MICROSTRUCTURE AND MECHANICAL PROPERTIES OF VIBRATED CASTINGS AND WELDMENTS: A REVIEW

ASHWE ABUGH *, IKPAMBESE KUMADEN KUNCY

Department of Mechanical Engineering, University of Agriculture, P.M.B. 2373 Makurdi-Nigeria

Abstract: A number of methods utilizing external forces have been applied to induce fluid flow during solidification of molten metal in casting and welding processes. These include mould rotation, mechanical vibration and electromagnetic stirring. Many articles describe the benefits of vibration during casting and welding on microstructure and mechanical properties of castings and weldments. In this paper, these effects are reviewed and discussed to provide a better understanding of the processes. Understanding of these processes and application of the procedures offer extensive scope for significant cost savings in design and fabrication of cast and welded products.

Keywords: vibration, grain-refinement, microstructure, fluid-flow, molten-metal

1. INTRODUCTION

Casting and welding are manufacturing techniques widely used in industry for fabricating products with complex shapes in very simple processing runs. Mechanical vibration has been used to improve microstructure and mechanical properties of castings and weldments by way of grain refinement and this practice has been used by researchers.

In the case of casting or welding under vibratory conditions, moulds or work pieces are held rigidly on a vibratory table and the table is rigidly coupled to the vibration exciter which generates vibrations at different frequencies of oscillation and transmits them to the table and moulds or work pieces which in turn vibrate at different frequencies of oscillation. The molten metal solidifies under these vibratory conditions.

Fluidity is one of the most important factors in casting and welding processes. It is defined variously as the distance covered by quality liquid metal in a channel of fixed geometry before solidifying. That is the ability of a melt to flow and fill very narrow spaces, whether in a mould cavity or in a gap between welding grooves [1]. From the available literature, it is clear that fluidity has a major effect on the filling of the mould and it has been demonstrated that sonic or ultrasonic vibrations of mechanical origin can be effective in increasing fluidity by as much as a factor of three.

A number of examples can be found in the literature where external forces have been applied to induce fluid flow during solidification in order to refine grain size hence improve mechanical properties. These methods include rotation of the mould, mechanical vibration and electromagnetic stirring.

* Corresponding author, email: abuashwe@yahoo.com

In earlier studies, Campbell [2] noticed grain refinement to occur and mechanical properties improved in castings due to the application of vibration during casting. Production of high strength structural materials is mainly based upon developing a product in which the grain size is as small as possible. A coarse grained structure may result in a variety of surface defects in alloys used in rolled or extruded form, while the size of defects such as micro-porosity may reduce as a result of fine grain structures since the solidification of smaller grains will allow the mould to fill more completely and avoid unfavourable micro and macro- porosity thereby producing sound castings. Grain refinement also, remains a very important means for improving the physical and mechanical properties of welded joints.

2. MICROSTRUCTURES AND MECHANICAL PROPERTIES OF CASTINGS AND WELDMENTS

Mechanical, ultrasonic and electromagnetic vibrations during solidification of molten metal have the advantage of promoting grain refinement and enhancing the quality of cast metals [3]. The introduction of high intensity ultrasonic vibration into the melt may control the undesirable columnar dendrite structure, reduce the size of eqiaxed grains, and under some conditions, produce globular non-dendrite grains. Vibration of liquid metal can contribute to increased rate of heat transfer and removal of liquid superheat, which decreases the likelihood of remelting the initial solid grains. Under such conditions, temperature gradient from the center to the edge of the pool is decreased and the undercooled zone is dispersed in the entire bulk liquid. Mechanical properties such as tensile strength, hardness, and elongation are modified as compared to castings without vibration. Studies conducted on composites have also indicated that vibration has a number of notable effects such as grain refinement, increased density, reduced shrinkage, size and distribution of second phases.

Three distinct regions, namely base metal, heat-affected zone, and fusion zone have been identified in fusion welding. Fusion zone is part of a weldment which melts during welding process. It comprises of metal from the original work piece and the filler metal which is melted during the welding process. Microstructure properties of weldments vary from region to region when the heat input interacts with the metal. The major component of weld microstructure as it cools from the liquid state (high temperature) to ambient temperatures is ferrite [4]. There may also be some martensite, retained austenite or degenerate pearlite. These later phases occur in very small fractions and are known collectively as micro-phases. The micro-phases are relatively hard and behave in many respects like brittle inclusions. They are therefore of importance in determining the toughness of weld deposits. Slower cooling rates favour the formation of pearlite relative to martensite and some austenite may be retained to ambient temperatures. Very slow cooling rate also promotes the formation of bainnite in the heat-affected zone which presents a lower impact resistance.

