were two such phenomenon which fastened this degradation along with the passage of time. Since, time couldn't be stopped, reducing friction and wear becomes the only task to slow down the degradation of metal and their properties. Friction caused serious energy dissipation when two moving surfaces came in contact with each other, resulting in poor surface properties. Removal of material from the surfaces of both moving contacting material resulting in the wear phenomenon. Just like friction, wear also resulted in the poor surface properties. Different types of wear were shown in fig. 1.1. To reduce the effect of friction and wear during working, the surface property of the metal should be of high quality. That could be done by adding a high quality of coating on the metal substrate surface. Tungsten carbide coating done by HVOF spray method was one such method to reduce the effect of friction and wear.

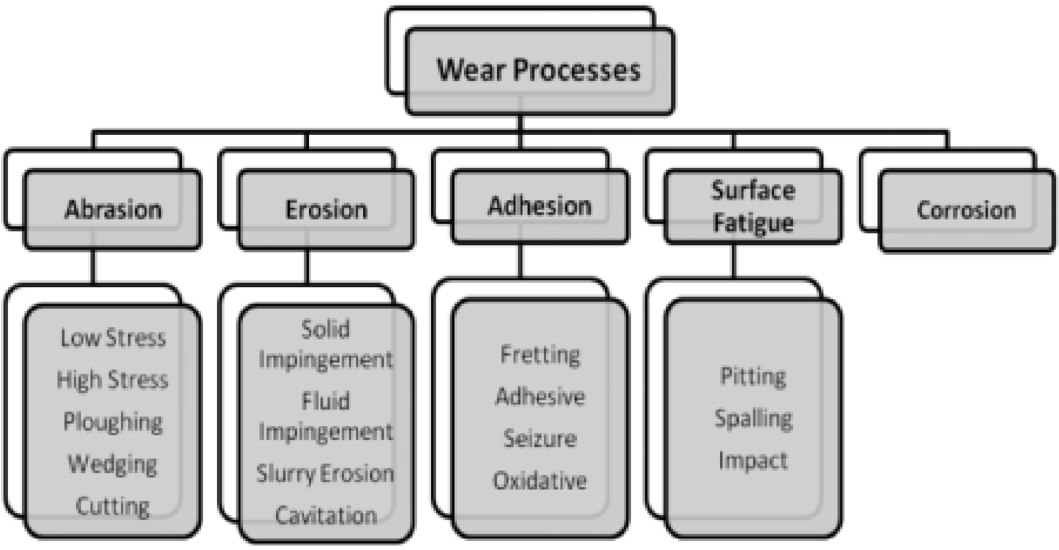

Fig. 1.1 Wear Types [11]

Tungsten carbide coating done HVOF spray method increased the surface properties of the metal by adding a layer of hard coating material. Also, this process produces smooth and shiny surfaces. Coating provides an added layer of surfaces to the metal surfaces, resulting in a new composite material which exhibits better properties than the metal alone.

1.2 TUNSTEN CARBIDE "WC" COATINGS

Tungsten carbide coating was a coating in which the layer of coating material Tungsten Carbide (WC) was added to the metal surface to increase the surface properties. WC existed in physical form in the form of grey powder. To increase the properties of coated layer, tungsten carbide was mixed with the other metal like cobalt and nickel in proportion to further increases the properties. However, the added metal resulted in the decreasing of properties like hardness, resistance, operating temperature [1]. WC coating had various applications in many different industries because of protection it provided against the wear at various different temperatures [9].

Tungsten carbide coating found an important place in the various different industries in fight against corrosion because it provides a high hardness, high melting point, low surface roughness to the material substrate. In most cases, tungsten carbide coating was used with the cobalt metal binder. This process was very energy consuming as it involves long grinding, and oxidation take place during this process which results in the bad coating material [10]. WC coating found an application in various industries like dental work, cutting tools, aerospace industries, automotive industries and so on. Richert et al. (2016) postulated that in comparison to conventional coating process, WC-CO coating showed better wear resistant properties [2]. WC-CO coating done by HVOF spray process showed even more increase in metal surface properties [6].

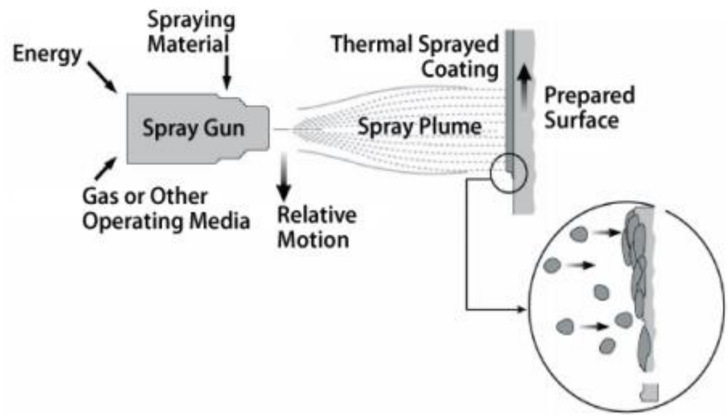

Fig. 1.2 Schematic diagram of spray coating [27]

1.3 PROPERTIES OF TUNGSTEN CARBIDE COATINGS

Tungsten Carbide Coatings have following properties [2]:

1. High Melting Point - about 2800ºC,
2. High Hardness - about 2200HV,
3. Low coefficient of friction,
4. High resistance against oxidation,
5. High electrical conductivity,
6. High modulus of elasticity (700 GNm^{-2})

1.4 TUNGSTEN CARBIDE COATINGS APPLICATIONS

Typical applications of HVOF tungsten carbide coatings are [3]:

1. In manufacturing industry, for extrusion, thread guides, forging, wire drawing, cam followers etc.,
2. In gas turbine industry, for coatings of nozzles, jet engine, manifold rings, aircraft flaps, etc.,
3. In petroleum industry, for plungers, liners, compressor rods etc.,
4. In chemical process industry, for valves and pump components.
5. In paper industry, for printing rolls,
6. In automotive industry, for piston rings, cylinder lining.
7. In aeroplane Industry, for landing gears and many more.

1.5 TUNSTEN CARBIDE POWDER PRODUCTION

A good quality of coating was entirely dependent on the production of its coating material. In case of WC-CO coating, the production of WC powder. For a good and high quality of WC-CO coating, fine grain of WC powder production was needed. There were tons of different methods for the production of WC powders, almost all of them required the carburisation of tungsten or reduction of tungsten oxide to tungsten and then subsequent carburisation. WC could be produced by reacting tungsten and carbon at very high temperature of about 1700°C (carburisation of tungsten),

$$W + C \rightarrow WC$$

Or, by reduction of tungsten oxide to tungsten then, subsequent carburisation to WC [14].

$$2WO_3 + 3C \rightarrow 2W + 3CO_2$$

$$W + C \rightarrow WC$$

Different methods were developed for the production of high-quality WC powder. Luković, J. et al. (2015) produced the WC powder by reacting tungsten powder with viscose rayon cloth (precursor for carbon) [21]. Sun, P.et al. (2007) produced WC powder by direct process of reduction and carburisation at high temperature [22].

$$WO_3 + 4C \rightarrow WC + 3CO$$

Another method for WC powder production was given by Sagadevan, S. et al. (2017). Tungsten carbide (WC) nanoparticles were obtained by using the hydrothermal method using reagents of AR grade to obtain the precursors (ammonium metatungstate). The WC powder were obtained by heating the tungsten and carbon precursors in a vacuum furnace at 1000^oC for about 1h [23]. Singla, G., et al. (2013) manufactured WC by reduction of WO_3. The samples were synthesized by taking WO_3 as tungsten sources and acetone as a carbon source. Activated magnesium turnings were used as reducing agent [24]. Liu, C. et al. (2016) used Sodium tungstate ($Na_2WO_4.2H_2O$) to produce tungsten carbide [25]. Kim, J.C. et al. (2007) produced tungsten carbide nanopowders by CVC methods [26]. Chemical Vapour Condensation (CVC) process was another method to produce nanostructured WC powders with high purity and grain size of <30 nm.

1.6 HIGH VELOCITY OXY-FUEL SPRAYING METHOD

In various different industries, HVOF spray method was used for providing a corrosion resisting layer on the metal surface. It was a new process as compared to many other coating processes. It was a process in which coating material in the form of powder was fed to the spray gun where coating powder was heated to almost their melting point. The resulting liquid matter in the form of droplet was accelerated towards the metal surface to be coated. It was established that HVOF spray method produced coating with higher resistance to wear as compared to any other coatings. Also, among many coating material, WC-COCr proved to be the best [3]. The molten droplets of coating material when came in contact with the cold metal surface, started to stick to the metal surface and after solidification, became a part of the metal surface itself. Thickness of coating depended on the number of passes [27].

Advantages of the HVOF spray process:

1. Any material that melts without decomposing could be processed by HVOF process.
2. Wide range of material could be coated.
3. Metal surface need not to be heated.
4. Able to renovate the damaged coating without any significant changes.

