ELECTROPLATED COPPER COATINGS ON 304L AND 316L STAINLESS STEELS FOR MITIGATION OF METAL DUSTING CORROSION IN METHANE/HYDROGEN ENVIRONMENT

BY

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A thesis submitted in fulfilment of the requirement for the degree of Doctor of Philosophy (Engineering)

Kulliyyah of Engineering
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FEBRUARY 2019

ABSTRACT

Metal dusting corrosion is high-temperature degradation of metals and alloys into dust-like fine particles. It is often encountered in petrochemical industry, where metals and alloys extensively exposed to carbon-containing gases at high temperature. It is a costly issue in the industry; millions of dollars have been invested annually in the fields of monitoring, controlling and prevention of metal dusting corrosion to avoid potential dangers in the environments. Metal dusting initiates as a result of unwanted carbon formation on the surface of metallic engineering installations. At high temperature, solid carbon diffuses into the metal/alloy matrix to form a carburised layer on the surface. Under certain conditions, this carburised region may become unstable and decompose into carbon and metal/alloy particles, as well as other corrosion products. Such as metal particles may further catalyse the carbon deposition and the process are hence accelerated. Thus, the primary aim of this study is to prevent carbon diffusion into metal in order to mitigate the metal dusting corrosion by using an electroplating copper coating on 304L and 316L stainless steels. Therefore, coated and uncoated 304L and 316L samples were exposed to metal dusting environment in a 10% to 50 % CH_4/H_2 gas mixture, at temperature range of 600 ˚C to 800 ˚C, and a pressure of 1 atm, leading to carbon activities from 0.203 to 3.289 for 100 hours. Optical microscopy (OM) results revealed that the electroplating copper coating mitigates carbon from diffuse into metal, so no carburization zone was formed, compared with non-coated samples which displayed clear carburization were formed for both 304L and 316L stainless steel at temperatures more than 600 ˚C and gas mixture 20 % CH_4/H_2 and above where carbon activity approach to 1. Weight gain test showed non-significant weight gain on coated samples compared to uncoated samples. These values of weight gain increase with increase the temperature or/and CH_4/H_2 gas mixture. These results were also confirmed by X-Ray Diffraction (XRD) and scanning electron microscope (SEM) coupled with energy dispersive x-ray (EDX) which showed no carbides formed on the surfaces of coated samples. M_7C_3 carbides were formed on the surface of uncoated samples as a result of carbon diffusion in the metal and react with elements. In these experiments, electroplated copper samples showed negligible carbon deposition on the surface and no carbon diffusion into the metal. Thus, copper electroplating coating is solution to mitigate metal dusting corrosion