In vibrated microstructures, two major factors contribute to the enhancement of grain size [5, 6]. These include dendrite fragmentation and detachment and total cooling rate. Vibration brings about formation of new grains which are formed in the weld pool because of dendrite fragmentation and grain detachment. Convection within the weld pool takes place due to different driving forces thus causing dendrite tip fragmentation. Dendrite fragments are taken into the bulk weld pool where they serve as nuclei for new grains formation. In grain detachment mechanism, partially melted grains are loosely held together by the liquid films between them. Vibration causes these grains to detach themselves from the base metal. If these grains are able to survive in the weld pool then, they act as nuclei for new grains. Vibration also enhances the total cooling rate of the weld pool by causing a positive effect on the effective value of thermal conductivity of the liquid pool. This stirring effect increases the heat transfer rate within the weld pool and thereby accelerates the rate of dendrite fragmentation and grain detachment with reduced dendrite spacing. Faster cooling of weld pool due to vibration produces harder phases with reduction in percent elongation of the welded joint [7].

3. EFFECTS OF VIBRATION ON MICROSTRUCTURE AND MECHANICAL PROPERTIES

Several investigators have found that mechanical vibrations of both sonic and ultrasonic character, when applied during the solidification of metals and alloys, modify conventionally obtained macrostructures and microstructures. The most commonly observed effects are the suppression of undesirable dendritic and columnar zones and the development of a fine-grained equiaxed structure. Casting/welding defects have been shown to reduce and become smaller with increase in vibration frequency while mechanical properties of specimens cast or welded with mechanical vibration are greatly improved.

Guo et al., [8], investigated the microstructure character of AZ80 magnesium alloy ingots cast under electromagnetic vibration. Microstructure of the ingots cast with the conventional Direct-Chill method exhibited relatively fine dendritic grains at the surface area, but coarse dendritic grains at the ½ radius and large equiaxed dendritic grains at the center. However under electromagnetic vibration casting condition, the microstructure of the ingots was significantly refined, especially those at the surface and at the center.

Yao et al., [9] also studied the effects of ultrasonic vibration on solidification structure and properties of Mg-8Li-3Al alloy. Microstructure, corrosion resistance and mechanical properties of the alloy were investigated. Experimental results showed that the morphology of α- phase was modified from coarse rosette-like structure to fine globular one with the application of ultrasonic vibration. Corrosion resistance of the alloy with ultrasonic vibration for 90 seconds was improved compared with the alloy without ultrasonic vibration. Tensile strength and elongation of the alloy treated with ultrasonic vibration improved by 9.5 % and 45.7 % respectively.

Adegbuyi et al., [10] while discussing the effect of pouring and vibration on cast quality of aluminum-copper alloys explained that upon vibration, crystal grains within casted materials were refined; solidification structure of the resulting structure was much finer than that produced without vibration.

The effects of mechanical vibration on macrostructure and mechanical properties of AC4C aluminum alloy castings were investigated by Omura et al [11]. The ingots were solidified at various vibration frequencies. In comparison with the grains formed in the as-cast state, the grains in the inner area of specimen became finer after mechanical vibration with columnar structure in its outer region under all vibration frequencies. Casting defects were observed to have reduced and became smaller with increase in vibration frequency.

Tamura et al., [12] found that the electromagnetic vibrations affected increase in the cooling rate and the decrease in the number of crystal nuclei directly when they investigated the effect of frequency of electromagnetic vibrations on glass-forming ability in Fe-Co-B-Si-Nb bulk metallic glasses. They concluded that vibrations give rise to considerable agitation of the melt and result in the newly formed nuclei being distributed throughout the solidifying pool and crystallization takes place uniformly inside the entire volume.

Zhao, et al., [13] investigated the effect of mechanical vibration on the microstructure, impact toughness and thermal fatigue behavior of cast hot working die steel. The cast hot working die steel was treated to mechanical vibration (MV) with a frequency of 50 Hz during the solidification process. The experimental results indicated that the MV broke off the dendrites growing from mould wall towards center in the steel during solidification. Therefore, the growth of the dendrites was restrained and the microstructure in the steel refined; furthermore, MV decreased the amount of defects such as shrinkage cavity and inclusion and enhanced the compactness of the steel. Impact toughness of the steel treated with MV was 1.5 times larger than that of the untreated steel. During thermal fatigue (TF) test, it was found that TF crack was longer and wider and the chap was more severe in the untreated steel than in the steel treated with MV. Simultaneously, the average velocity of crack propagation was 1.7 times faster in the untreated steel than in the steel treated with MV.

