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THERMAL STRESS ANALYSIS OF TIALN COATING DEPOSITED ON AUSTENITE STAINLESS STEEL 304 BY CATHODIC ARC EVAPORATION

Harsh B. Raval[1], Pina M. Bhatt[2], Dr. H N Shah[3]
[1]Mechanical Engineering Department, Merchant Engineering College, Basna, Mehsana, Gujarat, India.
[2]Ph.D. Scholar, R K University, Rajkot, Gujarat, India.
[3]Sardar Patel Institute of technology, Piludara, Mehsana, Gujarat, India.

Abstract: Thermal and tribological behavior of Thin hard coated component are enhanced in different environment. Due to this reason Ternary metal nitrides or carbides coating are widely used for thermal application in machining as well as automobile industries. Thermal stress is major aspect for thermal application. Aim of this work is to check thermal stress sustainability and work efficiency of coated engine component. The substrate material here in thermal stress investigation is ASTM 240-12, TYPE 304 Austenitic Stainless steel. The TiAlN Coating is applied at different deposition temperature from 25°C to750°C and the Service temperature ranges from 45°C to 850°C. Through the analytical and finite element analysis by ANSYS MULTIPHYSICS software the generated thermal stresses were found out from maximum service temperature to deposition temperature in both evaluator methods. The various physical, mechanical and thermal parameters of both coating & the substrate on which thermal stress depends can be listed as co-efficient of thermal expansion, young modulus, poisson's ratio and the temperature histories during maximum service temperature to deposition temperature. Thermal shock resistance test was performed and Finite Element Analysis results in terms of thermal stresses were compared with the analytical results.
Keywords: Thin hard coating, thermal stress, Arc evaporation

I. INTRODUCTION

TiAlN coating applied on the substrate of stainless steel provides the best mechanical and tribological properties in a high temperature environment and also the good thermal resistance should be provided in a high temperature zone. The combustion temperature of 850ºC and to bear the thermal stresses at this higher temperature this type of coating should be provided through cathodic Arc Evaporation Process. High temperature thermal stresses generation and their effect to the different engine component in terms of thermal erosion caused by the impact of the combustion product & unburnt carbon particles at high combustion temperature at 850°C. On the basis of economic and engineering prospective development of wear and high temperature thermal stress protection is highly recommended parameter. The thermal stresses are induced during the coating deposition process. ASTM 240-12, TYPE 304 Austenitic stainless steel is widely used as structural material due to its superior strength & good corrosion resistance **I.M.Berstein et al.** Further material wears resistance of this material is reasonably poor due to its low hardness**.** This research gives cost effective solution for the resolution of thermal stress problems, high temperature resistance, the effective method is to coat the substrate composition with the cathodic arc evaporation (PVD) technique at high temperature of 750°C, which has been used in current investigation. This work formulate prognosis model of thermal stresses in PVD coatings obtained on square specimen of austenitic stainless steel 304 materials with the use of finite element method as well as analytical method. Through this investigation the property of coating material were found out that it can bear the thermal stresses at maximum service temperature to deposition temperature without blister on the surface of the component. Formulated model allows considerable range limit for necessity of making expensive & time consuming experimental research. The thermal stress generation phenomenon occurred in coating as a result of thermodynamic process which proceeds during their evaporated particle spreading, during stress relaxation mechanism and also at maximum service temperature. The film growth in cathodic arc evaporation method during the deposition is controlled by the energy of atoms at the surface of growing film, which in turn depends on deposition parameters. If low energy ion impacts then the diffusion of the ions are limited & this phenomenon result in a porous structure with thin columns. Such that increased temperature diffusion increases & leading to an increased grain size & lower porosity. The ion implantation below the surface causes densification of film & result in compressive thermal stress. With increased ion energy the number of created defects increases which causes in magnetron sputters TiN films. In addition to the stresses arise from the defects in the film, the difference in co-efficient of thermal expansion (α) between the film and substrate can give rise to thermal stress when the film & substrate are cooled from maximum Service Temperature.

