Effect of mechanical vibration on the microstructure and thermal fatigue behavior of cast hot work die steel

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Vibrational energy has been used in many processes within the metallurgical and engineering field [1]. Different methods have been used to apply vibration during solidification. A review of the literature [2–17] reveals that the application of mechanical, electromagnetic, sonic, and ultrasonic vibration has a number of notable effects such as grain refinement, increased density, degassing, shrinkage, as well as the shape, size and distribution of the second phase. However, it was also reported that electromagnetic and ultrasonic vibration are costly and requires tremendous amount of current to be effective [2]. Comparatively, mechanical vibration (MV) is used more commonly because of its simplicity and low cost. MV as a technique for grain refinement was first reported early in the last century by Sokoloff [3]. Later a process was conceived for treating molten metals with high frequency MV [4]. It was found that gas inclusions, dross and slag were brought to the surface by the process. This produced uniform, fine-grained castings, and increased the toughness, ultimate tensile strength and yield strength of the cast material. Fisher [5] used vibration treatment on Al–Si alloy, and showed a reduction in the grain size and the primary dendrites were also reduced in size. Recently, Kocatepe and Burdett [6] applied MV to two types of LM6 alloy, one with grain refiner and sodium and the other with no additions. They have found that the grain size of the unmodified alloy was reduced by 52% by subjecting it to vibration, while the grain refinement was 76% for the modified alloy. Several other researchers have investigated the effect of MV on the microstructure of castings [7–10]. The beneficial effect of MV was observed with several types of metals, e.g., zinc, brass, aluminum, etc. The effects include promotion of nucleation and thus reducing as-cast grain size, reducing shrinkage porosities due to improved metal feeding, and producing a more homogenous metal structure.

From the above review it is obvious that the microstructures and the mechanical properties were definitely affected by the application of MV. However, most of the researches are focused on the effect of MV on the solidification of pure metals and low-melting alloys. In this paper we examine the effect of MV on microstructure and thermal fatigue behavior of the cast hot work die (CHWD) steel. The CHWD plays an important role in metalworking industry and is called as "black gold" because of their high cost and complicated machining process. In hot metal forming operations, the life of hot work die is restricted due to their extreme working conditions in terms of thermal and mechanical loadings [18]. The die material is damaged through a process of nonisothermal low-cycle fatigue under frequent hot and cold working conditions. Alternate heating and cooling of the die during the die-casting cycle causes thermal fatigue (TF) [19–23]. TF is a process of damage origination and growth in machine parts and structural components due to changes in internal stress caused by multiple cyclic or periodic changes of temperature [19, 20]. It has been indicated by much research that TF cracks not only reduce the life of hot work die, but also initiate other fractures. Consequently, how to improve the TF resistance of CHWD is always one of the key problems of concern to die industry.

Controlling the microstructure that results from the casting process is considered one of the main challenges faced by today's foundry industry. It is possible to improve properties of CHWD steel by suitable chemical, physical, and mechanical treatment, applied either in the molten state or at a suitable stage of solidification in the foundry. The object of the present work is to study the effect of MV with the constant frequency of 50 Hz and variable amplitudes on microstructure during solidification and TF behavior of the CHWD steel. It was expected that the preliminary results could be significant in enhancing the resistance of the TF and prolonging the life of the CHWD steel.

The composition of the CHWD steel used in this study is provided in Table I. The test materials were melted by medium frequency induction furnace, using nonoxidation method. After deoxidization with Al at 1600°C, the melt

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TABLE I The chemical composition of the CHWD steel (wt. %)

C	Cr	Mo	Ni	Si	Mn	S	P
0.3–0.5	10.0–13.0	0.5–1.2	0.8–1.0	0.7–1.0	0.2–1.0	<0.03	<0.03

was poured into the vibrated mold, and then the vibration was lasted for 2 min. The mould cavity had a height of 120 mm and a diameter of 60 mm. The transmission electron microscope (TEM) analysis and X-Ray diffraction (XRD) pattern of the CHWD steel in the as cast condition are shown in Fig. 1a and b, respectively. According to Fig. 1, the microstructure is mainly composed of martensite and some residual austenite. The detailed MV device has been reported elsewhere [11]. The MV parameters of 50 Hz constant frequency and variable amplitudes ranging from a smallest value of 0.4 mm to a maximum of 1.2 mm were used in this study. The TF samples were machined to a gage size of 55 × 14 × 6 mm^3 with an additional notch (0.18 mm in width and 6.0 mm in length). Before TF testing, the following heat treatment process was performed: austenizing at 1353 K for 1 hr, quenching in oil, followed by tempering at 853 K for 3 hr and air cooled. After heat treatment, the microstructures of the CHWD steel are mainly composed of martensite and bainite [11]. TF test apparatus with resistance furnace heating and water cooling was available for rapid thermal cycling of these samples. A complete TF cycle includes heating for 70 s up to the maximum cycling temperature (853 K) in resistance furnace, and then water cooling for 4 s to the minimum cycling temperature (298 K) in water tank.