Ji et al., [14] introduced mechanical vibration into the solidification of AZ91D magnesium alloy via lost foam (LF) casting in order to overcome the defects of coarse microstructure and low mechanical properties. The microstructure with fine uniform dendrite grains was achieved with mechanical vibration. They attributed this to cavitation and the melts flow induced by the mechanical vibration. Ultimate tensile strength of the AZ91D treated to vibration increased by 23% while elongation went up to 26%. The cavitation effect was in agreement with Vives [15], where very fine and homogenous microstructure was observed throughout the irradiated ingots and cavitation threshold depended on electromagnetic pressure peak.

Abu-Dheir [16] examined the effect of wide range of vibration amplitudes and frequencies on the solidification kinetics, microstructure formation and mechanical properties of Al-Si alloys. Results showed strong influence of mould vibration on the resulting casting. Porosity was significantly reduced as a result of mould vibration. Increasing the vibration amplitude reduced the lamellar spacing and changed the silicon morphology to become more fibrous. He concluded that ductility is more influenced by vibration than the tensile strength and can be increased by as much as 100% under certain conditions. The increase in ductility was believed to be due to structure refinement.

Chirita et al., [17] evaluated the influence of some variables on the mechanical properties of the vertical centrifugal casting. In their study, a comparison between castings obtained by centrifugal casting technique, vibration casting technique and gravity casting technique was made in order to fully understand the features that allow the improvement in mechanical properties during the vertical centrifugal casting technique. An analysis of the most important effects, on both mechanical properties and on some metallurgical features was made. They observed that the centrifugal effect substantially increased the rupture strength, rupture strain, and Young modulus, in some alloys as compared to the gravity casting technique.

Vijayaram et al., [18] investigated the effect of mechanical vibration on the properties, microstructure and fractography of titanium carbide (TiC) particulate-reinforced LM6 alloy composite casting. The composites were fabricated by vibration moulding sand casting technique at frequencies of 10.2, 12 and 15 Hz. Results showed that the impact strength and hardness of the composites increased with an increase in frequency of vibration and increasing titanium carbide particulate reinforcement in the LM6 alloy matrix composite. Increase in tensile strength was also observed at the frequency of 10.2 Hz when compared with the gravity die-casting without vibration. In another similar study [19], TiC particulate reinforced LM6 alloy matrix composites were fabricated by different particulate weight fraction of titanium dioxide and microstructure studies were conducted to determine effect on mechanical properties of the. Results showed that mechanical properties improved significantly when mould was vibrated during solidification compared to gravity castings without vibration.

HuaShan et al., [20] studied the microstructures and properties of ultrasonic and conventional cast 7050 aluminum alloys. Compared to the conventional cast alloy, the ultrasonic cast ingot (UI) was characterized with a finer microstructure than that in the conventional cast ingot (CI). It was observed that for the hot-rolled plates, the UI alloy can be aged faster and aging-strengthened easier than the CI alloy. When aged at 120 °C, the UI alloy reached its peak strength after 8 h, with tensile strength of 602 MPa, yield strength of 547 MPa and elongation of 12.7%, respectively, whereas the CI alloy plate had tensile strength, yield strength and elongation of 536 MPa, 462 MPa and 15.0%, respectively, after peak aged for 12 h.

Kuo et al., [21] undertook the characterization and mechanism of 304 stainless steel vibration welding. Gas tungsten arc welding was performed on the steel; steady-state vibration was produced by a mass-eccentric motor. The vibrated weld showed a very small δ-ferrite structure, uniform composition distribution, less residual stresses and less δ-ferrite content relative to the weld produced without vibration. The results illustrated that the vibration reduced the micro super-cooling and improved the nucleation of δ-ferrite to form a grain refined structure.

Tewari [22] introduced longitudinal oscillation to study the effects of specimen thickness on tensile properties of medium carbon steel welds. Medium steel workpieces (8 mm, 10 mm and 12 mm thick) were welded at different vibration frequencies (0 – 400Hz) and amplitudes (0 – 40 μm) of longitudinal oscillation. Yield strength, ultimate tensile strength, breaking strength improved significantly by 21%, 26% and 39% respectively, while percent elongation reduced by 5.5% in oscillatory prepared welds in comparison to stationary welded test specimens. The reason for this increase was attributed to grain size refinement, dendrite fragmentation and grain detachment mechanisms.