II. EXPERIMENT DETAILS

A. Development of coatings

TiAlN coatings were deposited on austenitic stainless steel ASTM 240-12, Type 304 substrate with a varying thickness of 0.0214 mm, 0.0145 mm, 0.0143 mm, 0.0132 mm, 0.0125 mm as per the coating thickness survey performed by linear measurement using MIC software at TCR advanced laboratory. The actual chemical composition of the substrate has been analyzed by optical emission spectrometer (spectromax X) Make Germany. The nominal and actual chemical composition of the substrate is reported in table 1. Specimen with dimension of approximately 25 mm × 25 mm × 2 mm were cut from the alloy sheet.

Elements	Nominal	Actual
Carbon	0.08	0.062
Silicon	0.75	0.390
Manganese	2.00	0.970
Phosphorus	0.045	0.040
Sulphur	0.030	0.012
Chromium	18.0-20.0	18.040
Nickel	8.0-10.5	8.200

Table 1:- Elemental Chemical constitution of Substrate composition.

Chemical composition analyses were performed at Test Well Laboratories at Ahmadabad.

B. Pre-treatment for the substrate material

Ultrasonic precleaner provided with the aqueous solutions without environmentally damaging hydrocarbon solvents. (Imeco, pune, India) used for sample cleaning. It provides outstanding cleaning of precision metal parts, based on a combination of spraying and immersion in heated baths with ultrasonic vibration. The cleaning process fully automatic which gives Automatic processes guarantee high reproducibility and permit unsupervised operation. The system automatically selects one of four different, defined cleaning processes. After thorough rinsing and drying with hot air, the surfaces are left free of residues and corrosion. And then ultrasonic cleaning machine including hot air dryer (Oerlikon Balzer Ltd, India) for 1.5 Hrs were used for drying purpose. Secondly the brushing machine is employed for precise BALINT FUTURA NANO (TiAlN) coating and then polished using emery papers of 220, 400, 600 grit sizes and subsequently on 1/0, 2/0, 3/0, and 4/0 grades, also mirror polished by cloth polishing wheel machine with $1\mu m$ lavigated alumina powder suspension.

C. Cathodic Arc Evaporation process

A Front loading Balzer`s Rapid coating system (RCS) Machine has been used for the deposition of the coatings. The machine is equipped with eight cathodic arc sources. Four of the eight sources were used to deposit a thin TiN sub-layer. The remaining four sources were employed to deposit the main layer of the coatings, which was obtained using customized sintered targets. By using compound cathodes containing several elements the composition of the film is controlled within this work, Ti-Al compound cathode s have been used in addition to the elemental Ti cathodes. Nitrogen is supplied by a flow into the deposition chamber. This is the most common way to introduce light elements such as nitrogen. The temperature of the deposition on the substrate material should be started from 25°C to 750°C. Deposited film on the substrate material reveals the TiAlN Coated components on ASTM 240-12, TYPE 304 substrate.

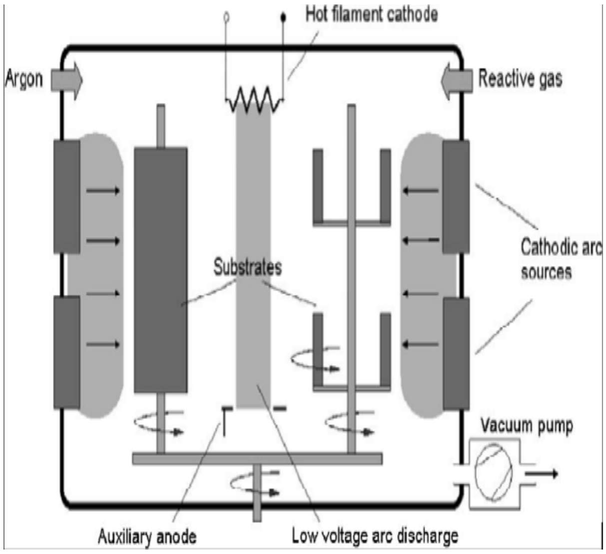

Fig 1:- Oerlikon Balzer’s Coating deposition System (CAE-PVD)