خلاصة البحث

تآكل الغبار المعدني ينتج عنه تحلل المعادن والسبائك الى جزيئات دقيقة تشبه الغبار عند درجات الحرارة العالية. وغالبا ما يواجه هذا النوع من التأكل في صناعة البتروكيماويات ، حيث تتعرض المعادن والسبائك الى نطاق واسع من الغازات المحتوية على الكربون عند درجة حرارة عالية. وهذه العملية مكلفة في الصناعة ؛ فقد استثمرت ملايين الدولارات سنوياً في مجالات مراقبة وضبط ومنع تآكل الغبار المعدني لتجنب المخاطر المحتملة كالانفجرات و – أوانبعاث الغازات السامة تحت ظروف الضغط والحرارة المرتفعة. يبدأ الغبار المعدني نتيجة ترسب الكربون غير المرغوب فيه على سطح المنشآت الهندسية المعدنية. عند درجة حرارة عالية ، ينتشر الكربون الصلب داخل مصفوفة المعدن / سبيكة لتشكيل طبقة كربنة على السطح. في ظل ظروف معينة ، قد تصبح هذه المنطقة الكربونية غير مستقرة وتتحلل الى جزيئات الكربون والمعادن وسبائك التآكل الأخرى. بعض الجسيمات المعدنية قد تزيد من تحفيز ترسيب الكربون مما يترتب عليه تسريع العملية. وبالتالي ، فإن الهدف الأساسي من هذه الدراسة هو منع انتشار الكربون إلى داخل المعدن من أجل التخفيف من حدة التآكل الغباري المعدني باستخدام طلاء نحاسي مطلي بالكهرباء على 304L و 316L الفولاذ المقاوم للصدأ. لذلك ، عرضت عينات 304L و 316L المطلية وغير المطلية لبيئة الغبار المعدني في خليط من غاز CH_4 / H_2 بنسب من 10% الى 50%، وفي نطاق درجة حرارة 600 درجة مئوية الى 800 درجة مئوية ، وضغط 1 ضغط جوي ، وكلن نشاط الكربون a_c يتراوح من 0.203 إلى 3.289 لمدة 100 ساعة. أظهرت نتائج الفحص الميكروسكوبي (OM)أن طلاء النحاس الكهربائي يخفف من الانتشار الكربوني إلى المعدن ، لذلك لم يتم تشكيل أي منطقة كربنة ، مقارنة بالعينات غير المغلفة التي عرضت كربنة واضحة تم تشكيلها لكلا من الفولاذ 304L و 316L في درجات حرارة أكثر من 600°C ونسبة مزيج الغاز 20٪ وما فوق CH_4 / H_2 حيث يصل النشاط الكربون a_c إلى 1. أظهر اختبار اكتساب الوزن عدم وجود وزن على العينات المطلية مقارنة مع العينات غير المطلية. تزداد قيم زيادة الوزن مع زيادة درجة الحرارة أو –و نسبة خليط الغاز CH_4 / H_2 هذه النتيجة أُكدت أيضا عن طريق حيود الأشعة السينية (XRD)والمجهر الإلكتروني الماسح (SEM) إلى جانب الأشعة السينية المشتتة للطاقة (EDX) التي أظهرت عدم وجود كربيد على أسطح العينات المطلية. تم تشكيل كربيد M_7C_3 على سطح العينات غير المطلية نتيجة للكربون المنتشر داخل المعدن وتفاعلة مع العناصر. في هذه التجارب ، أظهرت العينات المطلية بالنحاس بطريقة الكلاء الكهربي ترسب لا يذكر للكربون على السطح مما ادى لعدم وجود انتشار للكربون داخل المعادن. وبالتالي ، فإن طلاء النحاس الكهربائي هو حل للتخفيف من تآكل الغبار المعدني

APPROVAL PAGE

The thesis of Farg Ibraheem Mohamed Haider has been approved by the following:

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DECLARATION

I hereby declare that this thesis is the result of my own investigation, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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This thesis is dedicated to

My wife and our children

For their love, understanding and company comfort of eyes

forever and ever

ACKNOWLEDGEMENTS

Foremost, all praises are due to Almighty Allah (SWT) for granting me the wisdom, guidance, knowledge, and strength to complete this thesis.

I wish to express my gratitude and appreciation to my thesis supervisor Assoc. Prof. Dr. Suryanto ‘‘main supervisor’’, an Assoc. Professor in Kulliyah (Faculty) of Manufacturing and Materials Engineering in International Islamic University Malaysia (IIUM), who has given constant guidance, friendly enthusiasm, constructive criticism, valuable suggestions and encouragement during the pursuit of this research.

Furthermore, I would like to express my heartfelt appreciation to my thesis co-supervisor Assoc. Prof. Dr. Mohd Hanafi bin Ani, an Assoc. Professor in Kulliyah (Faculty) of Manufacturing and Materials Engineering in International Islamic University Malaysia (IIUM), for his scholarly advice and guidance from beginning till the very end of this thesis.

Apart from aforementioned in academic world, deepest gratitude to the technical team of IIUM involving Br. Edhuan (corrosion), Br. Zakaria (tool and die & metrology), Br. Ibrahim (metallography and SEM), Br. Faisal and Br. Zahir (workshop) and Br. Rahimie (surface engineering) and others I could not mention here. Without your help, the work can not be completed. You all are the unsung heroes.

