ALLOYING OF ALUMINIUM SURFACE WITH Q-SWITCHED Nd:YAG LASER

MOHD SHAFIQ BIN SHAHARIN

UNIVERSITI TEKNOLOGI MALAYSIA

ALLOYING OF ALUMINIUM SURFACE WITH
Q-SWITCHED Nd:YAG LASER

MOHD SHAFIQ BIN SHAHARIN

A thesis submitted in fulfillment of the
requirements for the award of degree of
Master of Science (Physic)

Faculty of Science
Universiti Teknologi Malaysia

APRIL 2015

Dedicate, with love,

To my beloved family especially my parents

Wan Zaharah binti Wan Ab Rahman & Shaharin bin Hj Mohammed

To all my lovely my friends,

Thank you for understanding and support through my endeavour till the end.

ACKNOWLEDGEMENT

Alhamdulillah. First and foremost, I am grateful to Allah SWT for His mercy, has given me the strength and health to complete this master study. I wish to express my deepest and sincere gratitude to my master degree supervisor, Prof. Dr. Noriah Bidin toward the successful completion of this study. Thank you for her expertise, sincerity, valuable guidance and encouragement extended to me.

My sincere thanks and appreciation go to Dr Waskito, Fakaruddin, Ganesan, Mundzir, Aiza, Hanum, Radhiana, Hida, Syuhada and Saleha for theirs assistance and guidance during my lab works. My warm thanks to my colleague and friends Luqman, Junaidi, Amirul, Mustakim, Ahmad, Syamsul and others for their thoughts, opinions, cooperation's and friendships throughout completing this research.

I owe my loving thanks to my parents and my family members. Thank you for their patience, support and motivation all the way from the beginning of this research. Last but not least, I take this opportunity to record my sincere thanks to all who, directly or indirectly, have lent their helping hands in this venture.

ABSTRACT

In surface modification, laser has been used as a tool to improve and enhance the surface properties of metallic alloys through laser alloying technique. Therefore, the aim of this study is to modify aluminium surface with iron (Fe) and copper (Cu) by Q-switched Nd:YAG laser. The Q-switched Nd:YAG laser is operating at a fundamental wavelength of 1064 nm with 10 ns pulse duration. The laser optimized parameters in this work are focus distance, pulse width and pulse energy. The target consists of a pure aluminium plate and the two alloying elements used are iron (Fe) and copper (Cu) powders. The alloying elements were well mixed and prepared in four different ratios (Fe:Cu) of (1:0), (1:1), (2:1), and (3:1). The surface alloying process was carried out by varying the laser output energy delivered to the targets from 67 to 331 mJ per pulse. The modified surfaces were characterized by using three types of analysis; structural elemental, and mechanical analysis. The results from field emission scanning electron microscopy (FESEM) showed that the surface microstructures change significantly compared to the untreated surface. The formation of alloyed layer due to the rapid melting and solidification processes of alloying elements with aluminium substrate was observed. In addition, all the treated surfaces show less porosity and are free from any cracks. X-ray diffraction (XRD) analysis of the treated surface showed the formation of new compounds which comprise AlCu, AlFe, CuFe and AlFeCu. The maximum hardness of the treated surfaces as measured using microhardness tester is 86.2 HV which is two times higher than that of the untreated surface. The formation of intermetallic phases and the change in the surface microstructures are responsible for the increase in the surface hardness compared to untreated one.

