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An Evaluation of the Residual Stresses in Wear Protection Coatings using Multi Techniques

A Thesis
Submitted to Council of College of Engineering, University of Diyala in Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering

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CHAPTER ONE

INTRODUCTION

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1.1 Overview

The ceramic coatings on metallic materials have shown a significant improvement since 1970, with developing technology, metals and metallic alloys require high performance in different environments. From 1980, the ceramic coatings have been applied to adiabatic engines. First of all, gas turbine wings were used in this area, and the piston, cylinder lining, valve, piston crown surface were used for ceramic coatings [1]. Ceramic coatings have been extensively employed in the surface modification field during the last decades due to their excellent properties [2]. The coating of metal surfaces with a thin ceramic layer has always been a useful means to enhance the mechanical performance of metallic substrates [3]. Ceramic coatings are mainly used for the protection of base alloys against hot corrosion and oxidation and also for the minimization of definition. Another function of ceramic coatings is to reduce the base metal temperature in the case of thermal barrier coatings [4]. Ceramic materials have many advanced properties such as heat resistance, corrosion resistance, wear resistance, electrical insulation, and so forth. At present, there is a variety of ceramic coating methods for protective application ceramic coatings, this methods differ in terms of coating quality attained, deposition efficiency and complexity of process and investment costs [5]. Advanced ceramic materials have many potential advantages in turbine applications. However, it is not feasible to produce a fully dense ceramic turbine engine and hence there is a requirement for the design and manufacture of metal-ceramic bonds. One major obstacle to the use of ceramic materials in turbine applications is the mismatch in coefficient of thermal expansion (CTE) between ceramics and metals. In service, thermal cycling could generate excessive strain at the metal/ceramic interface, possibly enough to cause catastrophic failure of the ceramic. Therefore, there is a need to address the various methods for joining ceramic materials such as silicon nitride, to high-temperature metals such as nickel alloys. A successful joint design and vacuum brazing procedure had been developed and optimized, based on a mechanically flexible metal interlayer being introduced between the metal and the ceramic. This accommodates the difference in CTE which causes strain within the joint. The difficulty of wetting the ceramic was overcome by the use of an active metal braze alloy or a surface wetting agent [6].

Increased use of thermal spray coatings, especially for high-temperature environmental resistance, requires confidence in coating durability, i.e., resistance to cracking, debonding, and spallation, both during application and in service. Residual stresses are known to play an important role in coating durability; for example, tensile residual stresses typically increase the susceptibility to cracking and debonding. Many studies have been devoted to the measurement of residual stresses in coatings [7,8]. Residual stresses develop during cooling of a thermal spray coating due to the mismatch of thermal expansion coefficients of the coating and substrate. Depending on the relative magnitudes of the thermal expansion coefficients of the coating and substrate residual stress can be either tensile or compressive [9]. Parameters that strongly affect the magnitude of residual stresses in coating and substrate are temperature during spray deposition and properties of the coating such as thickness, roughness, and porosity. Experiments have shown that residual stresses increase with coating thickness and deposition temperature [10]. Thermal barrier coatings (TBC_s) are the best way to protect components of gas turbine engines and the demand for such coatings is becoming more important as higher temperature engines are being developed [11-13]. Generally, the residual stresses of thermally sprayed coatings are induced by different mechanisms and sources [14]. In a thermal spray process with a high flame temperature, such like flame spray, plasma spray, or arc spray, fully and partially molten particles striking onto the surface of the substrate, are flattened, solidified, and cooled down in a very short period of time (few microseconds). After its solidification and adhesion onto the surface of the substrate, the contraction of the splats can be hindered by substrate material or the underlying solidified coating material, which results in tensile stresses which are called intrinsic, deposition, or quenching stress. Due to an extremely high-temperature difference, a high theoretical residual stress in the order of up to 1 GPa can be induced. However, due to the many relaxation mechanisms, such as the sliding of the splats, microcracks, plastic deformations, and material creep, the experimentally measured values are much lower (<100 MPa) [15]. X-Ray diffraction (XRD) was used as a complementary technique; it can determine stress only in a thin surface layer, whereas the penetrating power of neutrons enables through-thickness stress profiling without any material removal [16].