Disadvantages of the HVOF spray process:

1. Limitations of powder size.
2. Very complex process, required highly qualified personnel for best results.

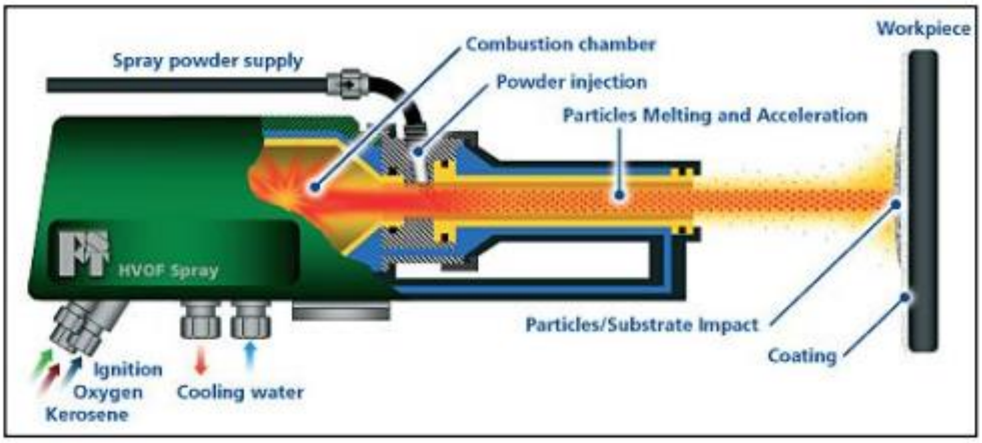

Fig. 1.3 Schematic figure of HVOF spray process [27]

In HVOF spray method, fuel gases like hydrogen, propane and oxygen gas were fed to combustion chamber together with the coating powder. Combustion of different gases created a high pressure and high temperature environment inside the chamber which melted the powder into liquid form. This high-pressured environment forced the molten droplets to be accelerated towards the metal surface to be coated via spray gun. Flame temperature varied from different fuels and gas pressure. (2500 °C to 3200 °C). Coating powder melting depended upon various factors like flame temperature, melting point of coating powder. In HVOF spray method, liquid droplets were fed to gun at very high supersonic speeds, resulting in a better improved coating than any other conventional method. HVOF spray method coating produced very dense coating resulting in better surface properties like high hardness and high thickness. Feedback mechanism (fig, 1.4) was used to improve the coating results.

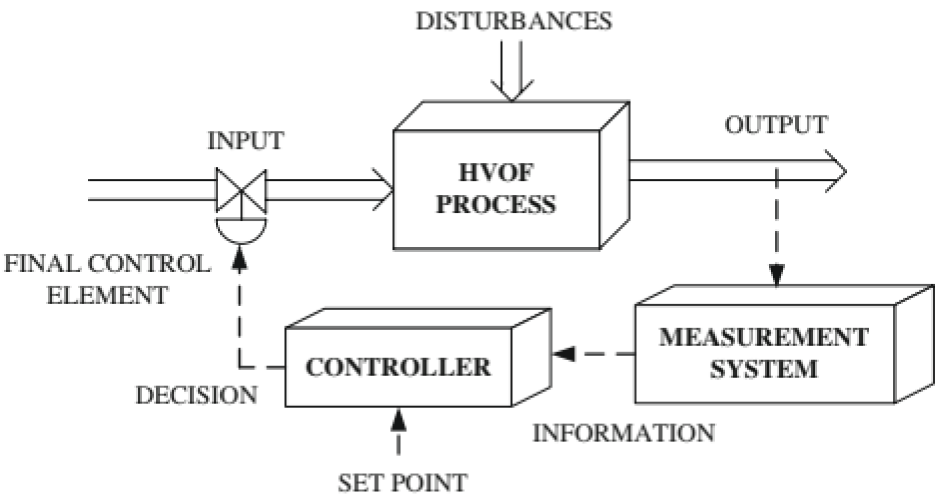

Fig.1.4 Feedback mechanism of HVOF spray method [28]

After the coating process, final result is compared with the initial requirement by using measurement techniques, any difference which was found was noticed and sent to the controller which made the final decision and ordered to make necessary changes at the input stages. Typical HVOF method operated at very high supersonic velocities. These high velocities helped to produce very dense coatings. Main characteristic of HVOF spray method was to produce dense and thick coating without the degradation of the metal with low oxidation and less residual stresses [27].

Table 1.1: Comparison of various spray coating processes [27]

Process	Coating Material Form	Heat Source	Flame Temp. (°C)	Gas Velocity (m/s)	Porosity (%)	Coating Adhesion (MPa)
Plasma Spray	Powder	Plasma flame	12000-16000	500-600	2-5	40-70
Wire Arc Spray	Powder	Electric arc	5000-6000	<300	5-10	28-41
Wire Flame Spray	Wire	Oxy-fuel combustion	3000	<300	5-10	14-21
HVOF	**Powder**	**Oxy-gas fuel combustion**	**3200**	**1200**	**1-2**	**>70**

HVOF was the best process among all the coating processes as concluded from the above table.

1.7 FACTORS AFFECTING PROPERTIES OF COATINGS

In HVOF spray method, degree of coating depended upon various factors like size, porosity of the WC powders [6]. In general, increasing WC content, increases the wear resistance of the coating and decrease the yield strength. Both these properties could be increased by use of small size of carbide particle.

The development of HVOF spray method resulted in continuous increase of the particle velocities and simultaneous decrease of their temperature. The temperature of coating particles depended on the several factors like, type of fuel, cooling gas used, location of injection of powders. High pressure resulted in higher velocities of powder particle which in turn led to the high hardness and high density of the coating [3]. Another important factors which affect the quality of coating was production of coating powders. Irregular shaped powder particle showed less mobility than the spherical shaped powders.

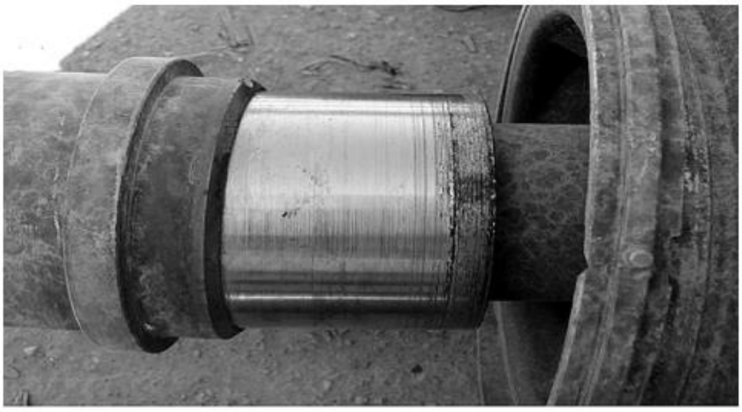

Fig.1.5 Worn shafts of gas turbine [12]

Fig. 1.5 showed the shaft of gas turbine engine degraded in quality over time. Generally, the use of powders with narrow sizes was beneficial in terms of coating density, as the particles impinging on the substrate surface became more and more homogeneous. The differences in expansion rate between the material and coating on cooling leads to residual stress build up and can result in cracking of the coating. While plasma sprayed coatings generally showed tensile residual stresses, high compressive residual stresses were obtained in the case of HVOF spray method. Compressive residual stresses were beneficial with regard to fatigue characteristics. WC-COCr promotes formation of compressive stress more than WC-Co [3]. Post-heat treatment of sprayed coatings can be carried out to influence the residual stresses [4].

During coating process, phase transformation of coating materials also occurs which very much decided the coating efficiency. The oxidation of WC-CO coating particles resulted in significant amount of phase like W_2C and other mixed carbides. Composition of powder and type of fuel used very much determined the phase transformation occurred during the process. Mixed carbides formed during phase transformation were also called η-phases. Phase transformation was maximum at the high temperature zone. It was found that phase transformation was less, when powder was injected behind the combustion chamber (low temperature zone). Impact velocity of the particle was the important factor in determining the hardness and strength of the coating. High hardness and strength were recorded where converging diverging nozzle was used. This type of nozzle produced very high impact velocities. During powder production, shape of particle very much determined the porosity of the coating. Dense and irregular shaped particles were hard to melt in HVOF spray method and therefore led to coating with high porosity.

In comparisons, WC-COCr and WC-CO coatings showed similar hardness, microstructure but corrosion resistance of WC-COCr was more as compared to WC-CO coatings [5]. Small grain size, low impact velocity and high temperatures during the HVOF spray method led to WC decomposition resulting in bad quality of coatings. Decomposition had been shown to affect the wear behaviour of the coating [6]. HVOF spray method shown to have decreased decomposition of WC material because of high impact velocities and fine grain sizes of powder. During decomposition, WC was decomposed to W_2C which led to the decrease in hardness of coating and depleting wear resistance [9]. Coating characteristics were also affected by the spray system and the spray parameters [10]. Oxidation during the spraying process was dominant factor in affecting the life of the components and was the major cause of failure. Oxidation became more dominant in high temperature situations. Humidity also played an important role in producing high wear resistant coating [11]. Repairment of turbine shafts by chromium plating could easily be replaced by the HVOF spray process [12]. Decarburization occurred during HVOF spray method at high temperatures couldn't be totally eliminated. That could be minimized by changing the flame condition [13].

- CHAPTER SUMMARY

1. Friction and wear led to the degradation of metal surface properties.
2. Tungsten carbide (WC) hard coatings done by HVOF spraying is one way to curb the problem of surface deterioration which is being studied in this report.
3. HVOF Spray method is a technology for applying corrosion resistant coatings on metal surfaces.
4. HVOF spray processes can be used on wide variety of materials. A major disadvantage is the particle size restriction and inability to coat deep small areas where gun couldn't enter.
5. Various factors affect the quality of coating like flame temperature, grain size, particle velocity.
6. It has been established that coatings done by HVOF Spraying has significant advantages over any other counterpart.

