UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF SHIP PROPELLER USING DYNAMIC CASTING METHOD

ISHAK BIN MOHMAD ALI

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DEVELOPMENT OF SHIP PROPELLER USING DYNAMIC CATING METHOD

By

ISHAK BIN MOHMAD ALI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirement for the Degree of Doctor of Philosophy

August 2016

In the Memory of

My Father, Allahyarham Mohmad Ali bin Abdul Ghani

And

My Mother, Allahyarhamah Hjh. Hawa binti Abdul Rahman

Special Dedication to

My Wife

Riza binti Abdul Majid

And

My Childrens

Nurhafizah
Muhammad Hafiz
Muhammad Hanif
Muhammad Hathim
Nurhananiah
and Nur Husna Hanisah

Ishak bin Mohmad Ali
2016

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

DEVELOPMENT OF SHIP PROPELLER USING DYNAMIC CASTING METHOD

By

ISHAK BIN MOHMAD ALI

August 2016

Chairman : Professor Shamsuddin Sulaiman, PhD
Faculty : Engineering

The ship propeller is a key component in producing the propulsion force of the ship motion. Therefore, the stability of structure strength is required to ensure the effectiveness of propulsion force generation. This research examines the existing ship propeller and the effects of dynamics casting mold on the changes of mechanical properties of the propeller structure. The specimen prepared is referred to ASTM E8 2008 standard and including two projections is Longitude and Latitude projected, according to the forces analysis exerted on blade structure. The experiments perform on the used propeller and casted specimen in order to verify the projections arrangement of changes in mechanical properties. The results show that the different of used propeller and casted specimen properties is less than 5% and the arrangement can be represented for dynamics casting analysis. The dynamics mold used are Centrifugal Mold and Vibration Mold with selection of centrifugal speeds are 0, 50rpm and 150rpm and the vibration frequencies are 0, 5Hz and 9Hz,

respectively. The mechanical testing is conducted on tensile test, hardness test and scanning electron microscope investigation. The result of casting experiment showed that the mechanical properties significantly increased by the vibration frequencies up to 9Hz and the centrifugal speed up to 150rpm and led to increase in tensile strength from 4.84% to 9.68% for vibration mold and from 1.70% to 14.86% for centrifugal mold, respectively. In the vibration mold casting, the tensile strength, yield strength and elongation percentage showed the approximation of the properties values of matching the frequency of vibration is over than 9Hz on both projections but not in the centrifugal mold. It was also found that hardness improved significantly with the increased in vibration frequency and centrifugal speed. The hardness value based Rockwell superficial 15N-S scale is 6% over than without vibration. In addition, the change in microstructure and mechanical properties were successfully represented by the changes in solidification characteristics. Various vibration frequencies have reduced the lamellar spacing that changes the microstructure of the composites which as a result became more fibrous. The corresponding changes in mechanical properties indicate that the vibration casting method significantly increased the mechanical properties of casted propeller and it should be applied as a method in ship propeller manufacturing on casting process.

Abstrak tesis dikemukakan kepada senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

MEMBANGUNKAN *PROPELLER* KAPAL DENGAN MENGGUNAKAN KAEDAH ACUAN DINAMIK

Oleh

ISHAK BIN MOHMAD ALI

Ogos 2016

Pengurusi : Profesor Shamsuddin Sulaiman, PhD
Fakulti : Kejuruteraan

Propeller kapal adalah komponen utama di dalam menghasilkan daya pendorong untuk kapal belayar. Oleh itu kestabilan dan kekuatan strukutr bilah adalah diperlukan untuk memastikan keberkesanan di dalam penghasilan daya tersebut. Kajian ini dilakukan untuk mengkaji *propeller* kapal yang sedia ada dan yang dihasilkan melalui kaedah acuan dinamik tentang perubahan sifat mekaniknya. *Specimen* disediakan adalah merujuk kepada piawaian ASTM E8 2008 dan berdasarkan kepada struktur unjuran bilah iaitu unjuran Longitude dan unjuran Latitude yang merujuk kepada tindakan daya pada struktur bilah. Ujikaji terhadap sifat mekanik dijalankan ke atas *specimen* daripada potongan bilah *propeller* terpakai dan *specimen* yang diacuankan di dalam menentusahkan kebolehpercayaan susunan unjuran *specimen* yang digunakan. Keputusan ujikaji menunjukkan bahawa perbezaan nilai properties yang kurang dari 5% dan menunjukkan bahawa susunan unjuran ini boleh digunakan di dalam analisa *dynamics casting*. Jenis acuan yang digunakan adalah *Centrifugal Mold* dengan pilihan kelajuan putaran di antara 0,