ABSTRAK

Dalam pengubahsuaian permukaan, laser telah digunakan sebagai alat untuk memperbaiki dan meningkatkan sifat-sifat permukaan aloi metalik melalui teknik pengaloian laser. Oleh itu, tujuan kajian ini adalah untuk mengubah suai permukaan aluminium dengan menggunakan besi (Fe) dan kuprum (Cu) dengan melalui laser Nd:YAG bersuis-Q. Laser Nd:YAG bersuis-Q ini beroperasi pada panjang gelombang asas 1064 nm dengan tempoh denyutan 10 ns. Parameter-parameter laser yang dioptimumkan dalam kerja ini adalah jarak fokus, lebar denyut dan tenaga denyut. Sasaran merupakan kepingan aluminium tulen dan dua bahan pengaloian digunakan adalah serbuk besi (Fe) dan kuprum (Cu). Bahan-bahan pengaloian dicampurkan dengan sekata dan disediakan dalam empat nisbah yang berbeza (Fe:Cu) iaitu (1:0), (1:1), (2:1), dan (3:1). Proses pengaloian permukaan telah dijalankan dengan mengubah tenaga keluaran laser kepada sasaran bermula 67 hingga 331 mJ per denyut. Permukaan yang diubahsuai telah dicirikan dengan menggunakan tiga jenis analisis; analisis struktur unsur dan mekanikal. Keputusan daripada mikroskopi elektron imbasan medan pancaran (FESEM) menunjukkan mikrostruktur permukaan telah berubah secara ketara berbanding permukaan yang tidak diubahsuai. Pembentukan lapisan aloi disebabkan oleh proses peleburan dan pemejalan yang laju berlaku antara bahan aloi dengan substrat aluminium telah diperhatikan. Tambahan pula, semua permukaan yang diubahsuai menunjukkan bilangan liang yang kurang dan bebas dari sebarang keretakan. Analisis pembelauan sinar x (XRD) pada permukaan yang diubahsuai menunjukkan pembentukan sebatian baru yang terdiri daripada AlCu, AlFe, CuFe dan AlFeCu. Kekerasan maksimum permukaan yang diubahsuai diukur menggunakan penguji kekerasan mikro adalah 86.2 HV yang mana dua kali lebih tinggi berbanding permukaan yang tidak diubahsuai. Pembentukan fasa-fasa intermetalik dan perubahan pada mikrostruktur permukaan bertanggungjawab terhadap peningkatan pada kekerasan permukaan berbanding yang tidak diubahsuai.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

cm	-	Centimeter
g	-	Gram
^{o}C	-	Celsius
W	-	Watt
m	-	meter
K	-	Kelvin
J	-	Joule
kg	-	Kilogram
Ω	-	Ohm
MPa	-	Megapascal
mm	-	Millimeter
ns	-	nanosecond
ms	-	millisecond
E_d	-	Energy density
d	-	Diameter
E	-	Energy
H_V	-	Vickers Hardness Number
F	-	Load
V	-	Volt
%	-	Percentages
Hz	-	Hertz

d	-	Diagonal length
θ	-	Angle between opposite face of the diamond

ABBREVIATIONS

FESEM	-	Field Emission Scanning Electron Microscopy
XRD	-	X-ray diffraction
EDXS	-	Energy-dispersive X-ray spectroscopy
LSA	-	Laser Surface Alloying
Nd:YAG	-	Neodymium-doped yttrium aluminium garnet
CO^2	-	Carbon dioxide
Ti	-	Titanium
Nb	-	Niobium
Fe	-	Iron
Cu	-	Copper
Cr	-	Chromium
Ni	-	Nickel

CHAPTER 1

INTRODUCTION

1.1 Background Information

Aluminium is extensively used in industry due to its excellent in conductivity for both thermal and electrical, high mechanical strength, low specific weight, good formability, and relatively low cost (Tomida and Nakata, 2003). Within excellent characteristic, poor surface properties such as hardness and wear resistance have limited it in application range. These limitations might be overcome if the surface properties could be improved while retaining the bulk properties. There are a few metallurgical techniques that may be utilized to improve surface properties, for example, flame spraying, plasma spraying and electroplating. However, these techniques are not usually applied because of the poor metallurgical bonding to the base material (Katipelli et al., 2000). Due to the rapid advancement in the field of surface engineering, conventional techniques for surface treatment have been replaced by techniques using advanced heat sources such as plasma, laser, ion, and electron.

For many years, lasers are practically well-known as a powerful tool that can be used for many applications such as cutting, welding, drilling and surface modification. Many research works have been conducted to enhance the surface properties of the material through laser material processing. Laser has many excellent features and one of them is the effective processes in surface treatment of the metallic substrates. Laser treatment is new and have various number of advantages in relation to processing and the most interesting one is the possibility of producing surface alloys or structures which not attainable by other methods.