CHAPTER – 2

LITERATURE REVIEW

2.1 STUDIES RELATETD TO TUNGSTEN CARBIDE COATINGS AND HVOF SPRAY PROCESS

A comprehensive literature survey of tungsten carbide coatings & HVOF spray process has been reported in the below matrix. (Table 2.1)

TABLE 2.1: Literature matrix

S.NO.	AUTHOR	JOURNAL	AIM	RESULTS & DISCUSSION
[1]	Kornaus et al. (2016)	Polish Journal of Chemical Technology	To check whether the addition of graphene nano platelets (GNP) to tungsten carbide (WC) would affect its properties.	Tungsten carbides graphene composites were possible to manufacture but addition of GNP decreases the thermal and mechanical properties of the tungsten carbide.
[2]	Richert et al. (2012)	Archives of Metallurgy and Materials	To produce the nanocomposites tungsten carbide WC coatings by EBPVD method	Coating containing Co and C carbides produced hardness of 510HV. While the WC coating produced hardness of 1266 HV (almost twice), this was because of presence of hard carbides which were not present in the former.
[3]	Wielage et al. (2003)	Conference on Modern Wear and Corrosion Resistant Coatings Obtained by Thermal Spraying	Different factors affecting the Properties of WC coatings were discussed.	Coatings produced by HVOF spray method showed higher wear resistance as compared to APS Cr_2O_3 and hard chromium coatings. Tungsten carbide produced the best coatings as compared to others. Higher thermal conductivity was shown by the coating of maximum hardness.
[4]	Kiilakoski et al. (2015)	Tribologia-Finnish Journal of Tribology	To study wear mechanism of WC coatings in paper machine environment	Properties of powder particles were turned out to be the important factor in deciding the effectiveness of HVOF spray produced coating. Strength of powder particles was important for increasing wear resistant.

[5]	Schwetzke et al. (1999)	Journal of thermal spray technology	To compare various different HVOF spray systems using different coating materials	Phase transformation occurred during WC based coatings determine the quality of coatings. This phase transformation depended on the amount of heat transferred to the coating particles in the different spray systems and the flame temperature used. Hardness and strength of coating were mainly determined by the impact velocity of the powder particles. Irregular shaped powder particles produced hindrance in the HVOF spray process. Corrosion resistance of WC-COCr proved to be the best among the other coating materials.
[6]	Özbek et al. (2016)	Acta Phys Polonica A	Woka 5810 powder was used as coating material to produce coating via HVOF spray method.	Coating process was affected by the process parameters and maximum hardness was found to be 1021 HV.
[7]	Angrisani et al. (2018)	Advanced Engineering Materials	Magnetic properties of tungsten carbide coating produced by HVOF spray method were investigated.	WC coatings contain cobalt matrix which was magnetic in nature. This property of coating could be exploited to use coatings as a magnetic storage unit. The thickness of the coating directly influenced the magnetic remanence.
[8]	Santos et al. (2017)	In Journal of Physics: Conference Series, IOP Publishing	Variation in properties of steel were studied after quenching, tempering and tungsten carbide coating	Hardness was improved by 5.5 % by quenching and tempering process while it showed 124.2% increase in hardness for WC coatings as compared to steel substrate. Material loss was lowest for WC coating as compared to quenching and tempering process.

[9]	Koutsomichalis et al. (2017)	In IOP Conference Series: Materials Science and Engineering, IOP Publishing	To study the wear behaviour of tungsten carbide coating on aluminium done HVOF spray method	Reduction in tensile strength was observed in case of WC coatings on aluminium. Increasing applied load increases the wear volume.
[10]	Krishna et al. (2002)	"International Journal of Refractory Metals and Hard Materials"	To evaluate the newly developed fuse WC coating produced by oxy-acetylene spray system using different fuel ratios	Fused WC contains two phases namely, WC and W_2C. Higher wear resistance coating could be produced by using fused WC. HVOF spray system could be used to produce more fine quality of coatings as compared to oxy-acetylene spray system
[11]	Bhosale et al. (2018)	An International Conference on Tribology	To study wear and oxidation of tungsten carbide coatings done by different spray methods.	Wear performance of WC coatings was strongly influenced by key factors such as, deposition techniques, substrate, thickness, temperature, humidity, load and speed. The hot corrosion resistance of WC-Cr_3C_2-Ni is superior to other WC coatings due to addition of chromium and nickel.
[12]	Sahraoui et al. (2003)	Materials & design	To study wear behaviour of Cr_3C_2-NiCr and WC–CO coatings done by HVOF spray process	WC coatings performed better than those of Cr_3C_2-NiCr coatings. HVOF spray method came out as a great alternative for hard chromium plating
[13]	Nerz et al. (1992)	Journal of Thermal Spray Technology	Tungsten carbide cobalt coatings produced by HEP and HVOF spray process was studied	Recrystallised coatings had superior wear resistance as compared to other coatings. This was due to the presence of eta phase.

[14]	Zhong et al. (2011)	Journal of Materials Science	Tungsten carbide cobalt powders was manufactured using WO_3, Co_3O_4 and graphite	For the first time IMTA process was used to produce nanostructured WC -CO powders. During carburisation, growth of grains had taken place.
[15]	Ksiazek et al. (2016)	Journal of Materials Engineering and Performance	Effect of nickel on the properties of WC-CO coatings on iron was studied	Dense coating with low porosity and high hardness was obtained by WC-CO + Ni coating done by HVOF spray method. Addition of nickel resulted in a high corrosion resistance of the coating.
[16]	Jacobs et al. (1998)	Journal of thermal spray technology	Comparisons of WC coatings produced by HVAF and HVOF spray methods were discussed	It was found that HVAF spray method did not change the chemistry of the coating powders during spraying. No oxidation took place during the HVAF resulting in 100% retention of WC powders. Also, no phase changes occurred during HVAF. HVAF produced better results in different tests (high hardness, better wear resistance). HVAF proved to be the better alternative for the HVOF spray method.
[17]	Shipway et al. (2005)	Wear	To compare the performance of conventional and nanostructured coating materials in the form of coatings done by HVOF spray method.	Higher level of decomposition was found in the case of nanostructured powder. nanostructured coatings exhibited higher wear rate than the crushed and sintered counterpart.

[18]	Stewart et al. (1999)	Wear	To study the wear performance of conventional and nanostructured coating materials in the form of coatings done by HVOF spray method	Wear resistance of the WC-CO sintered nanocomposites was more as compared to their conventional counterpart. However, under wide range of test conditions, WC-CO coatings done by HVOF spray method was shown to have higher wear rates as compared to conventional powders.
[19]	Stokes et al. (2004)	Surface and Coatings Technology	To calculate the residual stresses in spray processes based on their properties	Residual stress developed during spray process was depended on various different factors. Coating thickness was shown to have significant changes in the stress level.
[20]	Tan et al. (1999)	Journal of Materials Processing Technology	Damaged tools were repaired by using the HVOF spray method	The HVOF spray method was successfully used to repair the damaged stainless-steel tool. Either substrate was not able to be repaired with the WC-CO material within the range of used spray parameters. It was also found that long spraying time was required for repairing nitride components.

Li et al. [28] found that there were many areas inside the HVOF spray method that needed some major development like oxidation during process, melting of powders, solidification after process, effect of irregular shaped powder particles on the residual stresses and coating characteristics. Brandt [31] found that HVOF spray method produced coating with porosity level of less than 1% acted like homogenous material. Coating produced had higher young's modulus which make them suitable for aluminium industry. Manjunatha et al. [29] concluded that the erosion rate was decreased with increase in content of NiCr metallic binder and decrease in porosity of the coating by using HVOF method. It was also concluded that HVOF sprayed Cr_3C_2/NiCr coatings offered good corrosion resistance. As given in Fig. 2.1, it was observed that erosion rate first increases and attained maximum value at impingement angle 75^o, then decreases after reaching a minimum value at an impingement angle 90^o. Erosion resistance strongly depended upon the impact angle. Pre heating of coating material and addition of binder NiCr also enhances the resistance.

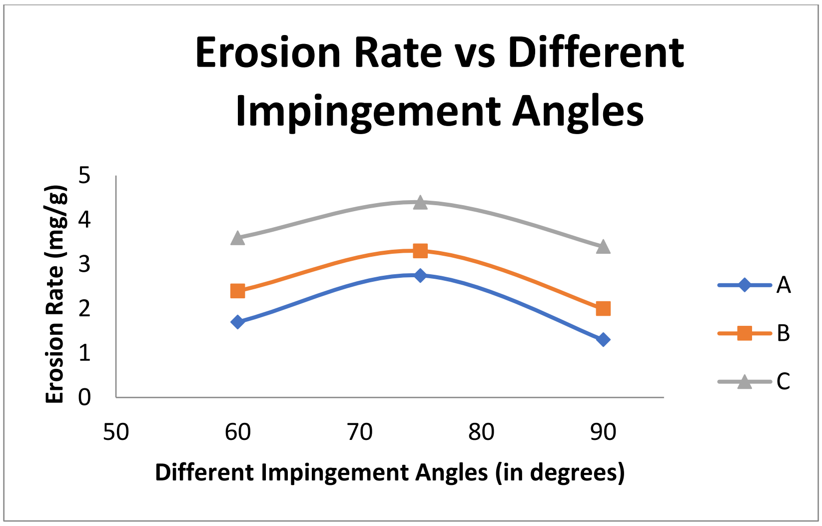

Fig.2.1 Erosion rate vs impingement angle for different samples [29]

Krelling et al. [30] found that wear resistance of tungsten carbide coating done by HVOF process was 500 times better than the Q&T condition. For chromium coating, wear resistance was 2 times better than the Q&T condition. Plastic deformation occurred during process (which led to abrasion) was the main reason for wear in the samples. Fig. 2.2, showed high hardness achieved during the tungsten carbide coating as compared to hard chromium plating.