Balasubramanian [23] investigated the effect of vibration during welding on hot cracking and grain size in AA 7075 aluminum alloy known to be highly prone to hot cracking. Vibration treatment was carried out in the frequency range of 100 Hz to 2050 Hz. Weldments made with and without vibratory treatment were compared using weld cracking tests and other characterization tests like micro structural analysis and hardness measurements. Test results showed that by applying vibratory treatment, hot cracking could be largely controlled in the arc welding process.

Hussein et al., [24] found that the vibration applied during welding at frequencies of 3, 5, 10 and 100Hz generally improved distinctively the bend property of the welding line as well as the tensile strength as compared to that which was welded without vibration.

In other investigations [25], it was established that changes in impact toughness due to vibration during welding do occur. Vibration stabilizes microstructures to become more resistant to heat affects that could minimize impact toughness. The type of fracture turns more ductile with vibration during welding and fracture toughness increases. There is strong evidence to show [26] that hardness also has a strong influence on the strength and toughness of welded joints. Impact energy dropped in areas of maximum hardness in welded joints and rises in the field of declined hardness or coarsening of carbides. According to John [27], a high hardness value indicates quite severe cooling conditions in the heat-effected zone in low carbon steel weldments. Hardness and tensile strength are also known to have influence on crack initiation and growth in opposite ways [28]. Higher values of hardness/strength are beneficial in terms of countering crack initiation, but usually lead to high crack growth rates.

4. CONCLUSIONS

In this paper a collective summary of the underlying micro-mechanisms and effects of vibration during casting/welding on macrostructure, microstructure and mechanical properties of castings and weldments was presented. Several examples drawn from the literature suggest vibration during casting and welding greatly benefits grain structure and mechanical properties of products. Dendrite fragmentation and detachment and total cooling rate have been identified as two major factors that contribute to the enhancement (refinement) of grain size of vibrated microstructures. Mechanical properties are dependent on these microstructural changes that take place during solidification of the melt. Vibration during casting and welding has now been fully documented and accepted as one important procedure for manufacturing high quality castings and weldments for commercial industrial use. Application of this procedure offers extensive scope for significant cost savings in design and fabrication.

REFERENCES

[1] Abdul-Karem, W., Kahlid F., Al-Raheem, F., Vibration improved the fluidity of aluminum alloys in thin wall investment casting, International Journal of Engineering Science and Technology, vol. 3, no. 1, 2011, p. 120 – 135.
[2] Campbell, J., Effect of vibration during solidification, International Metals Review, vol. 26, no. 2, 1981, p. 71-108.
[3] Verma, A., Tewari, S. P., Prakash, J., Vibratory stress, solidification and microstructure of weldments under vibratory welding condition – A review, International Journal of Engineering Science and Technology, vol. 3, no. 6, 2011, p. 5215 – 5220.
[4] Dong, J., Cui, J., Zeng, X., Ding, W., Effect of Low-Frequency electromagnetic vibration on cast-ability, microstructure and segregation of large-scale DC ingots of high-alloyed Al, Materials Transactions, vol. 46, no. 1, 2005, p. 94 – 99.
[5] Lah, N. A. C., Ali, A., Ismail, N., Characterization of fusion welded joints: A review, Pertanika Journal of Science and Technology, vol. 17, no. 2, 2009, p. 201 – 210.
[6] Tewari, S. P., Shanker, A., Effects of Longitudinal Vibration on Hardness of Weldment, Journal of Engineering Manufacture, vol. 207, no. B3, 1993, p. 173- 177.
[7] Dahunsi, O. A., Audu, A., The effect of vibration on the mechanical properties of low-carbon steel welded joints, NSE Technical Transactions, vol 41, no. 4, 2006, p. 61 – 72.
[8] Guo, S., Le, Q., Zhao, Z., Cui, J., Microstructure character of AZ80 magnesium alloy ingots cast under electromagnetic vibration, China Foundry, 2006, p. 022 – 025.
[9] Yao, L., Hao, H., Ji, S., Fang, C., Zhang, X., Effects of ultrasonic vibration on solidification structure and properties of Mg-8Li-3Al alloy. Transactions of Nonferrous Metals Society of China, vol. 21, 2011, p. 1241 – 1246.
[10] Adegbuyi, P. A. O., Uhomoibhi, J. O., Adedeji, K. A., Raji, N. A., The effect of pouring and vibration on cast quality, The Public Journal of Science and Technology, vol. 11, no. 1, 2010, p. 45 – 54.
[11] Omura, O., Murakami, Y., Li, M., Tamura, T., Miwa, K., Effects of mechanical vibration on macrostructure and mechanical properties of AC4C aluminum alloy castings, Materials Transactions, vol. 50, no. 11, 2009, p. 2578 – 2583.
[12] Tamura, T., Kamikihara, D., Omura, N., Miwa, K., Effect of frequency of electromagnetic vibrations on glass-forming ability in Fe-Co-B-Si-Nb bulk metallic glasses, Rev. Advanced Materials Science, vol. 18, 2008, p. 10 – 13.
[13] Zhao, Y. G., Liang, Y. H., Qin, Q. D., Zhou, W., Jiang, Q. C., Effect of Mechanical Vibration on the Microstructure, Impact Toughness and Thermal Fatigue Behavior of Cast Hot Working Die Steel, ISIJ Int (Iron Steel Inst Jpn), vol. 44, no. 7, 2004, p. 1167-1172.
[14] Ji, Q. L., Zi, T. F., Xuan, P. D., Wen, L., Xianyi, L., Microstructure and Mechanical Properties of Lost Foam Casting AZ91D Alloy Produced with Mechanical Vibration, Advanced Materials Research, vol. 213, no. 5, 2011, p. 5-8.
[15] Vives, C., Grain refinement in aluminum alloys by means of electromagnetic vibrations including cavitation phenomena, http//www.tms.org/pubs/journals/JOM/9802/Vives/ (27.12.2010).