The typical optical micrographs of the CHWD steels untreated and treated with MV at the constant frequency of 50 Hz and different amplitudes of 0.4, 0.9, and 1.2 mm in the as-cast condition are shown in Fig. 2a–d, respectively. From Fig. 2a, it is seen that there are quantities of the large dendritic structure in the casting untreated with MV. However, as seen in Fig. 2b, the microstructure resulted from MV with the lowest amplitude of 0.4 mm presents evidence that the majority of the large dendrites existed in the unvibrated casting have broken and many small dendrites were obtained. According to Fig. 2c, as the MV amplitude increases to 0.9 mm, the dendritic structure that persisted in the case of lower amplitudes and the unvibrated casting has almost disappeared and become a great quantity of small equiaxed grains structure. With further increase in the amplitude to 1.2 mm, there exhibits finer equiaxed structure in the microstructure of the casting as shown in Fig. 2d. It may be the main reason that the MV-induced movement of the liquid between the solid dendrites subjects the growing dendrites to bending stresses [6]. These dendrites have very little strength and ductility because the temperature is so close to the melting temperature. Fragmentation occurs due to impact of the liquid with the dendrites, and the small crystals generated by fracture of the dendrites which will act as nuclei are carried to the other parts of the liquid [12]. At the same time, these detached dendrites impinge on each other and on those still attached to the wall, causing further extensive dendrite damage, and consequently dendrites refinement occurs [13]. For the lower values of vibration amplitudes it is suspected that the vibration applied is not sufficiently vigorous to break the dendrites. Keeping the frequency constant at 50 Hz and increasing amplitude resulted in an increase in the degree of fragmentation of the dendrites. It is obvious that the transition of the microstructure from dendritic to equiaxed form has occurred by MV with increasing amplitude.

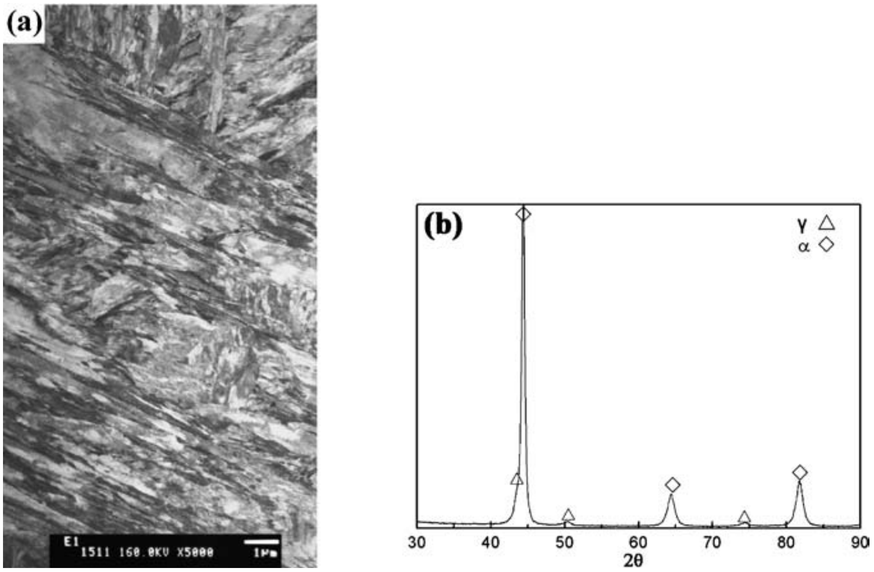

Figure 1 The TEM analysis and XRD pattern of the CHWD steel in the as cast condition. (a) TEM analysis, (b) XRD pattern.