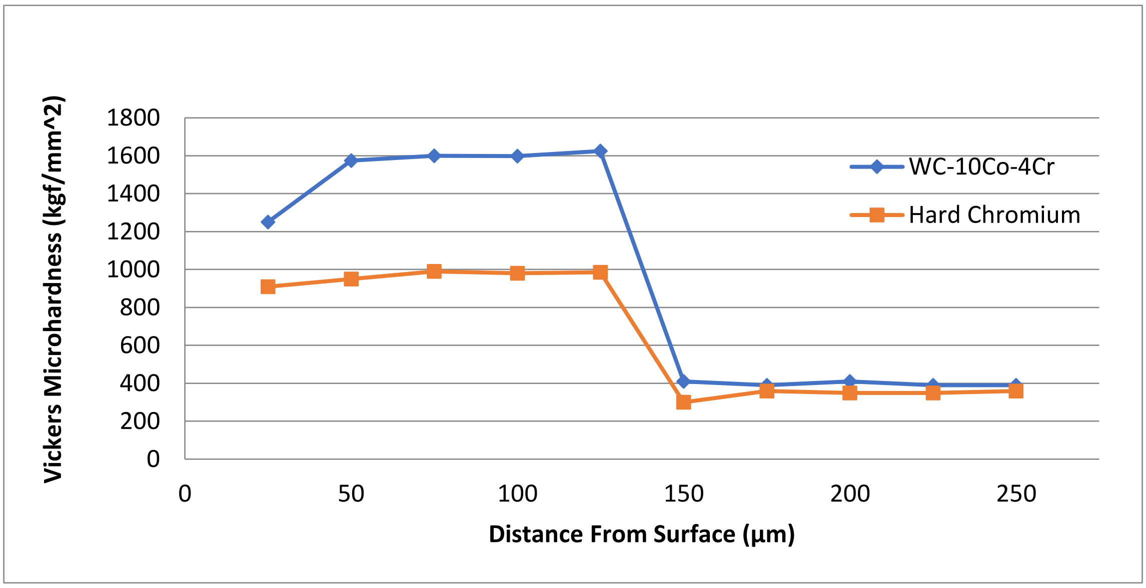

Fig.2.2 Hardness profiles of Hard Chromium and WC-10Co-4Cr HVOF sprayed coatings [30]

Moskowitz [32] investigated the use of HVOF spray method in petroleum industry. It was concluded that HVOF spray method offered the best cost-effective solutions for the problems encountered in harsh conditions of petroleum industry because of the rapidness, portability and low temperature to the base metal. With little modifications in gun motion, large areas could easily be coated with best results. Gupta et al. [33] concluded that with the help of HVOF spray method, coating hardness up to 1500HV could be achieved with less than 1% porosity level with overall uniform coating thickness. Nascimento et al. [34] compared WC coating done by HVOF spray process with the hard chromium electroplating on a steel substrate. It was observed that there was no change in microstructure to the base metal in both process and wear loss showed better outcome for WC coating as compared to hard chromium. Sidhu et al. [35] observed that HVOF spray method produced coatings of exceptional high quality with high thickness, high hardness and less effect on surrounding environment. But more detailed investigation needed to be done to explore the possibility of producing the coatings in high temperature environment. Guilemany et al. [36] found that temperature obtained by substrate (34Cr-4Mo) at the interface while coating by HVOF spray process was not high enough to melt the substrate which led to the residual stresses inside the system.

Lima et al. [37] found that adding hydroxyapatite (HA) on metal substrate during HVOF process led to high crystallize coating with no secondary phase. And after incubation period, layer of HA was found on coating which was thicker than any conventional HA coatings. The uniform coating produced during process was found to have met the requirements of ISO 13779-2. Scrivani et al. [38] found that WC/Mo compound processed by HVOF spray method had higher resistance than Inconel 625. Wielage et al. [39] in their findings found that HVOF spray coatings were capable to protect Al components which were subjected to dynamic loading without decreasing their fatigue strength. Also, cost of coatings could be decreased by the usage of fine powders because they would take less amount for the grinding process. Singh et al. [40] found that tungsten carbide and stellite-6 coating on GI250 iron showed less volume loss as compared to bare specimen. WC-12CO coating was used to reduce the wear rate of braking disc rotor.

Again, Ksiazek et al. [41] found that composite carbide coating (Cr_3C_2-NiCr+Ni) done by HVOF spray method produced dense coating with low porosity and high hardness. This coating gave good resistance to the cast iron against cracking. Failure only occurred inside the coating leaving the cast iron substrate surface intact. Interestingly, it was found that coating produced by tungsten carbide material could be used as a magnetic storage. Since, WC-CO coating contained magnetic cobalt matrix, they could be used as a storage unit of relevant data. For example, serial numbers could be directly fed into the coatings and that data information would be immune to the outside degrading environment. Conventionally, RFID Chips were used to store the data which were prone to be damaged by wear, humidity and friction. And, this type of data could not be changed easily. On the other hand, magnetically stored data could be replaced easily afterwards [7]. Nanostructured coating showed excellent properties and could improve the performance of conventional plasma coatings [8].

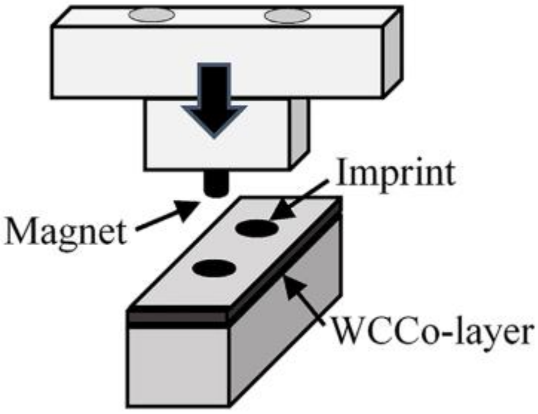

Fig.2.3 WC-CO coating used as a magnetic storage unit [7]

Żórawski [43] concluded that hardness obtained by WC-12CO coating done by HVOF spray process was 20% more as compared to the conventional coating. Singh et al. [44] obtained significant improvement in hardness in case of WC-12CO coated material. Also, same coated material showed improvement in erosion wear resistance among all other substrates namely mild steel, SS304, SS202. Using taguchi analysis, it was found that speed was the dominant factor which was also validated by ANOVA. Fayyazi et al. [45] used taguchi robust design to improve the resistance of tungsten carbide coating applied by HVOF spray method. It was found that grit blasting process had a major impact on the impact resistance.

2.2 RESEARCH GAP

The roughness of conventional WC coatings is still too large to permit direct usage in most industrial applications. Achieving smooth surface using diamonds while grinding led to the higher cost of the process, so alternate methods should be studied. For achieving great results, it was found that process optimization was a must to reduce the WC decomposition. Powder particles time at high temperature needed to be minimized for great coating results. HVAF (High Velocity Air Fuel) spay method was found to be a great alternative for HVOF spray method. HVAF used compressed air instead of oxygen which led to decreased flame temperature resulting in a superior wear resistance as compared to HVOF spray process. Residual stresses generated during HVAF spray process could be manged easily as compared to HVOF. Dense powders were difficult to process under HOVF, so more research was needed on that matter.

In general, HVOF spray method was a very good method to produce high quality of coatings, but more research was needed to reduce its operating costs and complexity. More research was needed to reduce the effect of residual stresses build up during the process. Powder injection process during the HVOF spray process played a very important role in the effectiveness of the coating, more research was needed on that matter as well.

- CHAPTER SUMMARY

Various previous studies regarding tungsten carbide coating and HVOF process were studied and mentioned in a matrix form. Pertaining to studies, it can be inferred that tungsten carbide coating improves the surface properties of metal surfaces.

CHAPTER – 3

EXPERIMENTAL SETUP ASSEMBLY

3.1 INTRODUCTION

HVOF spray system consists of two, namely:

1) The Spray system assembly.
2) The Support system assembly.

The spray system alone couldn't be able to perform coating operation efficiently until it was geared with support system assembly.