50rpm dan 150rpm dan *Mechanical Vibration Mold* pada frequency 0, 5 Hz dan 9 Hz. Ujian mekanikal yang dilakuan adalah ujian tegangan, ujian kekerasan dan penyiasatan *microscope* SEM. Keputusan ujikaji terhadap kaedah acuan telah menunjukkan peningkatan sebanyak 1.70% hingga 14.86% bagi kaedah *centrifugal* dan 4.84% hingga 9.68% bagi kaedah *vibration*. Walaubagaimanapun, kaedah getaran menunjukkan nilai sifat mekanik yang hampir sama bagi kedua-dua unjuran pada julat frequency melebihi 9 Hz dan perkara ini tidak berlaku pada kaedah *centrifugal*. Nilai *hardness* bertambah dengan bertambahnya nilai dinamik bagi kedua-dua kaedah. Berdasarkan kepada bacaan *Rockwell superficial* 15N-S adalah 6% bertambah berbanding dengan specimen yang tidak dikenakan nilai dinamik. Di samping itu, perubahan dalam mikrostruktur dan sifat-sifat mekanik telah berjaya diwakili oleh perubahan dalam ciri-ciri pemejalan. Getaran pelbagai telah mengurangkan jurang *lamellar* yang mengubah mikrostruktur bagi bahan yang menjadikannya lebih padat. Perubahan yang sama dalam sifat-sifat mekanik menunjukkan bahawa kemuluran adalah lebih dipengaruhi oleh kekerapan getaran daripada tanpa getaran dan kaedah getaran ini harus digunapakai sebagai suatu kaedah di dalam proses pembuatan propeller.

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APPROVAL

I certify that a Thesis Examination Committee has met on 19 August 2016 to conduct the final examination of Ishak bin Mohmad Ali on his thesis entitled "Design and Development of Ship Propeller Using Dynamic Casting Method" in accordance with the Universities and University College Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The committee recommends that the student be awarded the Doctor of Philosophy.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The Members of the Supervisory Committee were as follows:

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Supervisory
Committee: ____________________

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LIST OF ABBREVIATIONS

AA	- Aluminum Association
Al	- Aluminum
ASTM	- American Society for Testing and Materials
BS	- British Standard
C	- Carbon
CHWD	- Cast Hot Work Die Steel
CMC	- Ceramic matrix composite
CO_2	- Carbon dioxide
CP	- Commercial purity
Cu	- Copper
EDX	- Energy Dispersive X-ray
G	- Gage length (mm)
Hz	- Heize
ISO	- International Standard Organization
kN	- kilo Newton
L	- Overall length (mm)
lbf	- Pont
LM6	- Light Metal (Type of aluminum)
m	- Mass (kg)
Mg	- Magnesium
MMC	- Metal Matrix Composite
Mn	- Manganese
MP	- Mechanical Properties

MPa	- Mega Pascal
P	- Phosphorus
PM	- Powder metallurgy
PMC	- Polymer matrix composite
R	- Radius of fillet
RMS	- Root Mean Square Value
RQI	- Rheocasting Quality Index
S	- Sulfur
SEM	- Scanning Electron Microscope
Si	- Silicon
SiC	- Silicon carbide
t	- Thickness (mm)
T	- Tone
TiC	- Titanium carbide
UTS	- Ultimate Tensile Testin
V	- Volume (cc)
W	- Watt
Zn	- Zink
µm	- micrometer
ρ	- Density (gr/cm^3)

CHAPTER 1

INTRODUCTION

1.1 Introduction

The ship propeller is a key component of the motion mechanism of the ship and its play the main part in propulsion systems. Propulsion is the act or an instance of driving or pushing forward of a body (ship), by a propeller-ship propulsion (John, 2007). Apart from that, the efficiency of a propeller takes important roles in the design process, because its efficiency and stabilities directly related. In most condition, propellers are designed to absorb as minimal power as possible and to give maximum efficiency with less cavitation and hull vibration characteristics (Carlton, 2012). As for an effective propeller design, calculations of propeller strength must consider torque and the bending moments acting at the blades roots. The stress point accepted must allow for the cyclic variations in loads due to the wake and the increased forces due to ship motions (Rawson, 2001). At this point, the problems faced on the propeller are corrosion, blade breaking, fractures and distortions.

Many studies have been done on corrosion resistance and strength of the blade to select materials and appropriate size of propeller, however the other factor must be considered and are given more attention on the manufacturing process of the propeller to make it stronger and resistant to corrosion so as to overcome mentioned above. The manufacturing challenges are interpreting the complex hydrodynamic design into physical reality at the same time ensuring that the manufacturing process does not give rise to defect which could bring about the premature failure of the ship propeller (John, 2007). Mostly, the ship propellers are manufactured by traditional sand casting method. Sand casting is one of the oldest metal forming methods used by engineers. Over 70% of all metal castings are produced via a sand casting process (Carlton, 2009). It is relatively cheaper and utilizes expendable sand molds to form complex metal parts that can be made of nearly any alloy. The sand casting process involves the use of a furnace, metal, pattern and sand mold. The molten metal from the furnace is poured into the cavity of the sand mold, which is formed by the pattern. The sand mold separates along a parting line and the solidified casting can be removed.

The competition in the ship industries has been growing rapidly in recent years. This increased competition has compelled manufacturing industries to look for better quality ship propellers. Quality products not only enhance profits but also contribute towards the growth of the company. Hence, quality ship propellers play a significant role in the success of the company. Modern approaches to improve quality in casted products involve the use of dynamics casting method and the most popular is vibration casted method and centrifugal mold casting.