Maximum service temperature which is combustion temperature of engine component is considered here. . Analytical and theoretical analyses requires for the thermal stresses of coatings for linear plastic and elastic – plastic behavior and to enhance the properties. To measure the thermal stresses which generate during the process of coating deposition, the finite element analysis by using ANSYS MULTIPHYSICS software is the best techniques in the production technology. Due to coating the thermal, thermo - physical, chemical, mechanical properties are enhanced by providing this type of thin coatings on the base material (Austenitic stainless steel). Such that this coated material used for many application such as micro electromechanical systems, the armours on the military tanks, space vehicle fuel tanks (booster rocket). So the analytical study through the ANSYS software represent the titanium aluminum nitride material coating on the base structure Austenitic stainless steel 304 with varying thickness of coating and in different temperature zones.

III. THERMAL SHOCK TEST

Thermal shock testing is performed to determine the ability of parts and components to withstand sudden changes in temperature. The resistance to thermal shock is a measure of panel`s ability to withstand a sudden thermal shock. (E.g. splashing water on inner oven door panel)

A. Measurement method

Test specimen with defined surface (with SiC 220 grade

sand paper) are heated up at 200°C and then 500 ml of cold water (room temperature) at 20° C is poured on them in the centre. Same above tested method performed for 850°C for maximum operating temperature to investigate the coated component thermal shock resistance. In second experiment the temperature was remained at 850°C for one hour and after the cold water of 500 ml at 20°C temperature was applied and their result was observed that the investigated material can bear the thermal stresses or not.
Maximum Operating temperature in first test: - 200°C
Maximum Operating temperature in second test: - 850°C.

IV. MODELING OF PROBLEM

A. Analytical Method for thermal stress

For the Square geometry configuration in the square plate, Y.C. Tsui and T.W. Clyne (Tsui and Clyne, 1997) combining an analytical model with Stoney's equation for the measurement of progressively generation of residual thermal stresses on coatings at the Max. Service temperature to deposition temperature.

$$\sigma_f = \frac{E_{ef} \int_{T_r}^{T_d} (\alpha_s - \alpha_f) dT}{1 + 4(E_{ef}/E_{es})(h/H)}$$

Where Eef=[Ef/(1−Vf)], Ees=[Es/(1−Vs)], νs, νf, h, H, Td, Tr, αs, and αf are effective Young's modulus of the coating, effective Young's modulus of the substrate, Poisson ratio of the substrate, Poisson ratio of the coating, coating thickness, substrate thickness, Max. service temperature, deposition temperature, thermal expansion coefficients of the substrate and the coating, respectively. In analytical and theoretical analysis through the ANSYS software and calculation from above equation shows that the coating substrate system has been taken as a composite beam because the coated layer on the substrate which are made up Titanium aluminum nitride very thin as compare to substrate thickness. Substrate Properties I.M.Berstein **et al** and coating **from l..Rogstrom et al.**

Properties	Substrate	Coating
Density	7.85e – 006 Kg/m³	8.e – 006 Kg / m^3
Modulus of elasticity	200 GPa	450 GPa
Poisson`s Ratio	0.29	0.205
Co-efficient of thermal expansion	18.7×10^{-6} °C $^{-1}$	9.5×10^{-6} °C $^{-1}$

Table 2:- Properties of coating and substrate material.