3.2 SPRAY SYSTEM ASSEMBLY

Spray system assembly consisted of the equipment needed for spraying process and their associated units. For this report, HIPOJET 2700 HVOF Spray system, manufactured by Metallizing Equipment Co. Pvt. Ltd. was used. The main purpose of the spray assembly was to transfer coating powder at a very high speed for achieving better quality of coatings. Fig. 3.1 shows the spray system assembly. It consisted of the following:

1. Spray gun
2. Control console
3. Powder feeder
4. Gas regulator
5. Air control unit
6. Hose unit
7. Trolley

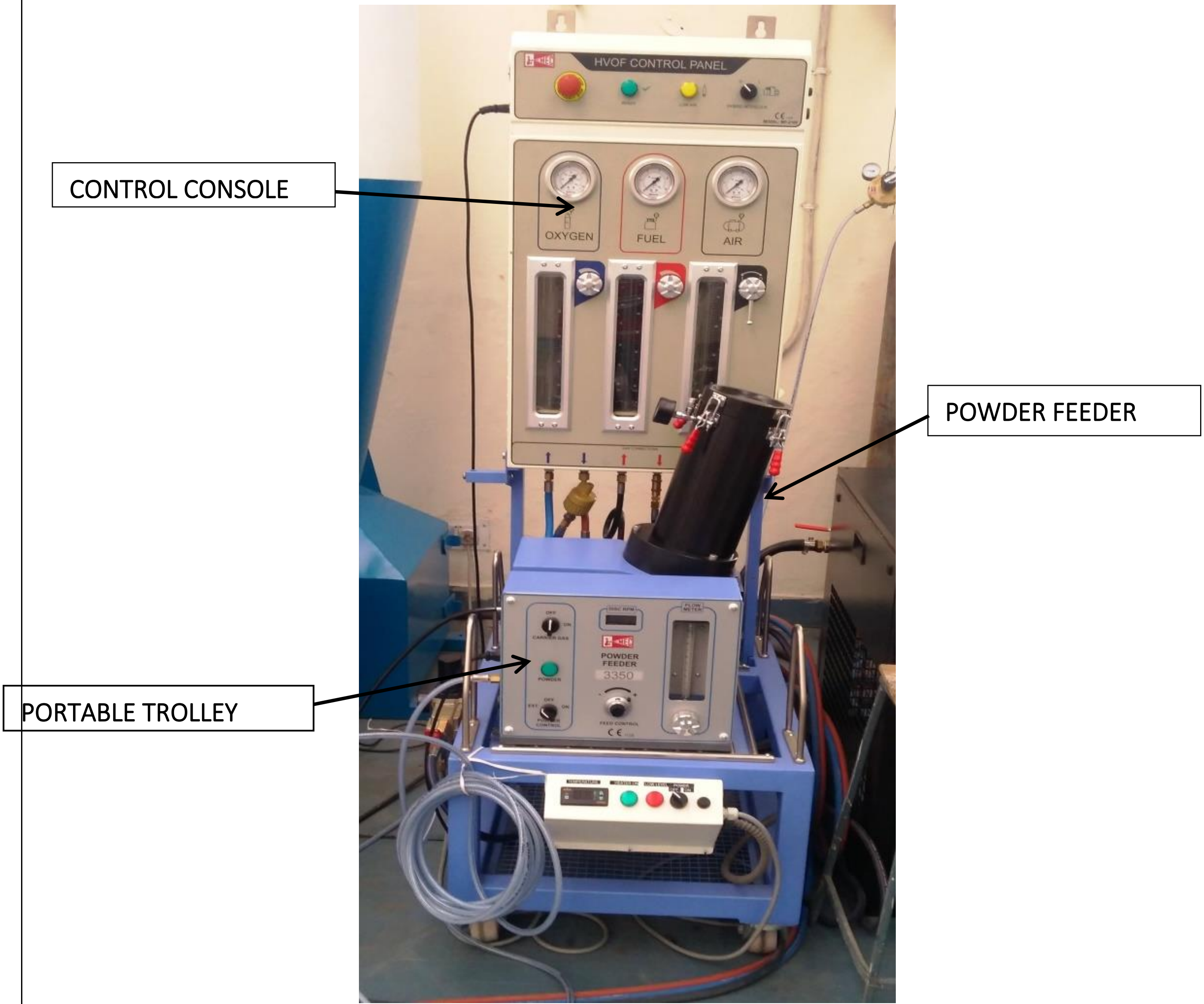

Fig. 3.1: HVOF Spraying System

Image Source: Precision Manufacturing Lab, Department of Mechanical Engineering, Delhi Technological University; Dated: 14/4/2019

3.2.1 SPRAY GUN

Spray gun was an important spray device. It was used for applying the main coating material on the substrate. It could be modified differently to suit different HVOF applications. Thermal efficiency of the gun was high, it had precise machined parts and could be used for long time.

Fig. 3.2: HIPOJET 2700M Spray Gun

Image Source: Precision Manufacturing Lab**,** Department Of Mechanical Engineering, Delhi Technological University; Dated: 14/4/2019

3.2.2 CONTROL CONSOLE

The console was the main part of the spray system. Connected between the gun and gas supplier, it acts as an indicator for gas flow. Three gauges were provided, each for different gases namely, oxygen, air and fuel gas. It contained flow meters for each of these gases. Valves were used to adjust the flow.

3.2.3 POWDER FEEDER

Powder feeder was used to deliver powder to the gun at a precise rate. Carrier gas pressurize the powder to move towards the spray gun. It was a robust machine designed to withstand harsh thermal spray temperatures.

3.2.4 GAS REGULATORS

Gas regulators regulates the flow of gases inside the HVOF spray assembly. It also consists of manifold to connect the multiple cylinders.

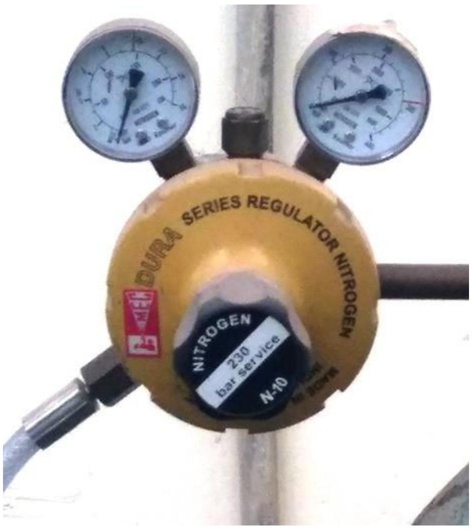

Fig. 3.3: Gas Regulator

Image Source: Precision Manufacturing Lab**,** Department of Mechanical Engineering, Delhi Technological University; Dated: 3/12/2019

3.2.5 HOSE UNITS

Hose units consisted of multiple high quality pressure hoses equipped with proper fittings for the spray gun. These hoses connected the gun with the console. It consisted of black hose for air, green for oxygen and red for fuel gas.

3.2.6 TROLLEY

Trolley was used for mounting and movement of the components namely, feeder, gun & console. Movement of various different parts helped in producing the good quality of coatings.

3.2.7 AIR CONTROL UNIT

Air control unit was needed for removing the moisture content from the compressed air with the help of filters. It also regulates the air pressure.

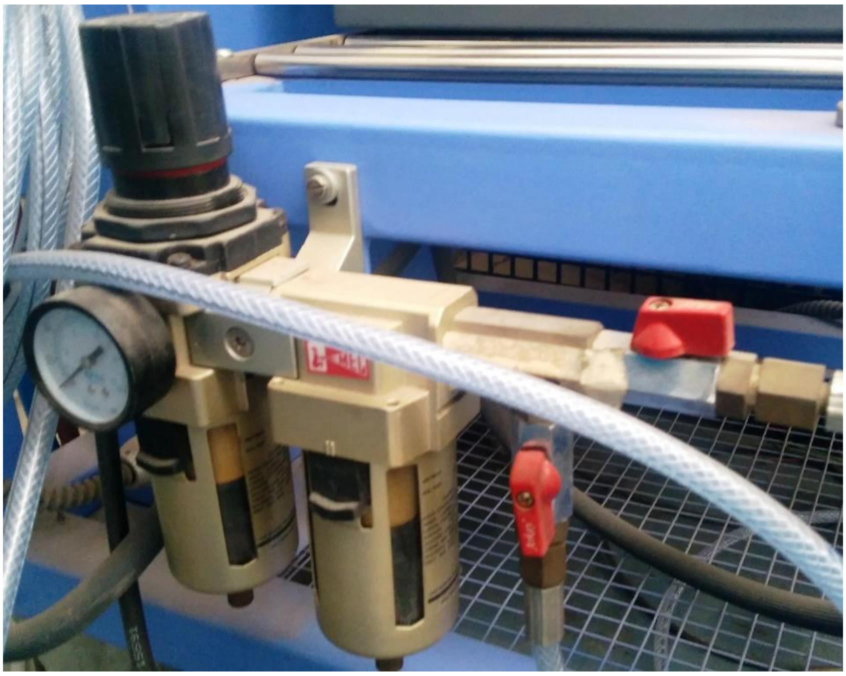

Fig. 3.4: Air Control Unit

Image Source: Precision Manufacturing Lab, Department of Mechanical Engineering, Delhi Technological University; Dated: 3/12/2019

3.3 THE SUPPORT SYSTEM ASSEMBLY

The support system assembly of HVOF was needed to ensure the safe working of the process. Substrate surface needed to be cleaned and roughened up before the procedure. Movement between gun and substrate was needed for high quality of coating. Safety of the operator was very important. To ensure all above mentioned factors, support system assembly was setup.