Vibration has been found to play a critical role in casting by eliminating defects and enhancing quality. According to the review by Feng-Wuan and Xiao-Ling (Feng et al., 2000), the use of vibration during solidification was first studied in 1800s. A study by Shukla et al. (Shukla et al., 1980) concluded that vibration can help in promotion of nucleation and thus reduce grain size, lower susceptibility to cracking and reduce shrinkage porosities. This leads to improved features and thereby improved mechanical properties. A significant increase in mechanical properties such as tensile strength and hardness is observed. Different types of vibration such as mechanical, ultrasonic or electromagnetic vibration may be applied to the metal through various means. Vibration energy has many applications within the manufacturing and engineering fields. The centrifugal casting process utilizes inertial forces caused by rotation, to distribute the molten metal into the mold cavities (Sidpara, 2012). Different types of centrifugal such as vertical centrifugal and horizontal centrifugal may be applied to the metal through various means. This study investigates the effects of horizontal centrifugal casting on the mechanical properties in comparison with products formed without centrifugal inertial forces.

Application of dynamics casting has significant effect on grain refinement (reduce in porosity), density, hardness, ultimate tensile strength, percent elongation, degassing, shrinkage (shape complexity and dimensional accuracy), and surface finishing. In this research, the proposal of solutions will be made in relation to the appropriate manufacturing method. At the end of the achievement of this tesis, it is hoped that practical manufacturing could be introduced and then carried out to prove its effectiveness in achieving the goal of producing propeller with strength and endurances is better than existing ones.

1.2 Problem Statement

The research is on propeller manufacturing process in producing a stronger propeller blade in terms of increased the mechanical properties without change the materials specification. The idea is to propose an alternative manufacturing process of propeller which is able to achieve the objective of this research. In the history of development of the strength blade, elimination of porosity formation has been thought of as a key factor in the propeller manufacturing. This is the main reason for the weakness blade structure and the cause of formations is due to high temperature required on melting and during casting. The others factors are pressure drop during inter-dendrite fluid molten flow, materials shrinkage during solidifications, gases bubble trapped during casting, non-uniform cooling rate and sand mold has low permeability (Kalpakjian, 2010). However, a major problem with this kind of application is the high melting temperature. The requirement of high temperature for melting as at 1100^{o}C, cause due to they need the molten to be a liquid for casting to flowing into mold casting and to avoid pressure drop during inter-dendrite of fluid molten flow (Kalpakjian, 2010). This cause due to sand casting mold is a static casting type, where it depending on the gravity flows of molten for flowing into mold. That is why they required the liquid, so to be more liquidize, they require more temperature. The high temperature is required because of casting molten fluid must be sufficiently liquid so that the molten can permeate into his mold cavity perfectly. To be stabilized in molten flowing into the cavity, the external force need to exerted to the molten alloy. This can be applied by created an external forces produce by dynamics mechanism such as vibration forces or centrifugal forces to the mold case.

Propeller blade surface will erode due to the friction that occurs between the surfaces of the blade with the flow of sea water while it is operating. The blade erosion would result in reduced thickness of the blade and blade surfaces are not flat and caused pitched surfaces. The illustration of blade eroded is shown in Figure 1.1. The pitched surface is caused by exposure to the porosity defects and pin holes formed in the blade body during the manufacturing due to casting process. These will be created the high cavitation flow occurred on the blade surface and the potential of unbalanced forced developed at the end of propulsion.

The illustration of the lack of ability to prevent failures due to unbalanced force acting in the operations of Propulsion can be explained by means of a mechanical shear stress.

Shear stress = force / cross section area of blade; $\tau = F / A$ (Hibbler, 2004)

Where; τ is shear stress N/mm^2

F is perpendicular force to surface (N)

A is cross section area (mm^2)

When the blade surface eroded heavily and caused the blade thickness reduced, then the shear stress is over the limit and in this condition the blade will be fractured.

$\tau_{after} > \tau_{limit}$ = cause the blade fracture

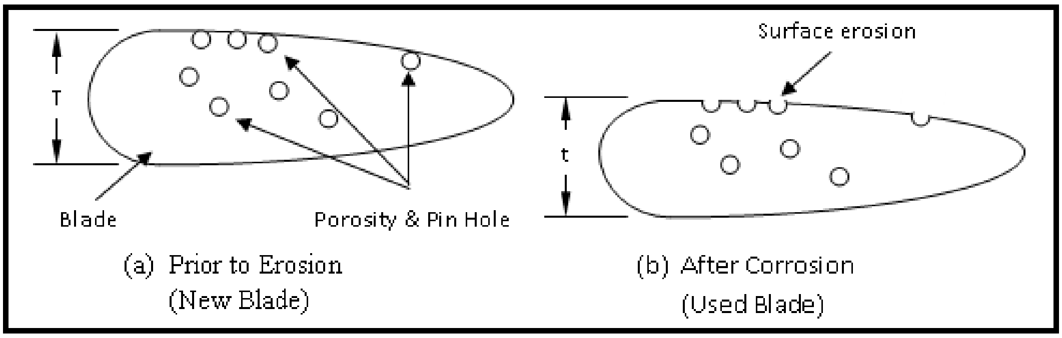

Figure 1.1: Circumstances in the event of blade erosion (Carlton, 2012)

The effect of the occurrence of extreme erosion will cause failure of the blade such as cavitations flow occurs or turbulence flows happened when the porosity or pin-hole scare exposed and resulting in strong shaking caused by unbalanced force act to the whole structure of Propeller blade and blade has a high shear stress that eventually causes the fracture. To avoid the formation of porosity and pin-holes in the blade, several factors need to be aware of such as to eliminate the porosity formation during casting process (John, 2007), selection of manufacturing compounds that can produce a mixture composite and propeller through the process of formation of an effective and accurate method of selection is required to produce.