Usually, laser material processing involve a thermal process where the absorption of large number of photons heats the metallic material to achieve the surface modification. Previous studies show that laser surface treatment and coating could be an ideal technique to protect die surfaces from thermal fatigue and extend die life by reducing the damage at contact surfaces (Jiang et al., 2001). Laser surface modification offers a solution to enhance the surface properties of metallic alloys (Almeida et al., 1995). The electromagnetic radiation of laser beam has been fully utilized as a part of thermal processes to modify the microstructure of the surface layer to enhance the surface properties in comparison with the material original properties. Within laser beam, the applied energy can be delivered precisely on the surface of an opaque material that is enabling in increasing the temperature of substrate material above the melting point.

Among the various surface modification techniques, laser surface alloying is considered to be the most effective technique to modify the surface properties of aluminium since previous studies by various authors have shown positive results (Tomida and Nakata, 2003; Jiang and Molian, 2001; Almeida et al., 1995; Tomida et al., 2001; Das, 2004; Ravi et al., 2000). The most important advantage of this process is the possibility of modifying the properties and composition within a thin surface layer without affecting the properties of the bulk material.

1.2 Problem Statement

Aluminum is currently receiving a great deal of attention from several industries such as aircraft, automotive and household appliance due to its unique and excellent properties. However, its tribological characteristics such as hardness, wear and corrosion resistance are poor in comparison to steel. Research on the aluminum has been carried out actively in the past few decades by laser alloying with various elements such as Cu, Nb, Ti, Fe, Cr and Ni (Tomida and Nakata, 2003; Katipelli et al., 2000; Man et al., 2007; Almeida et al., 1995; Das, 2004). Mostly, lasers used in surface modification are high energy, high power, continuous and long wavelength like CO_2 laser that reach up to 10 μm. However, it is not suitable and easy task to modify a localized area. Therefore, this work will be carried out in order to alloying aluminum by using Q-switched Nd:YAG laser. This versatile surface treatment technique utilized such laser with only low-level energy, faster, great precision, localized treatment and controllable with number of pulses.

1.3 Research Objectives

The main objective of this study is to alloy aluminum surface with Iron (Fe) and Copper (Cu) by a Q-switched Nd:YAG laser. In attempt to achieve this goal, the following works are performed:

1. To optimize laser ablation parameters in alloying process

2. To analyze the composition of new composite on alloy surface

3. To characterize the surface hardness of the alloy

1.4 Scope of the Study

In this study, a Q-switched Nd:YAG laser with a fundamental wavelength of 1064 nm and pulse duration of 10 ns was employed as a source of energy. The laser was focused by a biconvex lens with focal length of 10 cm. The target comprised of a pure aluminum plate that stand as a substrate material. The chosen alloying elements to alloy the aluminum substrate were iron (Fe) powder and copper (Cu) powder. Both powders was mixed (Fe:Cu) with ratios of 1:0, 1:1, 2:1 and 3:1. Bostik contact bond glue was selected as an adhesive material to bond between substrate and alloying element. The aluminum surface was painted with glue prior pre-coated with alloying element. The samples target were placed at the focal point in order to obtain the optimum energy density from the laser to ensure maximum melting at the coated surface. The alloying process was carried out by exposing the pre-coated sample to energy in the range of 66.88 mJ to 331.25 mJ. The modified sample was examined using the metallurgical techniques including FESEM (Field Emission Scanning Electron Microscopy), EDX (Energy Dispersive X-ray Spectroscopy) and XRD (X-ray Diffraction). The strength of the modified surface is measured by using a Vickers hardness tester.

1.5 Thesis Outline

The entire research was documented in the thesis, and it consists of five main chapters. Chapter 1 describes the introduction and background information of the thesis, problem statement, a list of the research objective and the scope of the research.

Chapter 2 is on the complete theory of the laser surface modification. It explains the basic process of alloying technique, the effect of laser parameter and its mechanism. The basic properties of aluminium and working principle of hardness tester also explained in this chapter.

Chapter 3 explains the methodology of the research. In this chapter, the sample preparation, experimental setups, and its process are discussed. The laser calibration such as laser output, beam density and sample target location were measured. Several characterization techniques involved in this project were also included.

Chapter 4 discuss the microstructure characterization and hardness evaluation in detail. All the results were presented and discussed in this chapter. This includes the analysis of microstructure alloyed surface and its elemental composition via FESEM and EDXS. Then followed by XRD analysis to determined the phase formation on alloyed surface. The hardness measurements of alloyed surface were also presented.