1. Electrical unit and gas supply unit
2. Spray booth
3. Exhaust system
4. Grit blasting equipment
5. Mechanical handling units
6. Furnace
7. Measuring Instruments

3.3.1 ELECTRICAL UNIT AND GAS SUPPLY UNIT

Powder feeder, compressor, dust collector, console unit needed electrical supply at different voltages. Specification of various parts of HVOF systems are given in Table 3.1. Different gases were needed inside the HVOF system for operation like nitrogen was required as a carrier gas, oxygen was used as oxidant for combustion, propylene was used as a fuel.

TABLE 3.1: Specification of various parts of HVOF systems

SPRAY GUN	
WEIGHT	1.85KG
GASES	Oxygen, Propane, Air
CONSOLE	
CONSOLE DIMENSIONS	870 x 500 x 140 mm
WEIGHT	39KG
ELECTRICITY	110 V-1P-50 Hz
POWDER FEEDER	
CAPACITY	700CC
WEIGHT	32 KG (70.4lb)
ELECTRICITY	110V/IP/60 Hz/140W

TABLE 3.2: Gas flow rate and their respective pressure

GAS	**FLOW (LPM)**	**OPERATING PRESSURE (Kg/cm^2)**
OXYGEN	250-350	10
PROPANE	60-80	7
AIR	600-700	7

TABLE 3.3: Spray rate and their respective deposit efficiency of different coating powders

POWDER	**SPRAY RATE (g/min)**	**DEPOSIT EFFICIENCY (%)**
WC-12CO	38	70
WC-17CO	38	60
WC-10CO-4Cr	38	70

3.3.2 SPRAY BOOTH

Spray booth in HVOF system was used to provide a protected area for coating to be done. During HVOF, this protected area provides a suitable place for the coating by minimizing the danger of dust explosion. Fig. 3.5 shows the spray booth.

Fig. 3.5: Spray Booth

Image Source: Precision Manufacturing Lab, Department of Mechanical Engineering, Delhi Technological University; Dated: 14/4/2019

3.3.3 EXHAUST SYSTEM

During HVOF process, dust gets accumulated and dangerous fumes were formed which could become hazardous for the operator. So, proper ventilation was required which was done by exhaust system.

3.3.4 GRIT BLASTING APPARATUS

Before applying coating on substrate, its surface needed to be cleaned and roughened. That ensured the better adhesion of coating material on the surface. This was done by using grit blasting apparatus.

3.3.5 MECHANICAL HANDLING UNITS

Movement between substrate and spray gun was essential for achieving better coating. This is done with the help of handling unit.

3.3.6 FURNACE

A furnace was used to heat the sample before coating so that better coating on the material could be achieved.

3.3.7 MEASURING INSTRUMENTS

During experimentation different parameters like coating thickness, hardness, roughness, porosity, wear rate needed to be measured. This was done by various measuring instruments.

- CHAPTER SUMMARY

Various parts of HVOF Spraying system had been thoroughly studied with their workings and respective specifications. The HVOF spray system consists of gun, controller, feeder, gas and air control unit and trolley. And, the support systems consist of electric supply and gas supply unit, spray booth, exhaust system, grit blasting apparatus, mechanical handling unit, furnace and measuring instruments.

CHAPTER - 4

EXPERIMENTAL PROCEDURE AND RESULTS

4.1 INTRODUCTION

Careful and precise experimentation was a necessity while doing any kind of research. Many factors decide the outcome of the experiments. Therefore, proper planning was needed before conducting any experiment. In this chapter experimental results were recorded after performing experiments involving different factors and their different levels. After that optimization of the process was done using Taguchi and ANOVA methods in MINITAB 17 software.

4.2 MATERIAL SELECTION

The SUS 400 stainless steel was chosen as specimen for experimentation. It contains 11-27% chromium, max 1% carbon and max 2.5% nickel. It had wide variety of application in industries involving motor shafts, turbine exhaust and more. It was not as corrosion resistance as the 300 series stainless steel but was stronger and provide a more cost-effective solution. Therefore, optimization of its surface properties was essential.

4.3 TAGUCHI METHOD

Taguchi method reduces the variation in the process by creating a robust design of experiments. Main target of this method was to increase the quality of product at a low cost. Taguchi proposed minimum amount of experimentation by conducting experiments only for important pair of combination of factors, thus saving time and resources.

Taguchi method involves the following steps:

1. Define the objective (whether to maximise or minimise something),
2. Define different parameters affecting the objective. Different parameters had different levels of operations.
3. Design a taguchi orthogonal array for the available parameters and their levels.
4. Perform experiments according to taguchi array to collect the data.
5. Analyse the data using s/n ratio to determine the effect of different parameter on the objective.

Taguchi used S/N ratio (signal to noise ratio) to calculate the optimized parameters. S/N ratio is divided into following:

1. Normal is better
2. Smaller is better
3. Larger is better

In this project report, larger is better was selected for computing maximum hardness and smaller is better was selected for computing minimize surface roughness.

For minimizing the performance, the definition of the S/N ratio used should be calculated as:

$$SNi = -10\log\left(\sum_{u=1}^{Ni}\frac{Yu^2}{Ni}\right)$$

For maximizing the performance, the definition of the S/N ratio used should be calculated as:

$$SNi = -10\log\left[\frac{1}{Ni}\left(\sum_{u=1}^{Ni}\frac{1}{Yu^2}\right)\right]$$

Where, i = experiment number,

u = trial number

Ni = number of trials for experiment i.

4.4 ANOVA

Analysis of variance (ANOVA) was an important decision-making tool to identify the significance of each important factors. It was used to get the percentage contribution for each parameter on the process. It was a very versatile method used to analyse the complex system with various variables and different levels.

4.5 EXPERIMENTAL PROCEDURE

SUS400 stainless steel substrate was coated with tungsten carbide (WC-12CO) with the help of HVOF spray method. The coating parameters were listed in Table 4.1 along with their different levels. Keeping in mind the parameters, experiments were done to obtain the optimum conditions for maximum hardness and minimum surface roughness. Four parameters were chosen namely, oxygen rate (O), propane rate (P), powder feed rate (PF) and spray gun distance (SD). Taguchi orthogonal array were shown in Table 4.2.

TABLE 4.1: Parameters with their range level [42]

PARAMETERS	**RANGE**	
	Level 1	**Level 2**
OXYGEN RATE (l/min) ‘O’	260	280
PROPANE RATE (l/min) ‘P’	16.7	18.3
POWDER FEED RATE (g/min) ‘PF’	102	111
SPRAY GUN DISTANCE (mm) ‘SD’	262	286

TABLE 4.2 Taguchi Orthogonal Array [42]

EXP	O	P	PF	SD	H (HV)	Ra (µm)
1	260	16.7	102	262	1329.55	6.842
2	260	16.7	111	286	1249.33	6.943
3	260	18.3	102	286	1208.63	6.944
4	260	18.3	111	262	1251.30	6.850
5	280	16.7	102	286	1308.70	6.961
6	280	16.7	111	262	1257.10	6.363
7	280	18.3	102	262	1248.40	6.333
8	280	18.3	111	286	1184.67	6.798

Here, maximum hardness was needed, so larger is better option was applied for hardness and minimum surface roughness was needed so, smaller is better option was applied. Table 4.3, depicts the S/N Ratio for both hardness and surface roughness.

TABLE 4.3: S/N Ratio for Hardness (H) (SNRA1) and Surface Roughness (Ra) (SNRA2)

H (HV)	SNRA1	Ra (µm)	SNRA2
1329.55	62.4741	6.842	-16.7037
1249.33	61.9335	6.943	-16.8309
1208.63	61.6459	6.944	-16.8322
1251.30	61.9472	6.850	-16.7138
1308.70	62.3368	6.961	-16.8534
1257.10	61.9874	6.363	-16.0732
1248.40	61.9271	6.333	-16.0322
1184.67	61.4719	6.798	-16.6476

4.6 RESULTS

4.6.1 For Hardness

- **S/N Ratio Method**

For maximum hardness, larger is better option was used. Therefore, the greater the value of delta indicated more effect of parameter on hardness. Table 4.4 depict the optimum conditions by using S/N Ratio.