In most condition, propellers are designed to absorb as minimal power as possible and to give maximum efficiency with less cavitation and hull vibration characteristics. As for a stronger propeller design, calculations of propeller strength must consider the torque and the bending moments acting at the blades roots. The stress point accepted must allow for the cyclic variations in loads due to the wake and the increased forces due to ship motions (Rawson, 2001). The forces are related to the strength of the propeller structure and this will comply with standard mechanical properties. These properties are referred to the ship classification society such as Det Norske Veritas (DNV), Lyod Register (LR), American Bureau of Shipping (ABS) and Germanisyer Lyod (GL) and to meet the requirements referring to the propeller materials as shown in Table 1.1.

Table 1.1: Mechanical properties for copper alloy propeller castings (DET, 2011)

Alloy Type	Yield Strength $R_{p\ 0.2}$ [N/mm^2] min.	Tensile Strength R_m [N/mm^2] min.	Elongation A [%] min.
Ni-Al-Br, Cu3	245	590	16

The mechanical properties magnitude had shown in Table 1.1 is a guide line as a standard requirement produced by International Ship Classification for ship propeller manufacturer. In this research, the main emphasis is given to respond to the structure of the propeller to the forces exerted externally. This led to a research of propeller manufacturing methods and the illustration of these forces can be seen as in Figure 1.2(a). The two forces acting known as a Centrifugal Force or Radial Force and Twist Force or Moment Force and they will affect the blade structure in term of blade bending and blade fracture.

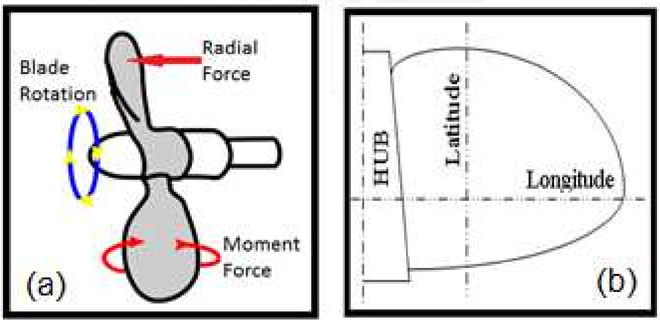

Figure 1.2: Forces action and strength required on a propeller (a) and Projection of Propeller Blade (b)

The Radial Force caused the projection blade is loaded in bending sense. The Moment Force is load distribution in blade twist affect. According to the expectations of its effect on the structural strength of the propeller, the propeller blade projection can be set as shown in Figure 1.2(b), where the projection Longitude is represent a projection of the Radial Force direction, which extends in a circle diameter propeller and the Latitude projection is represent a projection of the Moment Force direction, which extending the propeller hub line. The two projections of blade will be used in this research and to ensure the analysis of mechanical properties is more precise and knowing the method will affect the strength of the casting propeller.

The increasing of mechanical ability should be added as yield strength and tensile strength, while the elongation is reduced slightly and it will be improved the strength of the Propeller. The blade hardness also needs to be increased in terms of reduce the surface erosion rate (Kalpakjian, 2010). This will be reached if the modified manufacturing method based on the process and equipment can be performed. The propeller selection of this research had been classified by ship classification bodies such as Bureau Veritas (BV), Ship Classification of Malaysia (SCM), American Bureau of Shipping (ABS), Lloyd's Register (LR), Germnisyer Lyod (GL) and Nippon Kaiji Kyokai (NKK). The material is Copper base and the alloy is to be Nickel Aluminum Bronze (Ni-Al-Br) and the composition had been identified as shows in Table 1.2.

Table 1.2: Materials composition of Cu3, Nickel Aluminum Bronze (Ni-Al-Br) (DET, 2011)

Casting grade	Chemical Composition (%)							
	Cu	Al	Mn	Zn	Fe	Ni	Sn	Pb
Ni-Al-bronze, Cu 3	77-82	7.0-11.0	0.5-4.0	<1.0	2.0-6.0	3.0-6.0	<0.1	< 0.03

Referring to the problems statement and solutions needs to be done, the research is to study the methods of casting and focus in dynamics casting, as well as conducting experiments on the structure of the casting product testing on mechanical properties and investigate the microstructure grain. Hence the proposed test is Tensile Strength Test, Hardness Test and Scanning Electron Microscope Investigation. The data collection is to be handled in analysis and will be used is selecting the better method for ship propeller manufacturing process.

1.3 Objective of the Research

The research work is carried out in order to achieve the objective in provide the proposal and standardize the propeller manufacturing process in producing a better mechanical properties and good feature of the propeller in terms of stronger blades and has resistance to corrosion. Therefore, the objectives of the study are focused on the following areas, namely;

i. To determine the mechanical properties of current propeller.

ii. To develop the dynamic casting and compare the mechanical properties and microstructure of Copper Alloy specimens.

iii. To propose the best casting method in propeller manufacturing process.

1.4 Scopes of Research

The scope of the research to understands the existing practice in propeller manufacturing process such as materials, design and casting technique. The propeller fractures and problems faced on the propeller is coincide in the research in determining the better manufacturing process. The validation of good practices in research is continued by performing the mechanical test and microstructure investigation to the sample specimen of dynamics casting method. In the identifying of good practices of dynamics casting method, the research is performing in review on the effect of vibration in the sand casting of Copper Alloys. The specimen is casted with and without vibration to perform mechanical tests and microstructure analysis. Finally, the result is use in the selection of best method casting of propeller.

1.5 Thesis layout

The thesis has been structured into five chapters. Chapter 1 introduces the topic of sand casting and vibration used during the casting process. Chapter 2 presents a review of literature that relates to the investigation on the mechanical behavior and microstructure properties of Copper alloys with and without using mechanical vibration mold. Chapter 3 describes the research methodology and explains the processes used for the collection of data and information. Chapter 4 presents the results and discusses, analyzes and compares the effects of vibration mold casting and centrifugal mold casting on the mechanical properties of Copper alloys. Chapter 5 presents the conclusion of the research.

REFERENCES

Abd-El-Azim, A.N. (1982). Effect of low-frequency mechanical vibration on the structure of Al-Si eutectic alloy. Int. Leichtmetallag. 118-120.

Abdul-Karem, W. Green, N and Al-raheem, K. F. (2011). Vibration-assisted filling capability in thin wall investment casting. The International Journal of Advanced Manufacturing Technology, 61(9-12): 873-887.

ABS. (2009). American Bureau of Shipping Handbook; Propellers, Copyright © 2009, American Bureau of Shipping, ABS Plaza 16855 Northchase Drive Houtson, TX 77060 USA.

ABS. (2010). American Bureau of Shipping Handbook; Rules for Testing and Certification of Materials, Chapter 3: Materials for Machinery; Section 14 Bronze Casting, Copyright © 2010, American Bureau of Shipping, ABS Plaza 16855 Northchase Drive Houtson, TX 77060 USA.

Alireza, R., and Miwa, K. (2000). Effects of the intensity and frequency of electromagnetic vibrations on the microstructural refinement of hypoeutectic Al-Si alloys. Metallurgical and Materials transactions A, 31(3), 755-762.

Alonso Rasgado, M.T. and Davey, K. (2004). Vibration and casting surface finish. Journal of Materials Processing Technology. 153-154, 875-880.

Altan. (2007). Foundry Technology, Sand, Sand Additives, Sand Properties and Sand Reclamation. MSE-432, vol.3: pp.95-99.

Anthony F. Molland. (2008). Marine Engines and Auxiliary Machinery; The Maritime Engineering Reference Book. Elsevier Ltd. Chapter 6; pp. 346-482.

Apelian, D. (2009). Aluminum Cast Alloys: Enabling tools for improved performance. Wheeling: North American Die Casting Association

Apostolos, Papanikolaou. (2014). Machinery Installation, Propulsion and Steering Devices; Ship Design. Springer Science, Greece. pp. 393-437.

Archives of Materials Science and Engineering. (2007). Pouring Mould during Centrifugal Casting Process, Volume 28-Issue 7, OCSCO World Press.

Ariff, T.F., Kamaruddin, M.S., Haron, M.A. (2013). Dry Machining of Brass Using Titanium Carbonitride (TiCN) Coated Tool; Applied Mechanics and Materials. Trans Tech Ltd. Vol.372, pp. 495-500.

ASM. (1992). American Society of Metals Handbook; Casting. 10th Edition; Vol.15. ASM International, Materials Park, Ohio, USA.

ASTM. (2002). American Standard Testing Material Handbook; Standard B557M, Standard Test Methods of Tension Testing Wrought of Cast Aluminum and Magnesium Alloy Products. ASTM International, West Conshohocken, PA.

ASTM. (2003). American Standard Testing Material Handbook; Standard Specification for copper-base Alloy centrifugal Casting B 271-96, Copyright © ASTM International.

ASTM. (2007). American Standard Testing Material Handbook; Standard E466, Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials. ASTM International, West Conshohocken, PA.

ASTM. (2008). American Standard Testing Material Handbook; Standard E18, Standard Test Methods for Rockwell Hardness of Metallic Materials. ASTM International, West Conshohocken, PA.

Balatin, G.F., and Yakovler, P. (1964). Casting Production. 221.

Barbure, R. R., Hareesha, I., and Murthy, K.S.S. (1979). Influence of low frequency vibrations on aluminum eutectics. Br. Foundryman 72(2); 35-38.

Bast, J., Hubler, J. and Dommaschk, C. (2004). Influence of vibration during solidification of molten metals on structure and casting properties. Advanced Engineering Materials. 6: 550-554

Boswell, R. J. (1971). Design, cavitation performance, and open-water performance of a series of research skewed propellers (No. NSRDC-3339). David W Taylor naval ship research and development center Bethesda Md.

British Standards Institution. (1988). BS 1490:1988. Specification for aluminum and aluminum alloy ingots and castings for general engineering purposes. London, BSI.

Brown, J. R. (1999). Foseco Non-Ferrous Foundryman's Handbook, 11th edition. Oxford: Butterworth-Heinemann.

Callister, W. D. (2007). Materials Science and Engineering: An Introduction. 7th edition. Hoboken: John Wiley and Sons.

Campbell, J. (1981). Effect of vibration during solidification. International Material Reviews. 26: 71-108.

Carlton, J. (2012a). Propulsion Systems, Marine propellers and Propulsion 3rd Edition, pp. 11-28.