A square specimen (20.00 mm length in x and y direction 2.0 mm length in z-direction) with coating with different thickness are considered. The substrate thickness was large as compare to coating layer thickness in the analysis. Length of substrate in X & Z – direction consider as 25mm & in Y-direction 2.14e-002 mm for TiAlN coating & 2 mm for austenitic stainless steel 304 substrate. The Global co-ordinate a system is selected with the X-axis, Y-axis & Z-axis data represented as [1.0.0], [0.1.0], [0.0.1] respectively. The scope of thermal contact provided is on 1 face of plate composition where the target bodies were provided. The detection method, Penetration, elastic slip tolerance, normal stiffness, update stiffness, thermal conductance, and pinball region were program controlled. Numbers of nodes selected in meshing structure were 19440 and elements were 3364 and the automatic mesh based disfeaturing is on. The steady state thermal analysis was performed & the final temperature was remained at 850°C where the thermal stresses were found out by mechanical APDL solver target. The heat conductance, temperature convergence and line search were program controlled.

V. ANSYS MULTIPHYSISC SOFTWARE SIMULATION STUDY

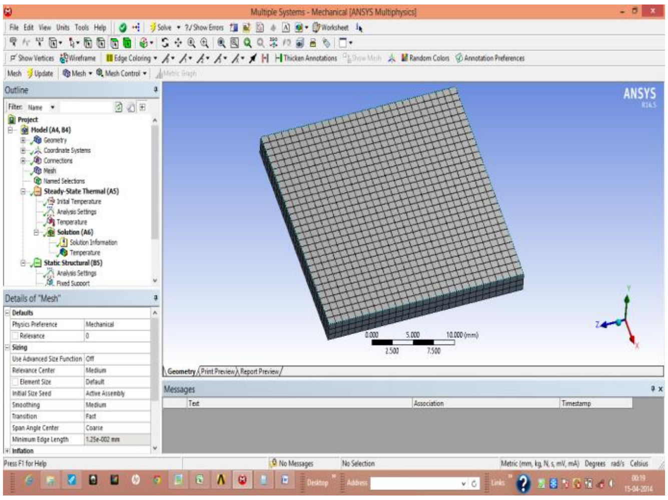

Fig 2:- Meshing structure with 19440 nodes and 3340 element in the system with a scale factor 2.2.

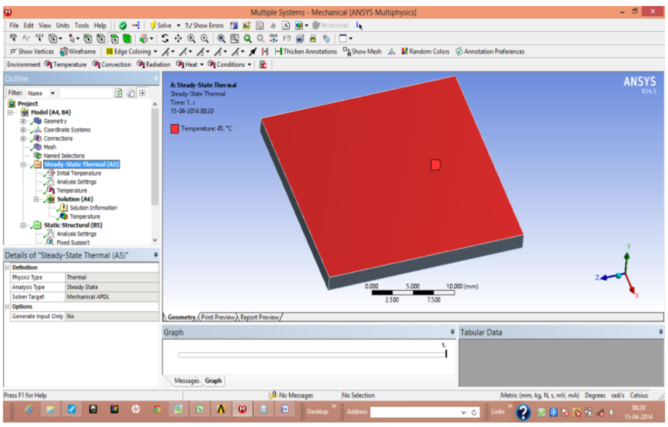

Fig 3:- 45ºC temperasture constrained is provided on the square specimen.

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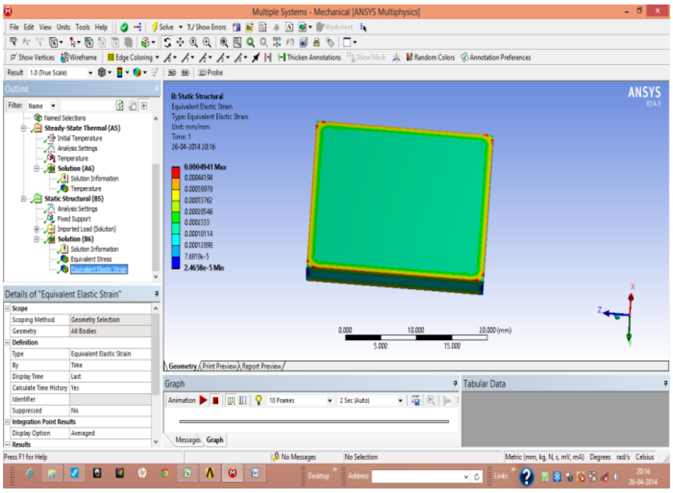

Fig 4:- The Equivalent stress condition is provided on the square specimen to measure the thermal stresses.