1.1 Thesis Outline

The present study consists of six chapters as below mentioned:

Chapter 1: The current chapter includes a general introduction about the residual stresses in wear protection coatings, research objective, and thesis outline.

Chapter 2: This chapter presents an overview of previous studies that shed light on the evaluation of the residual stresses in wear protection coating.

Chapter 3: This chapter describes wear protection coatings, and thermal spraying coating techniques, residual stresses and how to calculate them by X-Ray and finite element methods.

Chapter 4: This chapter describes laboratory procedures and equipment that have been addressed.

Chapter 5: This chapter deals with the results obtained as well as results discussions in a highly.

Chapter 6: This chapter addresses the most important conclusions, recommendations and suggestions for future works.

1.2 Aims and The Importance of The Present Work

The aims of the present work may be summarized as the following:

1. Using non-destructive methods represented by X-ray diffraction and the finite elements technology in evaluating the residual stresses in flame sprayed advance ceramic coatings.
2. Identifying the sign and quantity of residual stresses with high accuracy.
3. Identifying the best advanced composite coating with better mechanical properties (residual stresses).
4. Using experimental method (X-Ray diffraction) technique and numerical method (finite element method) to evaluate residual stresses and comparison between them.

ABSTRACT

The wear protection of thermal spray coating mainly depends on the coating properties such as microstructure, surface characteristics, thermal, mechanical properties, as well as on the residual stresses in the coating. The residual stresses are induced by a variety of influences for example, temperature gradients, difference of thermal expansion coefficient of coating/substrate material, and geometry of chemical components. The present work aims to investigate the residual stresses in advanced composite ceramic coatings (Al_2O_3, Al_2O_3-5,10,15wt% SiC, SiC, SiC-10,15wt% Al_2O_3, Al_2O_3-17,25,40wt% SiO_2) on mild steel substrate which are used as the wear protection coatings using experimental and numerical techniques. The residual stresses were determined by X-Ray diffraction technique ($\sin^2\psi$ method) as an experimentally method while, numerically technique used finite element method. To investigate microstructure and surface characteristic, optical and scanning electron microscope were used (SEM). While bonding strength was evaluated by use Tensile test. The best surface characteristics were Al_2O_3 ceramic coating less surface roughness 4.6 µm and low porosity percentage was 5.7% for advanced composite ceramic coating Al_2O_3-40wt% SiO_2. The best thermal conductivity was 0.22699 (W/m.k) for SiC ceramic coating. The phase structure of the ceramic coating layers was conducted using X-Ray diffraction technique (XRD), where the X-Ray results show α-Al_2O_3 as the prominent phase in pure Al_2O_3 ceramic coating, so in pure SiC ceramic coating was α-SiC, while in composite ceramic coating (Al_2O_3-5,10,15,90,85 wt% SiC): α-Al_2O_3 & α-SiC, and (Al_2O_3-17,25,40 wt% SiO_2): α-Al_2O_3 & α-SiO_2 respectively. The results of experimental measure of the residual stresses evolution during flame spraying technique which the coating ceramic layers are evaluated by X-Ray diffraction technique were in pure (SiC) ceramic

coating and advanced composite ceramic coating layers (Al_2O_3-5,10,15,85,90wt% SiC), (Al_2O_3-17,25,40wt% SiO_2) were compressive residual stresses respectively, so the higher value of the compressive residual stresses was (-866.9 MPa) in the (SiC) ceramic coating, while in pure (Al_2O_3) coating layer were tensile residual stresses (104.6 MPa). The compressive residual stresses in flame sprayed pure and composite ceramic wear protection coatings have a significant positive influence on the wear resistance where as tensile residual stresses have a negative effect. In the present work, the residual stresses evolution during flame spraying coating have been evaluated using experimental technique, also numerical simulations have been used of the several series of sample coated using flame spraying coating technique. A detailed finite element (FE) analysis of the flame spraying coating process has been developed to calculate the residual stresses induced through impacts and then composite ceramic wear protection coatings type effect has been taken in to account through an analytical model. The results of experimental and numerical approach confirm the considerable effect of the coating type on the eventual stresses distribution in the flame sprayed coating layers.

Finite element results of residual stresses showed a good agreement with experimental results where, the percentage of agreement between the experimental and analytical results at less was (81%) and more than.