Carlton, J. (2012b). Propeller Materials, Marine propellers and Propulsion 3rd Edition, pp. 459-467.

Carlton, J. (2012c). Operation Problems, Marine propellers and Propulsion 3rd Edition, pp. 385-396.

Carlton, J., Radosavljevic, D., & Whitworth, S. (2009). Rudder–Propeller–Hull Interaction: The Results of Some Recent Research, In-Service Problems and Their Solutions. In First International Symposium on Marine Proposers.

Carlton, J., (2007). Propeller Materials. Marine Propellers and Propulsion; Butterworth - Heinemann; 2nd Edition; pp. 382-393

Chirita, G., Soares D., Silva F.S. (2008). Advantages of the Centrifugal Casting Technique for the Production of Structural Components with Al-Si Alloys. Materials and Design, Vo. 29.

Chirita, G. Stefanescu, I., Barbosa, J., Puga, H., Soares, D., and Silva, F. S. (2009a). On assessment of processing variables in vertical centrifugal casting technique. International Journal of Cast Metals Research. Vol.22-5; pp. 382-389.

Chirita, G. Stefanescu, I., Soares, D., and Silva, F. S. (2009). Influence of vibration on the solidification behavior and tensile properties of an Al-18 wt%Si alloy; Materials and Design. 30(5); pp. 1575-1580.

Co. C. (2012). The Differences between Horizontal and Vertical Centrifugal Casting Machinery. Wordpress.com 2012/10/09.

Copper Development Association. (1991). Copper & Alloy Castings Properties & applications.

Cumberlan J. (1963). Centrifugal Casting Techniques; pp. 26-47, British Foundryman.

Currey, D. A., Pickles, and Dofasco. (1988). Electromagnetic stirring of Al-Si alloy. Journal of Material Science. 3576-3763.

Dave, G. (2001). The complete references of choosing, installing and understanding boat propeller. Propeller Handbooks. International Marine. McGraw Hill. Chapter 3: pp. 18-26.

Davids G.J. (1973). Solidification and Casting. Wiley, New York. ISBN 0470198710 – 9780470198711.

DET Norske Veritas. (2011a). Rules for Ships/High Speed, Light Craft and Naval Surface Craft, Sec.7 & Sec.10: Casting for Propeller.

DET Norske Veritas. (2011b), Modelling and analysis of marine operations. tech. rep. DNV-RP-H103.Det Norske Veritas.

Dianliang Yang and Zhenping Feng. (2007). Tip Leakage Flow and Heat Transfer Predictions for Turbine Blades, ASME Turbo Expo, Vol.4, pp. 589-596.

Dowling, N. E. (2007). Mechanical Behavior of Materials. 3rd edition. Upper Saddle River, Prentice Hall, NJ.

Eskin, G. I. (1994). Influence of cavitation treatment of melts on the processes of nucleation and growth of crystals during solidification of ingots and castings from light alloys. Ultrasonics Sonochemistry, 1(1), S59-S63.

Eskin, G. I., and Eskin, D.G. (2003). Production of natural and synthesized aluminum-based composite materials with the aid of ultrasonic (cavitation) treatment of the melt. Ultrasonics Sonochemistry, 10(4-5), 297-301.

Eskin, G.I. (1981). Effect of ultrasound treatment of a melt during solidification on the structure and properties of large slabs made from aluminum alloy. Mosk. Inst. StalsSplavov. 74-81.

Eskin, G.I., and Tsuetv. (1982). Use of ultrasound during continuous casting of ingots for increasing the quality of semifinished products. Metals 11. 35-40.

Feng-Wuan, W., and Xiao-Ling, h. (2000). The influence of vibration and shock on the crystal growth during solidification; Journal of Material Science, 35, pp. 1907-1910.

Firhat, M.H., (2015). Effect of Heat Treatment Parameters on the Mechanical and Microstructure Properties of Low-Alloy Steel. Journal of Surface Engineered Materials and Advanced Technology. Scientific Research Publishing Inc. Vol. 5; pp. 214-227.

Fisher, T. P. (1973). Effects of vibrational energy on the solidification of aluminum alloys. Br. Foundryman. 66-71.

Fosef, K., and Kououe. (1982). Concentration changes during solidification of alloy AlM5 in an electromagnetic field. Materialprufung. 617-630.

Gagg, C.R. (2005). Failure of components and products by ‘engineered-in’ defects: Case studies; Engineering Failure Analysis. Elsevier Ltd. Vol.12-6, pp. 1000-10026.

Gao, D., Li, Z., Han, Q., and Zhai, Q. (2009). Effect of ultrasonic power on microstructure and mechanical properties of AZ91 alloy; Materials Science and Engineering: A, 502(1-2), pp. 2-5.

Germanischer Lloyd Aktiengesellschaft. (2009). Materials for Propeller Fabrication; Rules for Classification and Construction; Hamburg Germany.

Germanischer Lloyd Aktiengesellschaft. (2011). Propeller; Chapter 2, Sec.6, Hamburg Germany.

Groover, M.P. (2010). Fundamentals of Modern Manufacturing, 4th edition. John Wiley and Sons, pp. 205-258.

Hall J.H. (1948). Centrifugal Casting of Steel; The Foundry 76(8):77pf & 76(9):74pf.

Hashemi, S. (2006). Foundations of Materials Science and Engineering. 4th edition. McGraw-Hill.

Hernandez, R., and Sokolowski, J. (2005). Novel image analysis to determine the Si modification for hypoeutectic and hypereutectic Al-Si alloys. JOM Journal of the Minerals, Metals and Materials Society. 57(11), 48-53.

Hibbeler, R.C. (2004). Engineering Mechanics Statics & Dynamics 10th Edition. Pearson Prentice Hall, New Jersey 07458, USA.

Indian Register of Shipping. (2011). Rules and Regulations for the Construction and Classification of Steel Ships, Chapter 8, Section 3: Casting for Propellers.

IPC-TM-650. (1995). Test Methods Manual; Subject Tensile Strength, Elongation, and Modulus Number; 2(4), 3-18.

Ivanov, A. A., and Krushenka, G. G, (2005). Preparation of Al-Si alloying composition by means of vibration, Liteinoe Proizvod 3; 7-8

Jahn, R., and Reisenger, C. (1935). High frequeny molten metal treatment. British Patent No. 456, 657.

Jain, P.L. (2006). Principle of Foundry Technology. Tata McGraw-Hill, 4th Edition. 3; 112-232.

Jian, X. Xu, H., Meek, T. T., and Han, Q. (2005). Effect of power ultrasound on solidification of aluminum A356 alloy. Materials Letters, 59(2-3), 190-193.

Jian, X., Meek, T. T., and Han, Q. (2006). Refinement of eutectic silicon phase of aluminum A356 alloy using high-intensity ultrasonic vibration. ScriptaMaterialia, 54(5), 893-896.

John Carlton. (2003). Fundamentals of Energy Dispersive X-Ray Analysis. Butterworth-Heinemann

John Carlton. (2007). Marine Propellers and Propulsion; Propeller maintenance and repair; Butterworth - Heinemann / Elsevier Ltd.; 2nd Edition; pp. 15-84.

Jozef, G. Bermand, P. Andrzej, Szajnar, Krzepmieeie. (1980). Effect of induced vibrations in molten metals without a penetrator intermediate on crystallization conditions of aluminum alloys. Met. Slop.

Kalpakjian, Steven R. Schmid. (2010). Manufacturing Engineering and Technology, 6th Edition, 2010, pp. 239 – 284, Pearson / Prentice-Hall.

Kamrani, A.K., Emad, A.N., (2010). Engineering Materials: An Overview. Engineering Design and Rapid Prototyping. Springer Link. Chapter 10: pp. 295-311.

Kang C.G, Rohatgi P.K, Narendranath C.S, Cole G.S. (1994). A solidification Analysis on Centrifugal Casting of Metal Matrix Composites Containing Graphite Particles. ISIJ International, Vol. 34; 3: pp. 247-254.

Kawasaki, N. (1993). Parametric study of thermal and chemical non-equilibrium nozzle flow; M.S. thesis, Dept. Electron. Eng., Osaka Univ., Osaka, Japan.

Klaas van Dokkum. (2011). Ship Knowledge: Ship design Construction and Operation, 7th edition.

Kocatepe, K. (2007). Effect of low frequency vibration on porosity of LM25 and LM6 alloys. Materials and Desifn, 28(6), 1767-1775.

Kocatepe, K., and Burdett, C.F. (2000). Effect of low frequency vibration on macro and micro structures of LM alloys. Journal of Materials Science, 35(13), 3327-3335.

Komvopoulos, K (2011). Mechanical Testing of Engineering Materials. 2nd edition. University Readers, San Diego, CA.

Konrad, J. A. (2002). Copper and copper alloys. Handbook of Materials Selection, pp. 135.

Kruger, F. (1931). German Patent No. 604, 486.

Lalena, J.N., Cleary, D.A., Carpenter, E., Dean, N.F., (2007). Materials Fabrication; Inorganic Materials Synthesis and Fabrication. John Wiley & Sons, Inc. Hoboken, NJ, USA. Chapter 7.

Lee, J.Y., Paik, B.G., Lee, S.J., (2009). PIV measurements of Hull wake behind a container ship model with varying loading condition, Ocean Engineering. Elsevier Ltd. Vol.36-5. pp. 377-385.

Liang, Y.H., Zhao, Y. G., Qin, Q. D., Shang, E. Y and Jiang, Q.C. (2006). Effect of mechanical vibration on the microstructure and thermal fatigue behavior of cast hot work die steel. Journal of Materials Science. 41(8): 2529-2532.

Liu, Osawa, Y., Takamori, S., and Mukai, T. (2008). Microstructure and mechanical properties of AZ91 alloy produced with ultrasonic vibration, Materials Science and Engineering: A, 487(1-2), 120-123.

Lloyd's Register Rules and Regulations, Jan. (2006). Rules for the Manufacture, Testing and Certification of Materials: Casting for Propeller, Rulefinder, Version 9.5.

Maesiar, Harold, and Stanislav, P. (1985). Ultrasound treatment of aluminum alloy melts in die casting, Gessereitech. 211-214.

Mikell, P. Groover. (1999). Fundamentals of Modern Manufacturing: Materials, Processes and Systems, John Wiley and Sons.

Mizutani, Y., Miwa, K, Tamura, T., Nakai, Y., and Otsuka, Y. (2006). Grain refinement of tough pitch copper by electromagnetic vibration during solidification. Materials Transactions, 47(7) 1793-1797.