Finally, special thanks to my ever loving and admirable sweet heart Asma and our lovely kids Khairia, Mohamed, Meiral, and Serein for their patient, sacrifice, and support. I pray Allah to grant us long life to enjoy the fruit of the sacrifice.

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LIST OF ABBREVIATIONS

BCC	Body centered cubic
CCD	Central composite design
CVD	Chemical vapour deposition
DOE	Design of experiment
EDM	Electrical discharge machining
EDX	Energy dispersive x-ray
FCC	Face centered cubic
MD	Metal dusting
mm	Millimetre
OM	Optical microscopy
PVD	Physical vapour deposition
RSM	Response surface methodology
SEM	Scanning electron microscopy

LIST OF SYMBOLS

P_{H_2}	Partial pressure of hydrogen
P_{CH_4}	Partial pressure of methane
ΔG	Gibbs energy
ΔH	Change in the enthalpy
µm	Micrometre
a_c	Carbon activity
Ar	Argon
C	Carbon
CH_4	Methane
CO	Carbon monoxide
Cr	Chromium
Cr_7C_3	Chromium carbide
Cu	Copper
$CuSO_4$	Copper sulphate
Fe	Iron
Fe_7C_3	Iron carbide
H_2	Hydrogen
H_2SO_4	Sulfuric acid
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
Ni	Nickel
P	Phosphorus
S	Sulfur
Si	Silicon

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF STUDY

Metal dusting (MD) can be defined as a high temperature phenomenon leading to the disintegration of materials, such as iron, nickel, and cobalt-based alloys, into powder (or dust) as shown in Figure 1.1. The powder is generally composed of metal, metal carbide, carbon and oxide particles. MD can alternatively be described as a catastrophic carburisation that occurs in environments with high carbon activities (i.e. more than unity) and low oxygen partial pressures (Gunawardana et al. (2013); Put et al., 2015; Slabbert, 2013). Carburisation plays a key role in the metal dusting process and unstable carbides are apparently a major factor in the reaction (Slabbert, 2012).

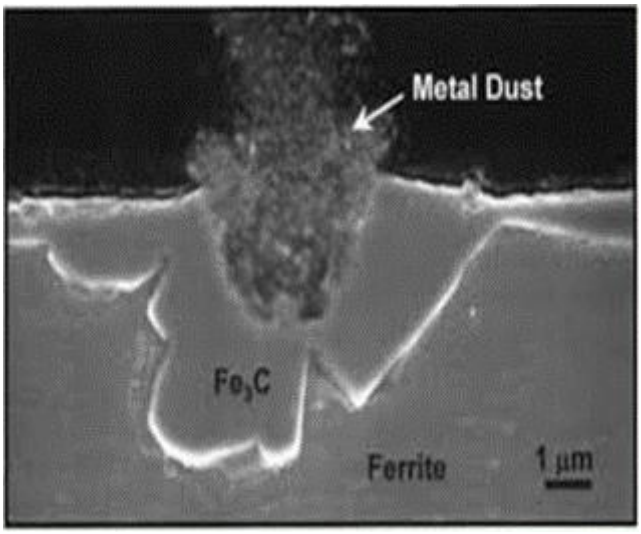

Figure 1.1: Metal dusting corrosion (Chun et al., 2002)

Metal dusting usually occurs at elevated temperatures within the range of 400-800 °C (Grabke (2003); Young et al., 2011). However, the temperature range has not

been well identified as it has also been reported to be 450-800 °C (Grabke, 1995; Voisey et al., 2006a) or 450-900 °C (Agarwal et al., 2001). On the contrary, in heat-treating industry, metal dusting has been reported to have at times occurred in the temperature range of 900-930 °C (Al-Meshari & Little, 2009). In addition, it is documented that metal dusting has happened at temperature as high as 1100 °C in strongly reducing environments (Hrivnak et al., 2005). Theoretically, metal dusting is possible at any temperature if the carbon activity is greater than one (Grabke, 1998).