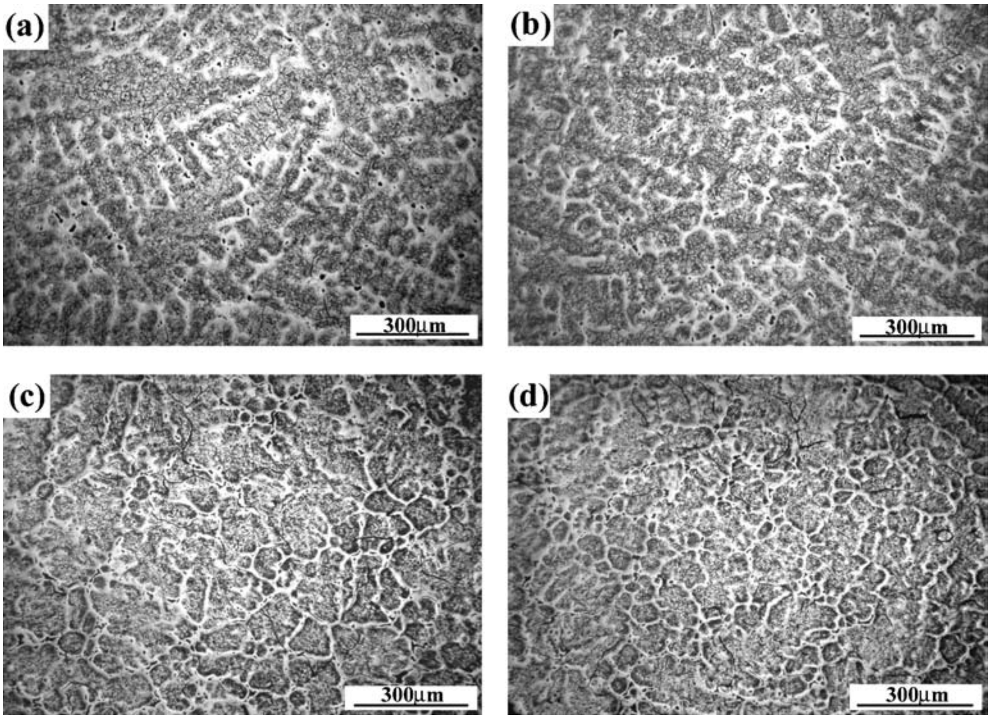

Figure 2 The optical micrographs of the CHWD steels untreated and treated with MV at different amplitudes of 0.4, 0.9, and 1.2 mm in the as cast condition. (a) untreated, (b) 0.4 mm, (c) 0.9 mm, (d) 1.2 mm.