Finally, all the works are concluded in Chapter 5. This includes the summary of the results achieved from the experiment works together with some recommendations for future study.

.

REFERENCES

Almeida, A., Anjos, M., Vilar, R., Li, R., Ferreira, M. G. S., Steen, W. M., and Watkins, K. G. (1995). Laser alloying of aluminium alloys with chromium. *Surface and Coatings Technology*. 70, 221-229.

Alwafi, Y. A., Bidin, N., Hussin, R., Hussain, M. S., and Gustiono, D. (2011). Microhardness Evaluation of Pure Aluminum Substrate after Laser Surface Alloying with Iron and Copper. *Journal of Materials Science and Engineering B. 1, 200-205.*

Alwafi, Y. A. (2012). *Laser Surface Alloying of Pure Aluminium Substrate with Iron and Copper by Q-Switched Nd:YAG Laser.* Doctor Philosophy, Universiti Teknologi Malaysia, Skudai.

Bass, M. (1983). “Laser materials processing.”, North Holand, Amsterdam.

Bergmann, H. W., Kupfer, R. and Mueller, D. (1990). Laser Hardfacing. *CO_2 Lasers and Applications II.* 1276, 375-390.

Bidin, N., Abdullah, M., Shaharin, S. M., Alwafi, Y., Riban, D., and Yasin, M. (2013a). Optimization of the super lateral energy in laser surface alloying of aluminum. *Laser Physics Letters*. 10, 106001.

Bidin, N., Abdullah, M., Shaharin, S. M., Alwafi, Y., Riban, D., and Yasin, M. (2013b). SEM-EDX Analysis of Laser Surface Alloying on Aluminium. Journal of Mathematic and Fundamental Science. 45(1), 53-60.

Bidin, N. (1995). *Studies on Laser induced cavitation erosion and mechanism of cavitation Damage.* Doctor Philosophy, Universiti Teknologi Malaysia, Skudai.

Brandl, E., Palm, F., Michailov, V., Viehweger, B., and Leyens, C. (2011). Mechanical Properties of Additive Manufactured Titanium (Ti-6Al-4V) Blocks Deposited by a Solid-State Laser and Wire, *Materials and Design*. 32(10), 4665-4675.

Buchfink, G. (2007). *The Laser as a Tool – A light beam conquers industrial Production*. (1st ed). *Würzburg*, Deutschland: *Vogel Buchverlag*.

Capello, E., and Previtali, B. (2006). The influence of operator skills, process parameters and materials on clad shape in repair using laser cladding by wire. *Journal of Materials Processing Technology*. 174, 223-232.

Chen, H., and Luo, Q. (1997). Study on Laser Gas Alloying for Titanium Alloy, *Jiguang Zazhi/Laser Journal*. 18 (3), 32-36, 44.

Chmelickova, H., Kucharicova, L., and Grezl, J. (1998). Powder Alloying of Low-Carbon Steel by CO_2 Laser. *Lasers and Physics of Thin Films*. 8(1), 349-351.

Cohen, M. I. (1972). *Material Processing*. In F. T.Arecchi, F. T. and Schulz-Dubois, E. O (Eds.) *Laser Handbook (pp* 1577-1647). Amsterdam: North-Holland. Pub. Co.

Cui, C., Hu, J., Liu, Y., Gao, K., and Guo, Z. (2008). Formation of nano-crystalline and amorphous phases on the surface of stainless steel by Nd:YAG pulsed laser irradiation. *Applied Surface Science*. 254(21), 6779-6782.

Das, S. (2004). Development of aluminium alloy composites for engineering applications. *Transactions of the Indian Institute of Metals*. 57(4), 325-334.

Das, D. K. (1994). Surface roughness created by laser surface alloying of aluminium with nickel. *Surface and Coatings Technology*. 64, 11-15.

DiMelfi, R. J., Sanders, P. G., Hunter, B., Eastman, J. A., Sawley, K.J., and Leong, K. H. (1998) Mitigation of subsurface crack propagation in railroad rails by laser surface modification. *Surface and Coatings Technology*. 106(1), 30-43.