Metal dusting is an old problem that is responsible for many early failures in a wide variety of industrial sectors. It has been encountered in carbon monoxide (CO) (Mishakov et al., 2013), methane (CH_4) and mixture of methane and hydrogen (CH_4/H_2) (Grabke et al., 2002; Liu et al., 2016a), ethane (C_2H_6) (Grabke, 1999), propane (C_3H_8) (Ackermann et al., 2005), and butane (C_4H_{10}) (Mishakov et al., 2013), and other mixtures of similar gases. Therefore, MD is most commonly encountered in steam reforming processes such as the production of hydrogen or syngas for ammonia and methanol applications. At elevated temperatures, CO and hydrocarbons tend to dissociate on metal surfaces and form carbon. The carbon is then transferred to the solid phase, draws the susceptible metals out of their homogeneous solid matrix, which leads to pitting, general attack, and finally to the breakdown of the materials (Grabke & Schütze, 2014b).

Controlling and mitigate MD corrosion needs to be taken into consideration since it poses issues to production units. The main method to eliminate the influence of MD on petrochemical industrial equipment currently is replacing the corroded section, and detailed monitoring and periodic inspection are required as well. While, these add large extra costs. For example, the US Department of Energy has reported that annually

220-290 million dollars is spent to replace unit due to metal dusting corrosion in hydrogen production industry (Ma, 2017)

1.2 PROBLEM STATEMENT

Metal dusting poses a great threat to the petrochemical industries such as steam reforming processes, production of hydrogen or syngas of ammonia. Metal dusting causes not only failures or degradation of components but also heavy economic loss. Extensive research efforts have been devoted to the mitigation of failures. Despite the efforts, these problems still remain troublesome and likely to continue to pose threat to the concerned industries. Therefore, there is a strong drive to operate deeper into the metal dusting region in order to create more energy efficient processes. So, there is a significant interest in protecting metal parts from metal dusting. The key to suppressing metal dusting is to stop the dissociation of the carbon source or subsequent carbon diffusion into the susceptible materials.

There are several methods to protect metal from MD, which have been discussed in the literature review including modifying the process conditions, surface poisoning, alloying, chemical, mechanical and laser treatments as well as coatings. Each method has advantages and disadvantages. Changes of process conditions are not an option due to the process requirements in most cases and the use of poisonous chemicals is still limited due to its interference with downstream processes. Newly developed alloys are sometimes not sufficiently resistant and expensive due to the large quantities involved. Mechanical and chemical surface treatments are not always applicable, and the lifetime of coatings is often limited by adhesion problems.

To tackle these challenges, surface coating of the austenitic stainless steel has been attempted by several researchers using the physical vapour deposition (PVD) and chemical vapour deposition (CVD) techniques. Despite these efforts, these techniques are expensive, complicated and difficult to recoating at the site because they operate at very high temperatures and vacuums also it requires a cooling water system to dissipate large heat loads. To overcome these previous issues, this research will be investigated how to use a copper coating on 314L, 316L by Electrodeposition technique against MD corrosion.

1.3 RESEARCH PHILOSOPHY

Significant efforts have been made on coating of austenitic stainless steel against MD corrosion. However, coating lifetime still the major problem of coating application. Moreover, repair/reapply coating on site is difficult and its cost is very expensive. Since Cu is non catalytic to carbon reaction with a metallic surface (Alstrup et al., 1998; Bernardo et al., 1985; Zhang et al., 2007), therefore, using copper coating by electroplating might improve the lifetime of the coating by repair/reapply coating on the site. Also, this technique is inexpensive and simple to use which may attract the chemical and petrochemical industries to use this technique to protect the stainless-steel structures and save them without catastrophic failure.

1.4 OBJECTIVES OF THE RESEARCH

The primary aim of this work is to study the electroplated copper coatings on 304L and 316L stainless steels for mitigation of metal dusting corrosion in CH_4/H_2 environment.

The objectives are: