EFFECT OF HEATING TEMPERATURES AND MOULD THICKNESS ON THE GEOMETRY SHAPE OF IN-SITU MELTING MAGNESIUM INVESTMENT CASTING

SITI NUR FAEZAH BINTI ABDUL RAZAK

A project report submitted in partially fulfilment of the
requirements for the award of the degree of
Master of Science (Advanced Manufacturing Technology)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

SEPTEMBER 2017

ACKNOWLEDGEMENT

I am grateful and would like to express my sincere gratitude to my supervisor, Prof. Dr. Mohd Hasbullah Idris for his invaluable guidance, continuous encouragement and constant support in making this Master Project possible. I really appreciate his guidance from the initial to the final level that enabled me to develop an understanding of this project thoroughly. Without his advice and assistance it would be a lot tougher to complete this Master Project.

My sincere thanks go to all lecturers and members of the staff of the Mechanical Engineering Department especially Foundry and Materials Science laboratories for their help and support in conducting the experiments until this project complete.

Finally, I would also like to take this opportunity to relay deepest appreciation to my parents, brother and sisters for their unconditional love, encouragement and support on this project. Special thanks to my coursemates in MSc. Advanced Manufacturing Technology, whom has guided me either directly or indirectly, especially in the early preparation of this Master Project and throughout my studies in Universiti Teknologi Malaysia (UTM).

ABSTRACT

Magnesium has recently gained more advances used in industrial application, especially in automotive and aerospace component because of its properties that provides light weight structural with high strength and better performance compares with other metal alloy. A new technique of casting magnesium alloys has been explored known as in-situ melting investment casting. Currently, this casting only satisfies to suppress the mould-metal reaction alloys in which air or moisture must be avoided in order to prevent the potential issues such as catastrophic burning and rapid oxidation throughout melting process, but not at the expenses of fluidity within the geometry thin section shell mould. Therefore, the objective of this study is to investigate the effect of temperature and mould thickness on geometry shape of shell mould using the in-situ melting technique. The heating temperature of the granule magnesium alloy involved 650, 700 and 750^{o}C whereas the mould thickness was made in the form of 3 and 5 layers. Based on observation, the result shows that increasing the heating temperature from 650 to 750^{o}C will significantly cause the oxide layer become thicker especially between granules, even though the two condition of flux and argon gas was applied during heating. Meanwhile, decreasing the thickness of the mould could increase melting rate of the granules which causes in small partial fusion between granules at heating temperature of 650 and 700^{o}C with relatively suppressed mould-metal reaction especially at large diameter of geometry ceramic shell mould. This is because before heating process conducted, most of granules already have the oxide gray film. It can be concluded that, the geometric shape of mould gives significant influence to the fluidity of molten metal to flow through the entire shell mould especially the part that having an intricate thin section.

ABSTRAK

Magnesium baru-baru ini lebih banyak digunakan dalam aplikasi industri, terutamanya dalam menghasilkan komponen bagi automotif dan aeroangkasa kerana sifat strukturnya yang ringan serta kuat dan mempunyai prestasi yang lebih baik berbanding logam aloi yang lain. Satu teknik baru dalam menuang aloi magnesium telah dieksplorasi dikenali sebagai peleburan in-situ invesmen. Buat seketika ini, tuangan logam hanya mampu menghentikan tindakbalas acuan-logam di mana udara atau kelembapan mesti dielakkan untuk mengelakkan isu-isu yang berpotensi seperti pembakaran dan pengoksidaan pesat sepanjang proses lebur, tetapi tidak pada kecairan didalam geometri cengkerang seramik yang sempit. Oleh itu, objektif untuk kajian ini merupakan menyelidikan pada kesan suhu dan ketebalan acuan pada bentuk geometri acuan cengkerang menggunakan teknik peleburan in-situ. Suhu pemanasan aloi magnesium granul melibatkan 650, 700 dan 750^{o}C manakala ketebalan acuan dibuat dalam bentuk lapisan 3 dan 5. Berdasarkan pemerhatian, hasilnya menunjukkan peningkatan suhu pemanasan dari 650 hingga 750^{o}C akan menyebabkan lapisan oksida menjadi lebih tebal terutama di antara granul, walaupun kedua-dua keadaan fluks dan gas argon digunakan semasa pemanasan. Sementara itu, penurunan ketebalan acuan dapat meningkatkan kadar lebur granul yang menyebabkan terbentuk gabungan separa diantara granul pada suhu pemanasan 650 dan 700^{o}C dengan menhentikan tindakbalas acuan-logam terutama pada diameter besar acuan cengkerang seramik geometri. ni kerana sebelum proses pemanasan dijalankan, kebanyakan granul sudah mempunyai permukaan kelabu oksida. Dapat disimpulkan bahawa, bentuk acuan geometri memberikan pengaruh yang signifikan terhadap kecairan logam lebur untuk mengalir melalui keseluruhan acuan cengkerang terutama bahagian yang mempunyai yang tempat nipis yang rumit.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

HPDC	-	High Pressure Die Casting
VP SEM	-	Variable-Pressure Scanning Electron Microscope
EDS	-	Energy Dispersive X-Ray Spectroscopy
ASTM	-	American Society for Testing and Materials
LED	-	Light-Emitting Diode
RP	-	Rapid Prototyping
LP	-	Liquid Petroleum

LIST OF SYMBOLS

Chemical symbol

AZ91D	-	Magnesium –aluminum 9% zinc
$Al_2O_3.SiO_2$	-	Aluminium Silicate
CaF_2	-	Calcium fluoride
Cl	-	Chloride
KCl	-	Potassium Chloride
$KMgCl_3$	-	Potassium Magnesium Chloride
Mg	-	Magnesium
$MgCl_2$	-	Anhydrous Magnesium Chloride
MgO	-	Magnesium Oxide
O	-	Oxygen
Si	-	Silicon
SiO_2	-	Silica
Zr	-	Zirconium
$ZrO_2.SiO_2$	-	Zircon

Greek Symbol

cm^3	-	Cubic Centimeter
g	-	Gram
K	-	Thermal Conductivity
Kg	-	Kilogram
kJ	-	Kilojoules
min	-	Minute
mm	-	Millimeter
Mpa	-	Megapascal
wt.%	-	Weight Percentage
^{O}C	-	Centigrade Degree

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research Background

In comparison with any other alloys and steel such as aluminum and copper, magnesium alloys have recently gained more popular in industrial application especially in automotive component due to their light weight structural with an advanced high strength and better functional material performance (Buldum, et al., 2013). On the other hand, some magnesium alloy is typically used as a light weight material with relatively low density in structural body part of vehicles in order to improve the fuel efficiency in term of reduction in fuel consumption. As the demand for lightweight vehicle is preferable day by day, the automotive manufacturers nowadays are start looking forward into lighter material than aluminum. In year 2014, Volkswagen XL1is a car model that classify to be the most excellent production car in the world which improve the fuel efficiency as it used magnesium alloy in frame body part which causes the car accelerated dramatically for about 313 miles per gallon (Muja, 2015).

Magnesium is the lightest metal among others, especially for structural application due to its atomic number is 12. Therefore, these types of metal are the lightest of all the engineering metals that has a density of 1783 kg/m^3, which is approximately two third of aluminum and about one sixth of steel (Wulandari, et al., 2010). Magnesium is eventually can be found in large quantities in the Earth's crust and can be extracted from inside seawater abundantly. Due to excellent physical and mechanical properties, magnesium have higher strength-to-weight ratios (tensile strength/ density) of precipitation hardened alloy compare to those other structural metals. Hence, magnesium and magnesium alloys exhibit several superior attributes such as high vibration damping capacity, good machinability, high specific stiffness, better heat conductivity and excellent castability (Li, 2004).

Magnesium alloy is consisting of additional small quantities of other commercial alloy elements such as aluminum, zinc, cerium, thorium, silver, zirconium and yttrium that contribute into different name of magnesium alloy. In order to determine the name of magnesium alloys, American Society for Testing Materials is used as reference for designated alloy. By additional significant amount of aluminum, zinc and manganese into magnesium, the mechanical properties can be improved which result in the increasing of strength, castability and ductility (Aravindan, et al., 2015). Currently, magnesium alloy production is used mainly in high pressure die casting (HPDC) especially in automotive industry. Unfortunately, the problem could be rise as the formation of porosity is frequently occurred which have tendency of air entrapment during die filling and solidification within the cavities of cast magnesium alloy (Wang, et al., 2006). In high pressure die casting, the formation of pore cannot be avoided in cast product as the presence of porosity defect can be appeared due to shrinkage result from solidification and by entrapped gas (Hangai & Kitahara, 2008).

In modern industrial casting, wide variety of processes has been developed and broadly defined in term the type of mould material used whether sand, metal or other material and the pouring method of molten metal into cavity either through gravity, vacuum, low pressure or high pressure. Investment casting process is regarded as the most precision castings due to its ability of providing a good surface finish for thin wall castings component with complex geometry and high degree of dimensional accuracy. In addition, this casting method also prefers as one of practical solutions for magnesium alloy to improve the consequence of the hexagonal lattice structure which causes the alloys go through some difficulties during the solid state formation (Kim, et al., 2000). Hence, recently most of the investments casting for magnesium produces value added components which normally used for the production in the aerospace engineering sector as it manufacture light density component and low cost in machining.

With increasing demand for the thin wall design (light weight engineering components) and net shape processes (reduce cost of production), have led to the complexity of manufacturing process mainly in precision casting technique. In order to design the minimum wall thickness, there are three important facts that need to take consideration such as the fluidity of the alloy and its ability to flow in the mould as well as a solidification range of alloy for proper feeding inside thin wall sections (Gwyn, 2009). In addition, the influences of geometry shape design also play an important role to identify the success of investment casting process. Due to the significant influence of geometrical shape and dimension of turbine blades, close dimension of tolerance is required to manufacture through investment casting as it can enhance the high quality of net-shaped complex part. The size of the blade produces from investment casting are usually smaller than die cavity because of some issues regarding to the shrinkage of wax and solidifying alloy material.

Necessary action need be taken while manufacturing the cast product by considering casting parameter, so that the material can be solidified in a manner that could maximize the mechanical properties as well as preventing potential defects, such as gas porosity, shrinkage and inclusion. Hence, it is important for designer or manufacture to understand the relationship between the process parameters and microstructure of magnesium alloys in order to achieve excellent mechanical properties and complex geometry in casting. Thus, in this work, further study will be conducted in order to determine the effect of temperature on the correlation between the geometric shapes with different thickness of mould for magnesium in-situ melted investment casting.

1.2 Problem Statement

Recent developments in the automotive and aerospace industries have captivated a broader interest in study of magnesium alloys. Magnesium alloys are well known as the most excellent metal that has better properties in term of low density, high vibration damping capacity, good machinability, high specific stiffness, better heat conductivity and excellent castability. However, the mould - metal reaction is the most crucial part of cast magnesium alloys in which air or moisture must be avoided in order to prevent the potential issues such as catastrophic burning and rapid oxidation throughout melting process. For overcome this problem, researcher come up with the new solution by using the application of flux and argon to reduce the mould-metal reaction especially in in-situ investment casting process but not at expenses of fluidity within the geometry shape.

When the liquid metal enters the mould, the first requirement is, it should satisfactorily fill the mould cavity and develops a smooth skin through intimate contact with the mould surface especially on the geometrical thin wall section as the investment casting process takes place. With this condition, misrun and cold shuts defect are most likely occur in thin wall section due to the insufficient fluidity and low melting temperature in which causes the molten metal unable to fill the mould cavity completely. The jet engine turbine consists of complicated profile designs such as an airfoil component as it requires a very thin casting wall thickness of 0.5 mm with the mould thickness for about 6.25mm. Based on this condition, large ratio of thermal mass between the molten metal and ceramic mould could be obtain and give effect on small increment in temperature loss of molten metal and form no-fill defect (Banerjee & Yu, 2002). No-fill defect is unique problems that may present when manufacture the thin-wall castings, mainly due to freezing of molten metal as it does not flow within the thin section with intricate geometric. Therefore, in-situ investment casting technique is used in this research to investigate the influence of different mould thickness in geometry shape and heating temperature in order to eliminate the mentioned problem.

1.3 Research Objectives

Based on the background and problem statement stated above, the objectives of this study are stated below:

1. To determine the effect of heating temperature and mould thickness on the geometric shape for magnesium in-situ melted investment casting.

1.4 Scope of Study

In order to achieve the objective of the research study, several scopes have been identified:

1. Heating temperature for magnesium granule is ranges between 650, 700 and 750^{o}C
2. Mould thickness will be investigated for about 3 & 5 layers with slurry viscosity approximately for about 20-22 second
3. Material used for casting will be AZ91D magnesium alloy.
4. The effect of heating temperature and mould thickness on the geometric shape for magnesium in-situ melted investment casting will be investigate through analysis
5. The analysis will be conducted to investigate the characterization of cast sample by using Variable-Pressure Scanning Electron Microscope (VP SEM) with energy dispersive X-ray Spectroscopy (EDS) as well as through visual observation.

REFERENCES

Aarstad, K. (2004). *Protective Films on Molten Magnesium.* Norwegian University of Science and Technology.

Adelman, R. L. (1976). *Patent No. US3998917 A.* United States of America.

Aravindan, S., Rao, P. V., & Ponappa, K. (2015). Evaluation of physical and mechanical properties of AZ91D/SiC composites by two step stir casting process. *Journal of Magnesium and Alloys, 3*(1), 52–62.

Banerjee, D. K., & Yu, K.-O. (2002). Investment casting. In K.-O. Yu (Ed.), *Modelling For Casting And Solidification Processing* (pp. 333-372). New York: Marcel Dekker, Inc.

Behera, R., Chatterjee, D., & Sutradhar, G. (2012). Effect of Reinforcement Particles on the Fluidity and Solidification Behavior of the Stir Cast Aluminum Alloy Metal Matrix Composites. *American Journal of Materials Science, 2*(3), 53-61.

Bhattacharjee, D., Bhattacharyya, T., Chatterjee, S., Dutta, M., & Ghosh, C. (2009). *Emerging Challenge for Metals and Materials Engineering and Technology* (1 ed.). Kolkata: Allied Publishers Pvt. Ltd.

Boothroyd, G., Dewhurst, P., & Knight, W. (2009). *Product Design for Manufacture and Assembly* (2nd ed.). New York: Taylor & Francis e-Library.

Boothroyd, G., Dewhurst, P., & Knight, W. A. (2011). *Product Design for Manufacture and Assembly* (3rd ed.). Boca Raton: Taylor and Francis Group,LLC.

Bralla, J. G. (1999). *Design for Manufacturability Handbook* (2nd ed.). New York: McGraw-Hill.

Brandes, E. A., & Brook, G. B. (1992). *Smithells Metals Reference Book* (7th ed.). Butterworth-Heinemann: Reed Educational and Professional Publishing Ltd.

Braszczynska-Malik, K. N. (2011). Precipitates of γ–Mg17Al12 Phase in AZ91 Alloy. In F. Czerwinski (Ed.), *Magnesium Alloys - Design, Processing and Properties* (pp. 95-112). Poland: InTech.

Braszczynska-Malik, K. N., Zawadzki, I., Walczak, W., & Braszczynski, J. (2008). Mechanical Properties of High-Pressure Die-Casting AZ91 Magnesium Alloy. *Archives of Foundry Engineering, 8*(4), 15-18.

Brown, R. E. (2006). Mechanical Engineers' Handbook: Materials and Mechanical Design. In Kutz, & Myer (Eds.), *Magnesium and its alloys* (pp. 278-286). Canada: John Wiley & Sons, Inc.

Brum, F. J., Amico, S. C., Vedana, I., & Spin Jr., J. A. (2009). Microwave dewaxing applied to the investment casting process. *Journal of Material Technology, 209*, 3166–3171.

Buldum, B. B., Sik, A., & Ozkul, I. (2013). Investigation Of Magesium Alloys Machinability. *International Journal Of Electronics; Mechanical and Mechatronics Engineering, 2*(3), 261-268.

Chino, Y., Mabuchi, M., & Kado, M. (2008). Compressive deformation behavior at room temperature – 773K in Mg–0.2mass%(0.035at.%)Ce alloy. *Acta Materialia, 39*(20), 387-394.

Courtenay, J., & Bryant, M. (2008). A new insight into the melting behaviour and performance of fused MgCl2/KCl refining fluxes. *Aluminium International Today, 26*, 26-28.

Czerwinski, F. (2012). Oxidation Characteristics of Magnesium Alloys. *Minerals, Metals & Materials Society, 64*(12), 1477-1483.

Dave, I. B., & Kaila, V. N. (2014). Optimazation of Ceramic Shell Mold Materials in Investment Casting. *International Journal of Research in Engineering and Technology, 3*(10), 30-33.

Ditze, A., & Scharf, C. (2008). *Recycling of Composite Material Scrap* (1st ed.). Germany: Clausthal-Zellerfeld : Papierflieger Verl.

Divandari, M., Jamali, V., & Shabestari, S. G. (2010). Effect of strips size and coating thickness on fluidity of A356 aluminium alloy in lost foam casting process. *International Journal of Cast Metals Research, 23*(1), 23-19.

Emami, S., & Sohn, H. Y. (2015). Formation and Evaluation of Protective Layer over Magnesium Melt Under CO2/Air Mixtures. *Metallurgical And Materials Transactions, 37*, 226-234.

Emley, E. F. (1996). *Principles of MagnesiumTechnology*. Oxford: Pergamon Press.

Gandara, M. J. (2011). Recent Growing Demand for Magnesium in the Automotive Industry. *Materials and Technology, 45*(6), 633-637.

Ghali, E., Dietzel, W., & Kainer, K. U. (2004). General and Localized Corrosion of Magnesium Alloys:. *Journal of Materials Engineering and Performance, 13*(1), 7-23.

Goodwin, F., Guruswamy, S., Kainer, K. U., Kammer, C., Knabi, W., Koethe, A., Warlimont, H. (2015). Part 3 Classes of Materials. In H. Warlimont, & W. Martienssen (Eds.), *Springer Handbook of Condensed Matter and Materials Data* (pp. 161-422). Germany: Springer Berlin Heidelberg.

Green-Spikesley, E. (1979). Investment Casting. *International Journal of Materials in Engineering Applications, 1*(6), 328-334.

Gwyn, M. (2009). Casting Design and Geometry. In S. Lampman (Ed.), *Casting Design and Performance* (pp. 101-155). United States: ASM International.

Han, Z., Pan, H., Li, Y., Luo, A. A., & Sachdev, A. K. (2015). Study on Pressurized Solidification Behavior and Microstructure Characteristics of Squeeze Casting Magnesium Alloy AZ91D. *Metallurgical and Materials Transaction B, 46*, 328-336.

Hangai, Y., & Kitahara, S. (2008). Quantitative Evaluation of Porosity in Aluminum Die Castings by Fractal Analysis of Perimeter. *Materials Transactions, 49*(4), 782-786.

Holtzer, M., & Bobrowski, A. (2008). Magnesium melt protection by covering gas . *Archives of Foundry Engineering, 8*(1), 131-136.

Hort, N., Wiese, B., Dieringa, H., & Kainer, K. U. (2015). Magnesium Melt Protection. *Materials Science Forum, 828-829*, 78-81.

Hua, W. G., Chun, D. J., Ming, S., & Jiang, D. W. (2010). Non-flux purification behavior of AZ91 magnesium alloy . *Transaction Nonferrous Metals Society of China , 20*, 2037-2045.

Idris, M. H., & Clegg, A. J. (1996). Processing and evaluation of investment. *American Foundry Society, 104*, 237–244.

Jafari, H., Idris, H. M., & Ourdjini, A. (2011). High temperature oxidation of AZ91D magnesium alloy granule during in-situ melting. *Corrosion Science, 53*, 655–663.

Jafari, h., Idris, M. H., & Ourdjini, A. (2014). An alternative approach in ceramic shell investment casting of AZ91D magnesium alloy: In situ melting technique. *Journal of Materials Processing Technology, 214*(4), 988-997.

Jafari, H., Idris, M. H., & Ourdjini, A. (2014). Effect of Thickness and Permeability of Ceramic Shell Mould on In-situ Melted AZ91D Investment Casting . *Applied Mechanics and Materials, 465-466*, 1087-1092.

Jafari, H., Idris, M. H., Ourdjini, A., Rafiq, M., & Kadir, A. (2012). Effect of Flux on In-Situ Melting Shell Investment Casting of AZ91D Magnesium Alloy. Singapore: International Conference on Thermal, Material and Mechanical Engineering (ICTMME'2012) .

Jafari, H., Sadeghi, R., Idris, M. H., & Ourdjini, A. (2012). Effect of Flux Composition on Mould-Magnesium Reaction during In-situ Meting. American Institure of Physics.

Jones, S., Jolly, M. R., & Lewis, K. (2002). Development of techniques for predicting ceramic shell properties for investment casting. *British Ceramic Transactions, 101*, 106-113.

Kennerknecht, S. (2001). S. Structural aerospace aluminium investment. USA: In 12th AeroMat Conference & Exposition 2001.

Kim, S., & Kim, Y. (2002). Process Improvement and mold development for Mg investment casting. Gyeongju, Korea: In Proceedings of 65th World Foundry Congress.

Kim, S., Kim, M., Hong, T., Kim, H., & Kim, Y. (2000). Investment Casting of AZ91HP Magnesium Alloy . *Metals and Materials, 6*(3), 275-279 .

Kulekci, M. K. (2008). Magnesium and Its Alloys Applications in Automotive industry. *International Journal Advance Manufacturing Technology*(39), 851-865.

Lee, B. D., Baek, U. H., Lee, K. W., Han, G. S., & Han, J. W. (2013). Protective Properties of SF6 under Various Carrier Gases for the Protection of Molten Mg. *Materials Transactions, 54*(1), 66-73.

Li, Y. Y. (2004). The present and future of the magnesium alloy researches. *China Academic Journal Electronic Punlishing House*(2), 1-6.

Liang, H., Bin, L., Yufeng, S., Qingyan, X., Zhiqiang, H., & Biacheng, L. (2009). Simulation of Magnesium Alloy AZ91D Microstructure Using Modified Cellular Automaton Method. *Tsinghua Science and Technology, 14*(3), 307-312.

Magnesium in aerospace and defence industry. (2012). Retrieved November 30, 2012, from www.hindustanmagnesium.com/HM.pdf

Maltais, A., Fiset, M., & Dude, D. (2003). Grain Refinement of Magnesium Alloy AZ91D cast in Permanent Mold Using Mechanical Vibrations. *Materials Science Forum, 426-432*, 527-532.

Muja, S. (2015). *New magnesium alloy is world's strongest and lightest metal*. Retrieved January 9, 2015, from https://www.linkedin.com

Musfirah, A. H., & Jaharah, A. G. (2012). Magnesium and Aluminum Alloys in Automotive Industry. *Journal of Applied Sciences Research, 8*(10), 4865-4875.

Nadolski, M., Konopka, Z., Lagiewka, M., & Zyska, A. (2008). Examining of slurries and production of moulds by spraying method in lost wax technology . *Archives of Foundry Engineering, 8*(2), 107 – 110 .

Nakaura, Y., Watanabe, A., & Ohori, K. (2006). Effects of Ca,Sr Additions on Properties of Mg-Al Based Alloys. *Materials Transactions, 47*(4), 1031-1039.

Okhuysen, V. (2011). *SF6 replacement evaluation in magnesium sand and investment casting, Technical report, Project 09–366.* Pomona: California Air Resources Board. Work.

Pattnaik, S., Karunakar, D. B., & Jha, P. K. (2012). Developments in investment casting process—A review. *ournal of Materials Processing Technology, 212*, 2332-2348.

Pekguleryuz, M. (2006). Melting, Alloying and Refining. In H. E. Friedrich, & B. L. Mordike (Eds.), *Magnesium Technology: Metallurgy, Design Data, Applications* (pp. 109-144). New York: Springer-Verlag Berlin Heidelberg.

Ping, Z. (2005). Chapter2: Experimental Methods. In *Correlation of the Microstructure and Creep Behaviour of Die-cast Mg-Al-base Alloys* (pp. 3-5). Gottingen: Cuvillier Verlag.

Prasad, R. (2012). Progress in Investment Castings. In M. Srinivasan (Ed.), *Science and Technology of Casting Processes.* InTech.

R., V., M., S. G., A., V., & P., R. (2016). Effect of Squeeze Cast Process Parameters on Fluidity of Aluminium LM6 Alloy Advancements in Technology. *International Journal of , 7*(2), 1-3.

Raza, M., & Irwin, M. (2014). The effect of shell thickness on defect formation in investment cast Ni-base alloys. Covington, KY: 61st Annual Technical Conference, Investment Casting Institute.

Raza, M., Irwin, M., & Fagerstrom, B. (2015). The Effect of Shell Thickness, Insulation and Casting Temperature on Defects Formation During Investment Casting of Ni-base Turbine Blades. *Archives of Foundry Engineering , 15*(4), 115-123 .

Reddy, A. C. (2015). Development of Alumino-Silicate Investment Shell Moulds to Cast 6061 Al-Alloy . *International Journal of Science and Research (IJSR) , 4*(11), 1183-1187.

Reding, J. N. (1971). Interfacial Tensions Between Molten Magnesium and Salts of the MgClrKCI-BaCI2 System . *Journal of Chemical and Engineering Data, 16*(2), 190-195.

Sharma, P., Kasana, D., Kumar, V., & Goel, C. (2013). Analysis the Properties of Lost Wax Process and Its Use ability Exploring Possibilities. *International Journal of Engineering Science Invention, 2*(2), 32-35.

Sidhu, B. S., Kumar, P., & Mishra, B. K. (2008). Effect of Slurry Compostion on Plate Weight in Ceramic Shell Investment Casting. *Journal of Materials Engineering and Performance, 17*(4), 489-498.

Sin, L. S., Dude, D., & Tremblay, R. (2006). nterfacial reactions between AZ91D magnesium alloy and plaster mould material during investment casting. *Materials Science and Technology, 22*(12), 1456-1463.

Sin, S. L., & Dube, D. (2004). Influence of the process parameters on fluidity of investment-cast Z91D magnesium alloy. *Material Science and Engineering A, 386*, 34-42.

Sin, S. L., Bichler, L., & Ravindran, C. (2009). Unique Challenges in Casting Magnesium Alloys. In D. Bhattacharjee, T. Bhattacharyya, S. Chatterjee, M. Dutta, & C. Ghosh (Eds.), *Metals and Materials* (pp. 191-210). Kalkota: Allied Publesher Pvt.Ltd.

Sin, S. L., Dube, D., & Tremblay, R. (2008). An investigation on microstructural and mechanical properties of solid mould investment casting of AZ91D magnesium alloy. *Material Characterization, 59*, 178-187.

Sin, S. L., Dude, D., & Trembly, R. (2007). Characterization of Al–Mn particles in AZ91D investment castings. *Materials Characterization*, *58*(10), 989-996.

Singh, K., & Suri, N. M. (2016). Magnesium Alloys and its Machining: A Review. *International Research Journal of Engineering and Technology (IRJET), 3*(5), 2111-2119.

Stoll, H. W. (2003). Casting Design. In G. E. Totten, & D. S. MacKenzie (Eds.), *Handbook of Aluminum: Vol. 1: Physical Metallurgy and Processes* (p. 536). New York: Marcel Dekker, Inc.

Sumida, M., Jung, S., & Okane, T. (2009). Solidification Microstructure, Thermal Properties and Hardness of Magnesium Alloy 20 mass% Gd Added AZ91D*1. *Materials Transactions, 50*(5), 1161-1168.

Wang, Y., Liu, G., & Fan, Z. (2006). Microstructural evolution of rheo-diecast AZ91D magnesium alloy during heat treatment. *Acta Materialia, 54*, 689–699.

Wei, D. Y., Kun, B., Qing, D. Y., & Hua, Z. D. (2011). Determination of wax pattern die profile for investment casting of turbine blades. *Transactions of Nonferrous Metal Society Of China, 21*(2), 378-387.

Weimin, Z., Yong, S., Haipeng, L., & Chunyoung, L. (2006). The effects of some elements on the igniting temperature of magnesium alloys. *Materials Science and Engineering B, 127*, 105-107.

Westengen, H., & Aune, T. K. (2006). Magnesium Casting Alloy. In H. E. Friedrich, & B. L. Mordike (Eds.), *Magnesium Technology: Metallurgy, Design Data, Applications* (pp. 145-199). Germany: Springer-Verlag Berlin Heidelberg.

Wulandari, W., Brooks, G. A., Rhamdhani, M. A., & Monaghan, B. J. (2010). Magnesium: Current And Alternative Production Routes. South Australia: Chemeca:Australasian Conference on Chemical Engineering.

Xuan-pu, D., He-boa, W., Nar-yu, H., Zi-tian, F., & Xue-feng, T. (2005). Microstructure and Mechanical Properties of Magnesium Alloy Prepared by Loat Foam Casting. *Transaction Nonferrous Metals Society of China, 15*(1), 7-13.

Yadaz, N., & Karunakar, D. B. (2011). Effect of Process Parameters on Mechanical Properties of the Investment Castings Produced by using Expandable Polystyrene Pattern. *International Journal of Advances in Engineering & Technology, 1*(3), 128-137.

Yang, C.-W. (2013). Tensile Mechanical Properties and Failure Behaviors of Friction Stir Processing (FSP) Modified Mg-Al-Zn and Dual-Phase Mg-Li-Al-Zn Alloys. In Y. Mastai (Ed.), *Material Science-Advanced Topics.* Intech.

Zesheng, J., & Shuyan, W. (2009). Microstructure and Mechanical Properties of AZ31B Magnesium alloy recycled by solid state process from different size chips. *Journal of Materials Processing Technology, 209*(12-13), 5319-5324.