VI. FINITE ELEMENT ANALYSIS AND NUMERICAL EVALUATION WORK VALIDATION

The thermal stress of TiAlN coating deposited on austenitic stainless steel 304 substrate has been simulated by finite element simulation package ANSYS MULTIPHYSICS software & compared with that of Analytical model. The thermal stress of coating exhibits a linear relationship with Max. Service temperature to the deposition temperature range but it exhibits an inverse relationship with coating thickness due to the stress relaxation mechanism.

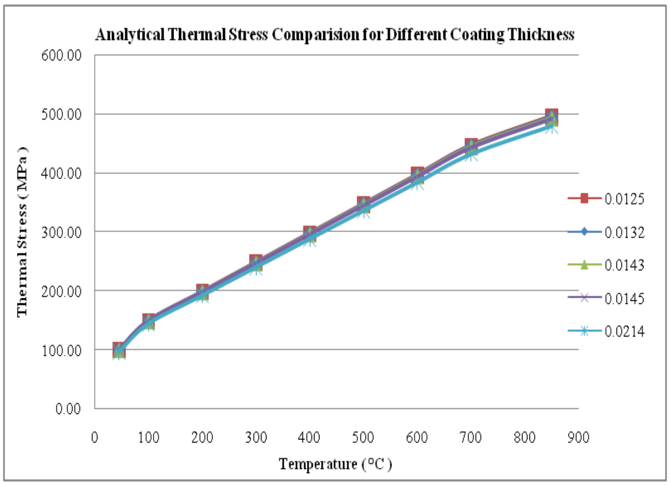

Fig 5:- Analytical thermal stress comparison for different coating thickness.

As shown in the above graph of analytical thermal stress comparison for different coating thickness the following results can be seen from 45°C to 850°C temperature zone. The highest thermal stress developed 495.85 MPa and lowest one was 95.90 MPa. But in the both cases the coated component can bear the stress without any thermal cracks and also in the experimental investigation through thermal shock test no blisters were developed on the coating such that the good agreement was found.

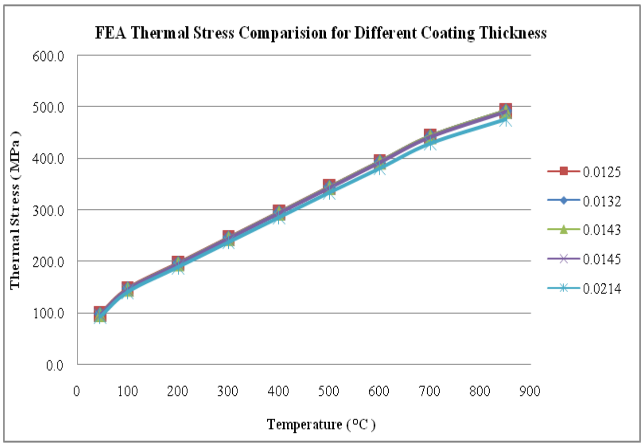

Fig 6:- FEA thermal stress comparison for different coating thickness.