[16] Abu-Dheir, N., Experimental and numerical study of the effect of mold vibration on aluminum castings alloys, http://proquest.umi.com/pqdlink?did=932388531&Fmt=7&clientId79356&RQT=309&VName=PQD (26.09.2012).
[17] Chirita, G. I. Stefanescu, D. S., Silva., F.S., Effect of Gravity/ Vibration/ Centrifugal Process on Mechanical Properties of an Al-Si Alloy, Materials Science Forum, vol. IV, 2008, p. 587-588, 395.
[18] Vijayaram, T. R., Sayuti, M., Sulaiman, S., Effect of mechanical vibration on the properties, microstructure and fractography of titanium carbide particulate-reinforced LM6 alloy composite castings, Indian foundry Journal, vol. 58, no. 1, 2012, p. 23 – 33.
[19] Mohd, S., Shamsuddin, S., Hang Tuah Baharudin, B.T., Mohd Khairol, H. A., Suraya, S., Gholamreza, E., Mechanical Vibration Technique for Enhancing Mechanical Properties of Particulate Reinforced Aluminium Alloy Matrix Composite, Composite Science and Technology, vol 471 – 472, 2011, p. 721-726
[20] Hua Shan, l., Xiang, Q., Zhi Hong, C., RongPiao, J., Xiao Quian, L., Effect of ultrasonic vibration during casting on microstructure and properties of 7050 Al alloy, Journal of Materials Science. vol. 46, no. 11, 2011, p. 3923 – 3927.
[21] Kuo, C., Lin, C., Lai, G., Chen, Y. Characterization and mechanism of 304 stainless steel vibration welding, Materials Transactions, vol. 48, no. 9, p. 2319 – 2323.
[22] Tewari, S. P., Effect of Longitudinal vibration oscillation on tensile properties of medium carbon steel welds of different thickness, International Journal of Science and Technology, vol. 14, no. 4, 2007, p. 17-27.
[23] Balasubramanian, K., Studies on the effect of vibration on hot cracking and grain size in AA 7075 aluminum alloy welding, International Journal of Engineering Science and Technology, vol. 3, no. 1, 2011, pp. 681 – 686.
[24] Hussein, A. R., Jail. N. A., Talib, A. R. A., Improvement of mechanical welding properties by using induced harmonic vibration, Journal of Applied Sciences, vol. 11, 2011, p. 348 – 353.
[25] Pucko, B., Gliha, V., Charpy Toughness of Vibrated Microstructures, Matallurgija, vol. 4, no. 2, 2005, p. 103 -106.
[26] Liu, P., Li, Y., Geng, H., Wang, J., Microstructure characteristics in TIG Welded Joints of Mg/Al dissimilar materials, Journal of Materials Letters, vol. 61, 2007, p. 1288-1291.
[27] John, W. H. P., Anna, M. P., Ibrahim, I., Trevor, R. F., Residual stress evaluation in welds and implications for design for pressure vessels application, Journal of Pressure Vessels Technology, vol. 128, 2006, p. 638-643.
[28] Babu, G. R., Murti, K. G. K., Janaradhana, G.R., An experimental study on the effect of welding parameters on mechanical and microstructure properties of AA6082-T6 Titanum Stir welded butt joints, Journal of Engineering and Applied Science, vol. 3, no. 6, 2008, p. 68-75.