Glass, A. J and A. H Guenther (1978). *Proceedings of Laser Induced Damage in Optical Materials*. NBS Spec. Publ., Washington DC.

Glass, A. J., Guenther, A. H. (1979). *Proceedings of Laser Induced Damage in Optical Materials.* NBS Spec. Publ., Washington.

Guo, B., Jiansong, Z., Shitang, Z., Huidi Z., Yuping, P., and Jianmin, C. (2002). Tribological properties of titanium aluminides coatingsproduced onpure Ti by laser surface alloying. *Surface and Coatings Technology*. 202(17), 4121-4129.

Hirsch, M, and H. Oskam (1978). Gaseous Electronics, Volume 1: Electrical Discharges, New York: Academic Press.

Herziger, G. and Kreutz, E. (1986). Fundamentals of laser microprocessing of metals. *Physica Scripta.* 1986, 139.

Ippen, E., Shank, C. V., and Woerner, R. (1977). "Picosecond dynamics of azulene." Chemical Physics Letters. 46(1), 20-23.

Jiang, W., and Molian, P. (2001). Nanocrystalline TiC powder alloying and glazing of H13 steel using a CO2 laser for improved life of die-casting dies. *Surface and Coatings Technology*. 135(2-3), 139-149.

Kalyon, M., and Yilbas, B. S. (2003) Laser pulse heating: a formulation of desired temperature at the surface. *Optics and Lasers in Engineering* .39(1), 109-119.

Katipelli, L. R., Agarwal, A., and Dahotre, N. B. (2000). Laser surface engineered TiC coating on 6061 Al alloy. microstructure and wear. *Applied Surface Science*. 153, 65-78.

Kamal H. Butruna (2001).Composite Formation on Surface of Hypereutectic Al-Si Alloy by SiC and Cr Using Ruby Laser. M. Sc., Al-Fateh University.

Kong, C. Y., Caroll, P. A., Brown, P., and Scudamore, R. J. (2007). The effect of average powder particle size on deposition efficiency, deposit height and surface roughness in the direct metal laser deposition process. *Proceedings of the International Conference on Joining of Materials*. 29 April - 2 May. Helsingør, Denmark.

Koster, U., W. Liu, Liebertz, H and Michel, M. (1993). Mechanical properties of quasicrystalline and crystalline phases in Al-Cu-Fe alloys. *Journal of Non-Crystalline Solids.* 153, 446-452.

Lyle, J. P., Granger, D. A., and Sanders, R. E. (2000). Aluminum Alloys. *Ullmann's Encyclopedia of Industrial Chemistry.* Germany: Wiley-VCH.

Lei, Y. P., Marakawa, H., Shi, Y. W., and Li, X. Y. (2001). Numerical analysis of the competitive influence of Marangoni flow and evaporation on heat surface temperature and molten pool shape in laser surface remelting. *Computation Materials Science*. 21, 276-290.

Lim, YY., and Chaudhri, MM. (2002). The influence of grain size on the indentation hardness of high-purity copper and aluminium. *Philosophical Magazine A*. 82(10), 2071.

Liu, J., Luo, Q., and Zou, Z. (1993). Laser Gas Alloying of Titanium Alloy with Nitrogen. *Surface and Coatings Technology*. 57 (2-3), 191-195.

Majumdar, J. D. (2008). Development of wear resistant composite surface on mild steel by laser surface alloying with silicon and reactive melting. *Materials Letters.* 62(27), 4257-4259.

Majumdar, J. D., and Manna, I. (2003). *Laser processing of materials*. India: Sadhana.

Man, H.C., Leong, K. H., and Ho, K. L. (2008). Process monitoring of powder pre-paste laser surface Alloying. *Optics and laser In Engineering*. 46(10), 739-745.

Man, H. C., Zhang, S., and Cheng, F. T. (2007). Improving the wear resistance of AA 6061 by laser alloying with NiTi. *Materials Letter*. 61(19-20), 4058-4061.

Moore, P. G and L. S Weinman (1980). ASM Engineering Bookshelf-Source Book on Application Of The Laser In Metalworking, ASM. 318.

Meek, J. M and J. D Craggs (1978). "Electrical breakdown of gases."