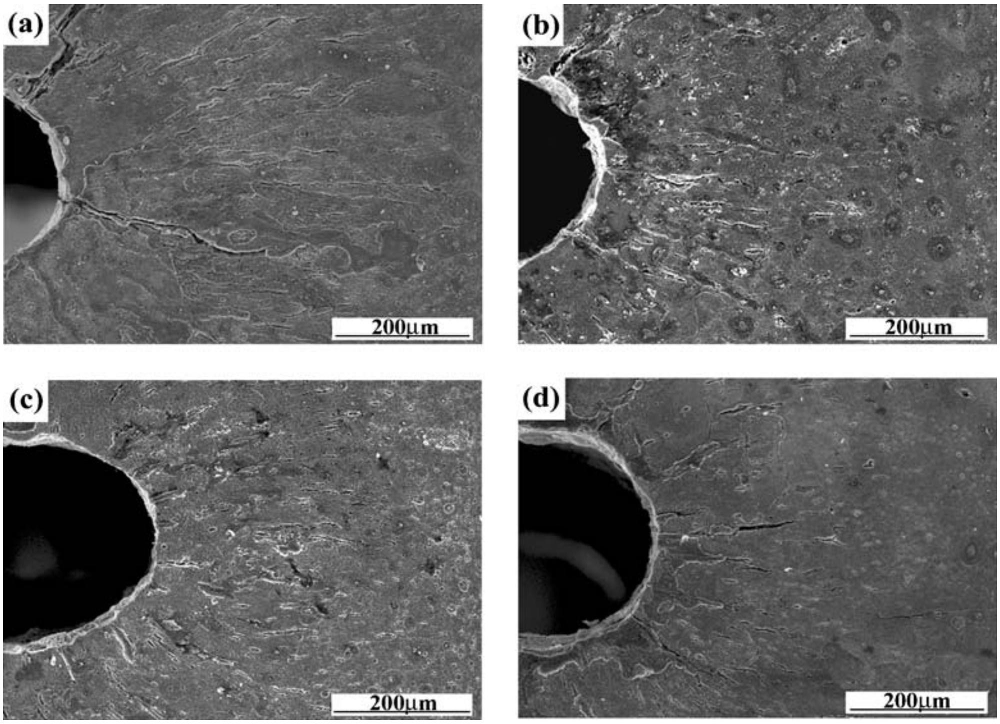

Figure 3 The SEM micrographs of TF crack morphology of the samples untreated and treated with MV at different amplitudes of 0.4, 0.9, and 1.2 mm after 650 cycles. (a) untreated, (b) 0.4 mm, (c) 0.9 mm, (d) 1.2 mm.

The typical scanning electron microscopy (SEM) micrographs of TF-crack morphology of the samples untreated and treated with MV at the different amplitudes after 650 cycles are shown in Fig. 3. The results indicate that the two main cracks formed in the untreated sample (Fig. 3a) are longer and wider. The TF cracks of the sample treated with MV at amplitude of 0.4 mm are finer (Fig. 3b), compared with unvibrated sample. As the MV amplitude is increased to 0.9 mm, the tiny cracks just nucleate at notch root (Fig. 3c). However, when the

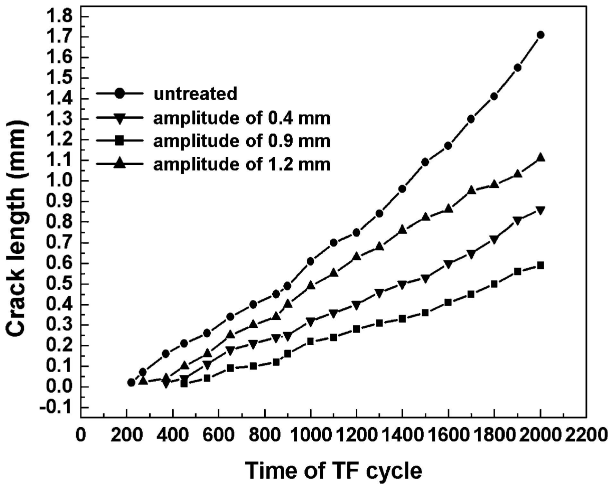

Figure 4 The nucleation and propagation characteristic of the TF crack of the samples untreated and treated with MV at different amplitudes of 0.4, 0.9, and 1.2 mm.

amplitude is increased to 1.2 mm (Fig. 3d), it can be seen clearly that the TF cracks are longer and wider again than those in the samples vibrated at lower amplitudes.

TF resistance of materials is subjected to the resistance of crack nucleation and propagation. The nucleation and propagation characteristic of the TF crack of the samples untreated and treated with MV at the constant frequency of 50 Hz and different amplitudes of 0.4, 0.9, and 1.2 mm are shown in Fig. 4 It is found that the nucleation of the TF crack is earlier and its propagation is quicker in the untreated sample than those in the samples treated with MV. As the amplitude of MV increased, the nucleation of the TF crack became later and the propagation became slower. It can be concluded that the increasing amplitude can be advantageous in retarding the nucleation and propagation of the TF crack and in improving the TF resistance of the CHWD steel. It should be mentioned that when the amplitude increased to 1.2 mm, the resistance of TF crack nucleation and propagation decreased, in comparison with the castings vibrated at lower amplitudes, however it is higher than that of unvibrated castings. The main reason for this result is that the MV can cause fragmentation of the dendrites and formation of small equiaxed grains structure. Furthermore, the MV can decrease the amount of defects such as shrinkage cavity and inclusion and refine the sizes of grain and inclusion [11]. These improved features are favorable to lowering susceptibility to cracking and improving the resistance of the TF. However, on one hand, increasing the amplitude to 1.2 mm should also be strong enough to break the dendrites; on the other hand, it may also produce some microcracks and defects in the CHWD steel, which results in the decreasing of the TF resistance.

On the basis of the above observation it can be concluded that the MV can cause breaking of the dendrites and formation of small equiaxed grains structure. Keeping the frequency constant at 50 Hz and increasing amplitude resulted in an increase in the degree of fragmentation of the dendrites. In addition, the MV with increasing amplitude is advantageous in enhancing the resistance of the TF crack nucleation and propagation in the CHWD steel. However, the resistance of the TF reduced when the amplitude increased to 1.2 mm.

Acknowledgments

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