Simultaneously through the use of finite element simulation package ANSYS MULTIPHYSICS software the thermal stresses generated for the different coating thickness of 0.0125 mm to 0.0214 mm for the temperature range from 45°C to 850°C the stresses range from 93.8 MPa to 493.1MPa which was equally validated with the analytical model for the coated component result. Also we can see that for the 0.0125 mm coating thickness the stress was 98.6 MPa to 493.1 MPa whereas for 0.0214 coating thickness the result was 93.8 MPa to 476.5 MPa. Here from this figure no.7 we can see that the inverse relationship with the coating thickness which revealed that at 45ºC and 0.0125 mm coating thickness the micro porosity was developed because of it was the initial temperature of the cathodic arc evaporation process which revealed by the figures. The analytical Thermal stress comparison for the different temperature range from 45ºC to 850ºC and the coating thickness of 0.0125 to 0.0214 mm the thermal stresses produced were from 99.17 MPa to 479.51 MPa and also for the 45ºC temperature the thermal stresses were developed as from 99.17 MPa to 95.90 MPa Which shows also the similar result that observed in above two fiure no. 5 and figure no.6 because the coating thickness not only increases the thermal strength but as well as it created the dense and uniform morphology in the coating behavior.

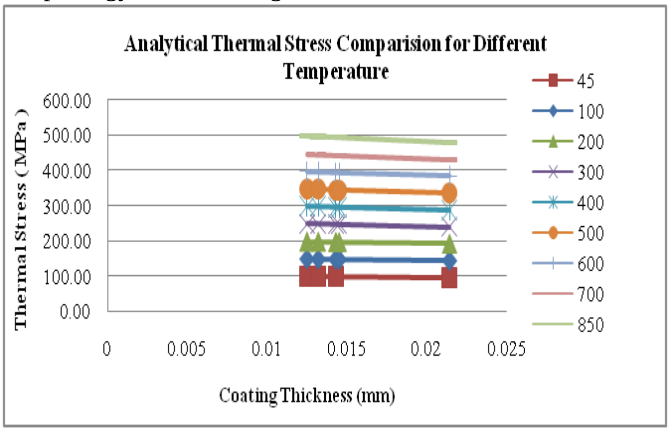

Fig 7:- Analytical thermal stress comparison for different temperature.

As shown from the below figure no.8; we can see that through the ANSYS simulation the thermal stresses development for the different temperature zone showed that at 45ºC temperature the value of the thermal stress was 98.6 MPa to 93.8 MPa and similarly for the 850ºC temperature the thermal stresses produced were 493.1 to 476.5 MPa which also show that higher temperature the higher thermal stresses were developed but our coating material also bear this thermal stresses at this highest temperature which also validated with the thermal shock test result at 850ºC temperature.

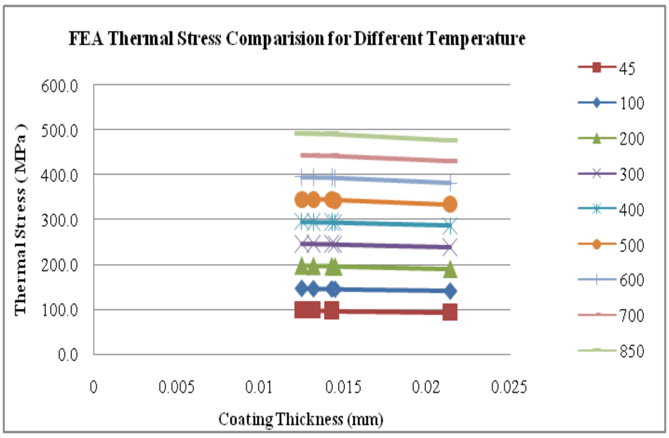

Fig 8:- FEA thermal stress comparison for different temperature.

The Result from the thermal shock resistance test shows that at lower temperature of 200ºC as well as higher temperature of 850ºC; no blisters are observed which revealed that the specimen should be gone through this higher temperature.

VII. CONCLUSION

Present work analyzing the greatest loading from the steady state point of view has been calculated the effects of change according to the coating thickness and temperature and also through the thermal shock resistance test. The above result revealed that at high temperature environment, the higher thermal stresses were developed but by applying this type of TiAlN coating on the substrate it can bear the overall thermal stresses at this peak thermal environment in engine components such as valves. Such that at last the stresses and blister free surface at this higher temperature provided by TiAlN coating which are beneficial for the engine components.

VIII. ACKNOWLEDGEMENT

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