Ng, K.W., Man, H. C., and Yue, T. M. (2008). Corrosion and wear properties of laser surface modified NiTi with Mo and Zr02. *Applied Surface Science*. 254(21), 6725-6730.

Neto, O. D., and Vilar, D. S. (1998). Interaction between the Laser Beam and the Powder Jet in Blown Powder Laser Alloying and Cladding. *Proceedings of International Congress on the Applications of Lasers and Electro-Optics*. America, 180-188.

Poate, J. M. and J. W. Mayer (1982). Laser anneaing of semiconductors, Academic Press New York.

Qindeel, R. (2008). *Interaction of Q-Switched Nd:YAG Laser with Different Target Materials.* Doctor Philosophy,Universiti Teknologi Malaysia, Skudai.

Ravi, N., Sastikumar, D., Subramanian, N., Nath, A. K., and Masilamani, V. (2000). Microhardness and microstructure studies on laser surface alloyed aluminium alloy with Ni-Cr. *Materials and Manufacturing Processes*. 15(3), 395-404.

Ready, J. F. (1997). Industrial applications of lasers, Academic Press, New York.

Riabkina-Fishman, M., Zahavi, J. (1996). Laser alloying and cladding for improving surface properties. *Applied Surface Science*. 106, 263-267.

Ready, J. F., Farson, D. F and Feeley, T. (2001). LIA Handbook of Laser Materials Processing, Orlando, Florida: Laser Institute of America.

Rykalin, N. N., Uglov, A., (1978). Laser machining and welding, Pergamon Press.

Saleh, B. E. A., and Teich, M. C. (2007). *Fundamentals of Photonics*. (2nd ed.). Hoboken, New Jersey: John Wiley & Sons.

Shapiro, S. L. and D. Auston (1977). Ultrashort light pulses: picoseconds techniques and applications, Springer-Verlag.

Steen, W.M. and Mazumder, J. (2010). *Laser Material processing*. (4th ed.). London: Springer-Verlag.

Toyserkani, E., Khajepour, A., and Corbin, S. (2005). *Laser cladding*. USA: CRC Press.

Tomida, T., Nakata, K., Saji, S., and Kubo, T. (2001). Formation of metal matrix composite layer on aluminium alloy with TiC-Cu powder by laser surface alloying process. *Surface and Coatings Technology*. 142-144, 585-589.

Tomida, S., and Nakata, K. (2003). Fe-Al composite layers on aluminium alloy formed by laser surface alloying with iron powder. *Surface and CoatingsTechnology*. 174 -175, 559-563.

Va, Serban., C, Codrean., D, Utu., and A, Ercuta. (2009). Fe-based bulk metallic glasses used for magnetic shielding. *Journal of Physics: Conference Series*. 144(1), 012037.

Vaziri, S. A., Shahverdi, H. R., Torkamany, M. J., and Shabestari, S. G. (2009). Effect of laser parameters on properties of surface-alloyed Al substrate with Ni. *Optics and Lasers in Engineering*. 47, 971-975.

Velde, O., Gritzki, R., and Grundmann, R. (2001). Numerical investigations of Lorentz force influenced Marangoni convection relevant to aluminium surface alloying. *International Journal of Heat and Mass Transfer*. 44, 2751-2762.

Westbrook, J. H., H. Conrad, et al. (1973). The science of hardness testing and its research applications, American Society for Metals Metals Park, Ohio.

Xia, Y., Liu, W., and Xue, Q. (2005). Comparative study of the tribological properties of various modified mild steels under boundary lubrication condition. *Tribology International*. 38(5), 508-514.

Yang, S., Chen, N., Liu, W., and Zhong, M. (2003). In situ formation of MoSi2/SiC composite coating on pure Al by laser cladding. *Materials Letters*. 57, 3412-3416

Yue, T. M, Xu, J. H., and Man, H. C. (1997). Pulsed Nd:YAG laser welding of a SiC particulate reinforced aluminium alloy composite. *Applied Composite Materials*. 4, 53-64.

Yovanovich, M. M. (2006). Micro and Macro Hardness Measurements, Correlations, and Contact Models. *AIAA Aerospace Science Meeting and Exhibit*, 9-12 January. Reno, Nevada, 1–28.