Mondolfo, LF. (1979). Aluminum alloys structures and properties. ASM International, London: Butterworths. 759.

Mottonen Matti. (2008). Manufacturing Process Capability and Specification Limits; The Open Industrial and Manufacturing Engineering Journal, 1874-1525.

Nathan Janco. (1988). Centrifugal Casting. American Foundry Society, Des Plaines, Illinois, USA.

Nelson, John, T., (2003). The perfect matchplate molding operation: before MORDEN CASTING could name the three best matchplate molding operations; Morden Casting. American Foundry Society, Inc. Vol. 93.

Niedzwiedzki, Zenon, Pietrowski, Stanislaw, and Krzepaniecie. (1980). Properties of cast hypoeutectic and eutectic silumins in a permanent mould, an electromagnetic mould and a sand mould. Metals Stopow. 3; 304-314.

Numan, A. D., Kharaisheh, M., Saito, K., and Male, A. (2005). Silicon morphology modification in the eutectic Al-Si alloy using mechanical mould vibration. Materials Science and Engineering A, 393(1-2), 109-117.

Pak, Y. E., Choi, J. P., Park, J. P., Kim, K. B., Yoon, W. Y., Kim, M. H, et al. (2005). The effect of frequency of electromagnetic vibration on the primary silicon size in hypereutectic Al-Si alloy. Materials Science Forum, 475-479, 413-416.

Pak, Y. E., Choi, J. P., Seo, Y. S., and Nam, T. W. (2007). The continuous elimination of inclusions in molten aluminum by direct and alternative electromagnetic force. Materials Science Forum, 539-543, 499-502.

Pilaorz, G. Jozef, Andrej, Szajnar, Jam, andZez. (1980). Use of vibrations induced by electrodynamic forces in casting aluminum alloys. Naut Z. PolitechSlaska Mech. 69; 13-23.

Pillai, N.R. (1972). Effect of low frequency mechanical vibration on structure of modified Al-Si eutectic, Metallic Transistions. 3(5); 1313-1316.

Pillai, R. M., Kumar, B., K., S., and Pai, B. C. (2004). A simple inexpensive technique for enhancing density and mechanical properties of Al-Si alloys. Journal of Materials Processing Technology, 146(3), 338-348.

Ramana, M Venkata. (2014a). Modelling of CO_2 molding process; Global Journal of Advanced Engineering Technologies; pp. 190-194.

Ramana, M Venkata. (2014b). Modelling of the properties of sand mold of reclaimed sand; Journal of Engineering Research and Applications; vol.4:12(part 6); pp. 245-248.

Rao, T. V. (2003). Metal Casting: Principles and Practice. New Age International.

Ravi, B. (2005). Metal casting Computer-Aided Design and Analysis. Prentice Hall of India, New Delhi.

Rawson, K. (2001). Powering of Ship Application; Basic Ship Theory.

Richards, R. S., and Rostoker, W. (1956). ASM Trans. 48; 884.

Schwartz, M. (2002). Encyclopedia of Materials, Parts and Finishes. 2nd Edition. CRC Press.

Showa Aluminum KK. (1981). Degassing Metals. Kakai Tokyo Koho, Japan. 770.

Shukla, D.P., Goel, D.B., and Pandey, P.C. (1980). Effect of vibration on the formation of porosity in aluminum alloy ingots. Metallurgical Transactions B, 11B, pp. 166-168.

Siemens and Halsake. (1956). Gessellschaft m bH Patent No. 823, 419.

Sidpara, A., Ravisankarand, M. D. M. (2012). Micromanufacturing; Micromanufacturing Process. CRC Press, Taylor & Francis Group, NW. pp. 3-37.

Singh, Gurpreet., Siddique, Rafat., (2012). Effect of wast foundry sand (WFS) as partial replacement of sand on the strength, ultrasonic pulse velocity and permeability of concrete; Construction and Building Materials. Reed Business Information, Inc. Vol.26.

Sokoloff, S. Y. (1935). Mechanical vibration and molten metals. Acta Physiochemistry, USSR,3; 939.

Sokoloff, S. Y. (1993). ActaPhysicochim. USSR. 3; 930.

Sufei Wei and Steve Lampman. (2008). Centrifugal Casting. ASM International.

Sulaiman, S. (2001). Modeling of the thermal history of the sand casting process; Journal of Materials Processing Technology. Vol. 113-1-3. pp. 245-250.

Vives. (1996). Effect of force electromagnetic vibration during the solidification of aluminum alloys: solidification in the presence of colinear variable and stationary magnetic fields. Metallurgical and Materials Transactions B, 27B (3), pp. 457-464.

Weber, J. A., and Rearwin, E. W. (1961). Soundwaves improve die casting quality. Foundry. 19(2); 69.

Wikipedia. (2014). Marine Propeller Cavitation. https://en.wikipedia.org/wiki/ Propeller. Retrieved: 15th April, 2014.

Xinbao, L., Osawa, Y., Takamori, S., and Mukai, T. (2008). Grain refinement of AZ91 alloy by introducing ultrasonic vibration suring solidification. Materials Letters, 62(17-180, pp. 2872-2875.

Yoneda, H., Kondo, T., Ishino, T. (1991). Influence of the vibration during solidification on the primary crystal morphology in hypotactic Al-Cu alloys and their strength. Foundrymens Society. pp. 17-22