TABLE 4.4 Conditions for hardness by using S/N Ratios (Hardness)

LEVEL	O	P	PF	SD
1	62.00	62.18	62.10	62.08
2	61.93	61.75	61.84	61.85
DELTA	0.07	0.43	0.26	0.24
RANK	4	1	2	3

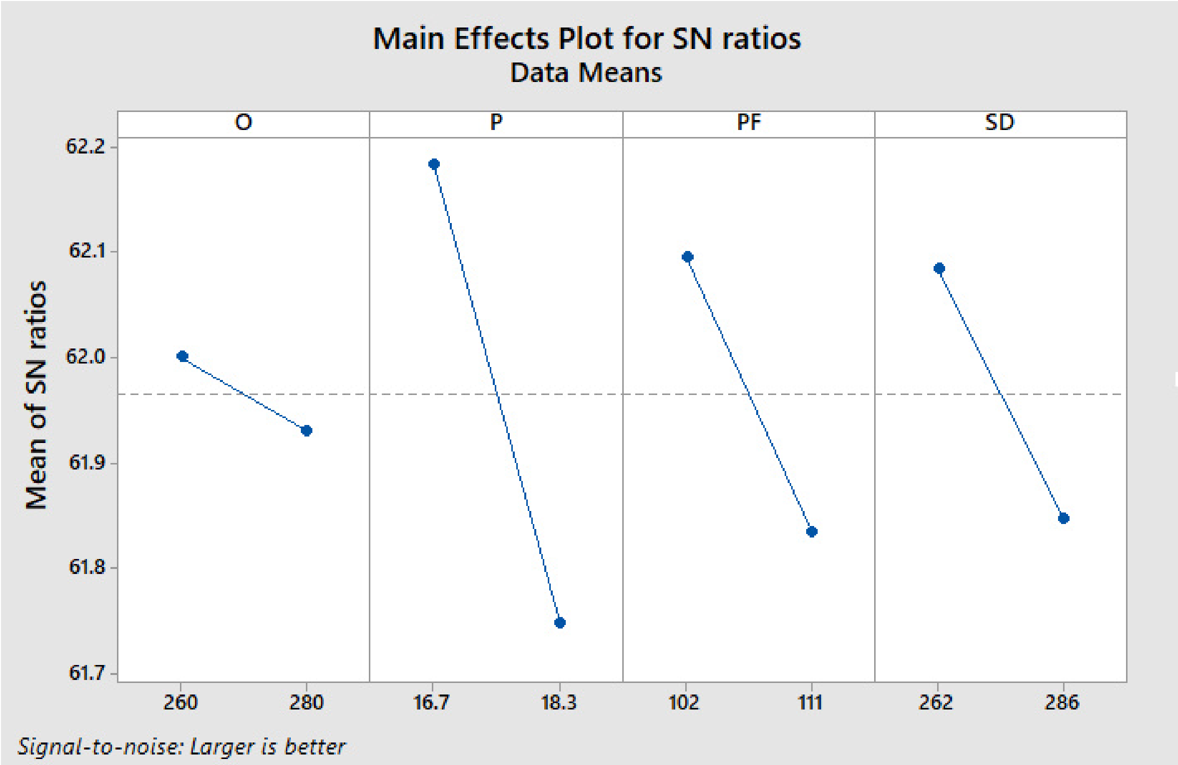

Fig. 4.1: S/N Ratios plot (Hardness)

Source: MINITAB 17

Table 4.4 showed the delta values of each parameter. According to that, most important parameter for achieving maximum hardness was turned out to be the Propane rate (P), followed by the Powder feed rate (PF), Spraying Distance (SD) and Oxygen rate (O). And, the optimum conditions for each parameter (according to Fig. 4.1) were as follows: (O, 260), (P,16.7), (PF, 102) and (SD, 262).

- **ANOVA Approach**

Percentage contribution for each parameter was obtained by ANOVA. As shown in Table 4.5, Parameter Propane (P) contribution was highest (around 50.78%) which was predicted by taguchi as well. Others parameters also influenced the experiment like Powder Feed (PF) around 17.83%, Spray Distance (SD) around 15.53% and Oxygen (O) around 1.31%. same relation also shown in fig. 4.3.

TABLE 4.5 ANOVA Approach (Hardness)

Parameter	DF	F-Value	p-Value	Contribution
O	1	0.27	0.639	1.31%
P	1	10.48	0.048	50.78%
PF	1	3.68	0.151	17.83%
SD	1	3.21	0.171	15.53%
ERROR	3			14.54%
TOTAL	7			100%

- **Verification**

Verification test was conducted to authenticate the validity of predicted value obtained by using S/N ratio. The predicted value was 1327.15 HV as shown in Fig. 4.2.

Predicted values

```
S/N Ratio     Mean
  62.4666  1327.15
```

Fig. 4.2: Predicted Values (Hardness)

Source: MINITAB 17

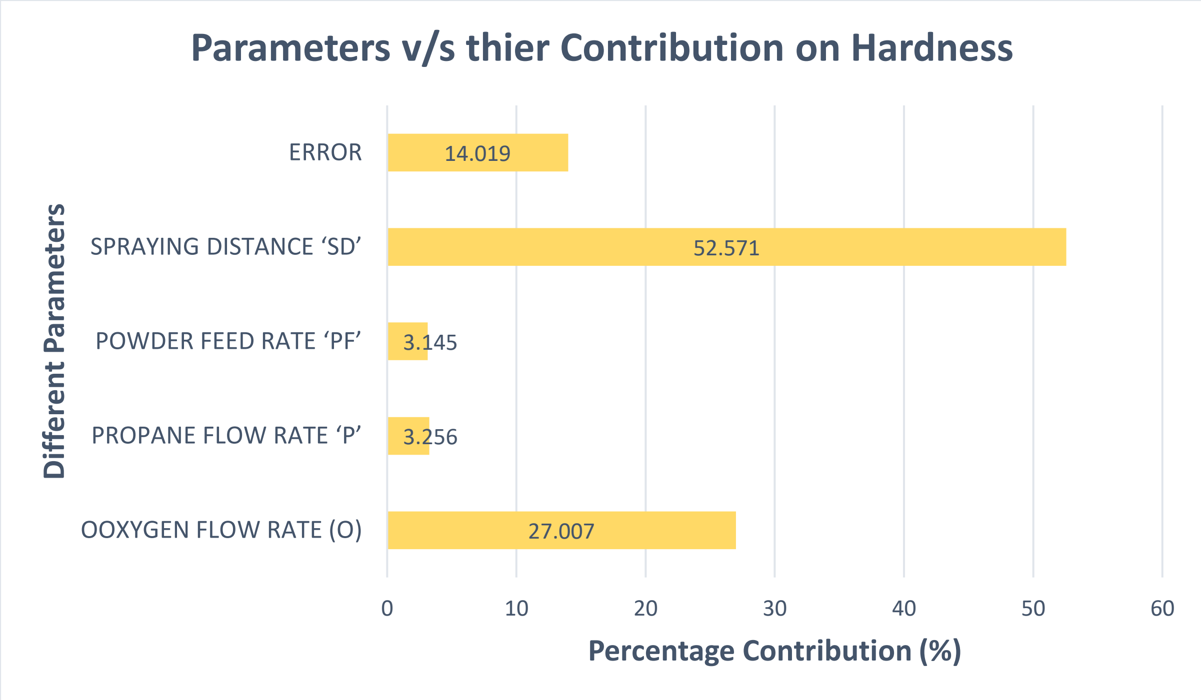

Fig. 4.3: Graph depicting the percentage contribution of each parameter on hardness

Source: Self made

TABLE 4.6 Verification Table (Hardness)

Optimum Parameters		**Hardness (HV) (Actual)**	**Hardness (HV) (Predicted)**	**Error %**
OXYGEN RATE 'O'	260 l/min	1329.55	1327.15	**0.181**
PROPANE RATE 'P'	16.7 l/min			
POWDER FEED RATE 'PF'	102 g/min			
SPRAY GUN DISTANCE 'SD'	262 mm			

As shown in table 4.5 Actual value and predicted value is almost same with the error of 0.181%. The optimal condition using different approaches was verified.

4.6.2 For Surface Roughness

- **S/N Ratio Approach**

As mentioned before, for minimum surface roughness, smaller is better option was used. Therefore, the greater value of delta indicated more effect of parameter on hardness. Table 4.7 depict the optimum conditions obtained by S/N Ratio.

TABLE 4.7: Conditions for surface roughness obtained by S/N Ratio (Surface Roughness)

LEVEL	O	P	PF	SD
1	-16.77	-16.61	-16.61	-16.38
2	-16.40	-16.56	-16.57	-16.79
DELTA	0.37	0.06	0.04	0.41
RANK	2	3	4	1

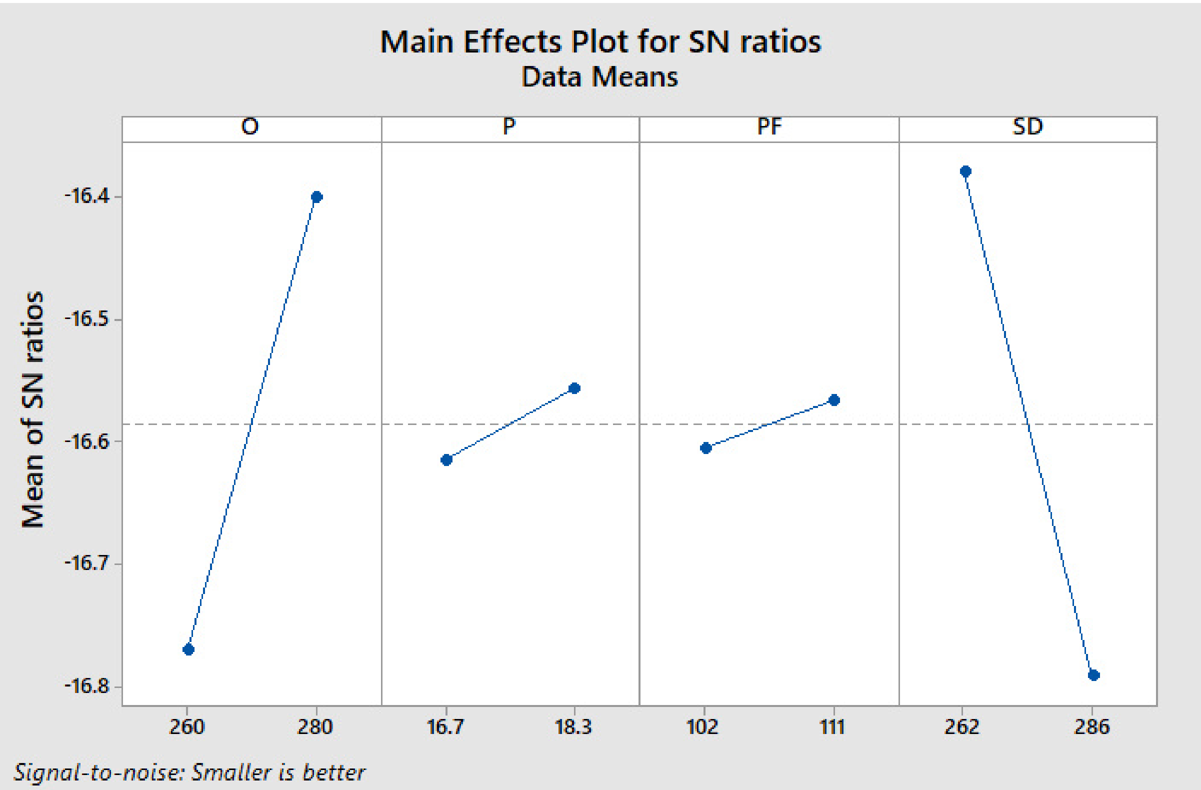

Fig. 4.4: S/N Ratio plot (Surface Roughness)

Source: MINITAB 17

Table 4.7 showed the delta values of each parameter. According to that, most important parameter for achieving minimum surface roughness was turned out to be the Spraying Distance (SD) followed by Oxygen rate (O), Propane rate(P) and Powder feed rate (PF). And, the optimum conditions for each parameter (according to Fig. 4.4) were as follows: (O, 280), (P,18.3), (PF, 111) and (SD, 262).

- **ANOVA Approach**

As shown in Table 4.8, Parameter Spraying Distance (SD) contribution was highest (around 52.57%) which was predicted by taguchi as well. Others parameters also influenced the experiment like Oxygen rate (O) around 27%, and Propane rate (P) around 3.26%, Powder Feed rate (PF) around 3.145%, same relationship was also shown in fig. 4.6.

TABLE 4.8 ANOVA Approach (Surface Roughness)

Parameter	DF	F-Value	p-Value	Contribution
O	1	5.78	0.096	27.007 %
P	1	0.70	0.465	3.256%
PF	1	0.67	0.472	3.145%
SD	1	11.25	0.044	52.571%
ERROR	3			14.019%
TOTAL	7			100%

- **Verification**

Verification test was conducted to authenticate the validity of predicted value obtained by using S/N ratio. The predicted value was 6.41775 µm as shown in fig. 4.5.

Predicted values

```
S/N Ratio     Mean
 -16.1475  6.41775
```

Fig. 4.5: Predicted Values (surface roughness)

Source: MINITAB 17

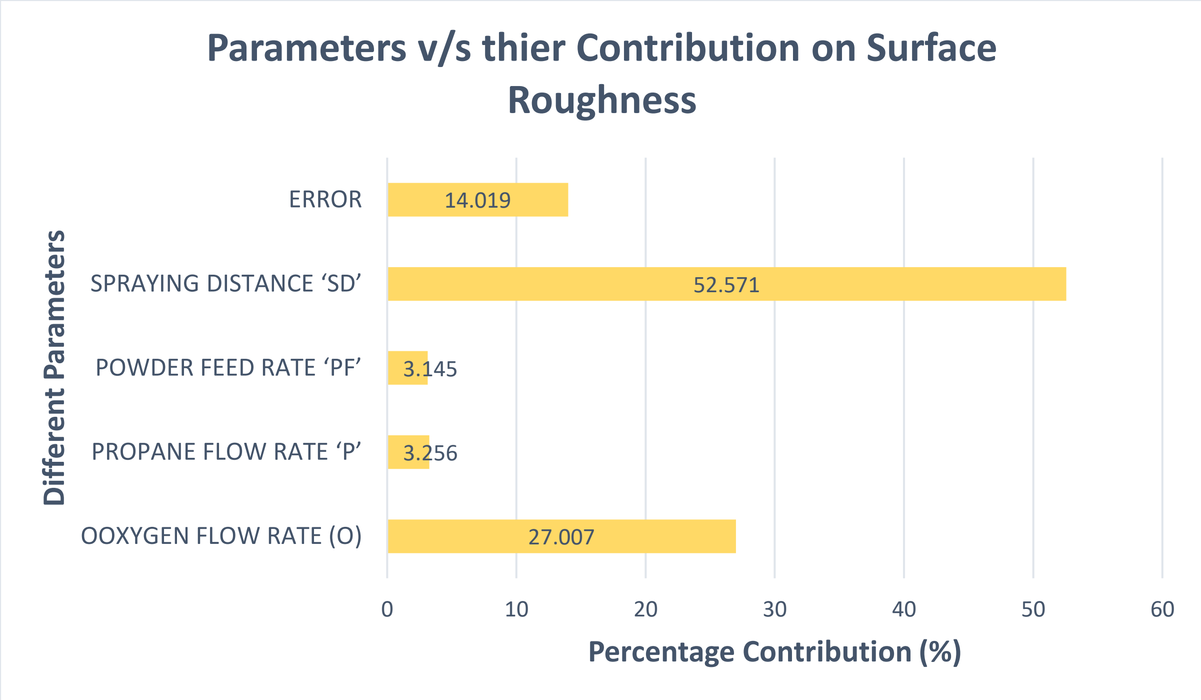

Fig. 4.6: Graph depicting the percentage contribution of each parameter on surface roughness

Source: Self made

TABLE 4.9 Verification Table (Surface Roughness)

Optimum Parameters		Surface Roughness (µm) (Actual)	Surface Roughness (µm) (Predicted)	Error %
OXYGEN RATE 'O'	280 l/min	**6.407**	**6.418**	**0.172**
PROPANE RATE 'P'	18.3 l/min			
POWDER FEED RATE 'PF'	111 g/min			
SPRAY GUN DISTANCE 'SD'	262 mm			

As shown in table 4.9, Actual value and predicted value is almost same with the error of 0.172%. The optimal condition using different approaches was verified.

- CHAPTER SUMMARY

Contribution of different parameters namely, oxygen rate, propane rate, powder rate and spray gun distance on hardness and surface roughness of a substrate was calculated. Substrate was SUS 400 Stainless Steel which was WC-12Co coated with HVOF Spraying method.

It was found that, achieving maximum hardness was greatly influenced by the propane (fuel) rate (P) followed by powder rate (PF), spray gun distance (SD) and oxygen rate (O). Hardness decreases with increasing fuel rate. And, achieving minimum surface roughness was greatly influenced by spray gun distance (SD) followed by oxygen rate (O), propane rate (P), powder feed rate (PF). Surface Roughness increases with increasing spray gun distance.

CHAPTER – 5

CONCLUSIONS & FUTURE SCOPE OF STUDY

5.1 CONCLUSIONS

HVOF spray method was investigated to produce fine tungsten carbide coatings on a SUS 400 stainless steel. It was clearly postulated from the study that HVOF Spray coating produce coatings of very high quality along with the several advantages. These were as follows:

1. As the impact velocity was very high, higher density of coating was achieved.
2. Smoother surface was obtained.
3. Wear resistance was high due to strong hard coating.
4. Hardness value was increased which led to improved corrosion protection.
5. Less residual stresses led to thicker coating.

Apart from having considerable advantages over the other coating processes, HVOF spraying process had various disadvantages also. These were as follows:

1. HVOF method was a very complex process as it depends upon a lot of process variables. Range of powder sizes was restricted.
2. HVOF method required experienced personnel to ensure safe operation and to get desirable results.

Also, HVOF system assemblies were studied. HVOF system was divided into two, namely spray system assembly and support system assembly. For the better functioning of the system, both these systems were needed. Spray system helps to apply the layer of corrosion resistant coating on the metal substrate.

1. Spray system contains gun, control console, powder feeder, gas and air regulators, control units. Spray system needs support to make the process safe for operator. Therefore, support system was needed.
2. Support system includes equipment like spray booth, material handling unit, exhaust system, gas and electric supply unit.

Automatic operation of spray gun was recommended as manual operation could be dangerous for the operators. Difficulty was countered while coating on to small internal surfaces.

Experiments were done to analyse the various effect of different parameters namely, oxygen rate, propane (fuel) rate, powder feed rate, and spray gun distance on hardness and surface roughness of a SUS 400 Stainless Steel substrate. Substrate was SUS 400 Stainless Steel which was WC-12Co coated with HVOF spray method. It was found that,

1. Achieving maximum hardness was greatly influenced by propane (fuel) rate (P) followed by powder feed rate (PF), spray gun distance (SD) and oxygen rate (O). Hardness decreases with increasing fuel rate.
2. Achieving minimum surface roughness was greatly influenced by spray gun distance (SD) followed by oxygen rate (O), propane rate (P), powder feed rate (PF). Surface Roughness increases with increasing spray gun distance.

5.2 FUTURE SCOPE OF STUDY

More study development should be done to improve the capabilities of the present HVOF system. Powder flow from feeder should be increased and automated. The system should be capable of withstanding increased number of mixed powders. This would allow the system to perform with more complex coatings. More and more material should be investigated with the present system to widen the range of operation.

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