DYNAMICS AND SOLIDIFICATION BEHAVIOR OF THE METALLIC MELT LEVITATED BY SIMULTANIOUS IMPOSITION OF ALTERNATING AND STATIC MAGNETIC FIELDS

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A levitation method using the static and the alternating magnetic fields has been developed. Intensity of the convection and the oscillation can be controlled by changing the static magnetic field. Only the oscillation of the single mode was observed at an optimum magnetic field, while several oscillation modes were observed in the conventional method. The convection was hardly observed at the static magnetic fields exceeding 1 T. By using the present method, the effect of the melt flow on the solidified structure during the undercooled melt solidification is also examined. In the lower undercooling region, the melt flow significantly contributed to the formation of the equiaxed grains.

Introduction. The electromagnetic levitation method has several advantages to measure thermophysical properties [1] and to investigate solidification from the undercooled melts [2]. Since the alternating magnetic field intrinsically causes the stirring forces, the turbulent flow occurs in the melt. The melt flow often influences the solidification behavior. Thus, it is desired to develop an alternative technique in which the melts flow can be controlled for metallic melts. It has been reported that titanium was statically melted in a cold crucible when a high static magnetic field was imposed [3]. A levitation technique using the alternating and the static magnetic fields has been developed [4]. The melt flow in the levitated melt and the oscillation due to the surface tension were reduced by the static magnetic field. A theoretical approach has been also investigated [5].

The oscillation of the levitated melt has been used to measure surface tension [6]. Surface tension is theoretically related to the Rayleigh frequency for a spherical droplet. In the measurements under the terrestrial conditions, the melt became aspherical due to the electromagnetic force and the gravitational force. The deviation from the spherical shape results in the split of the fundamental frequencies [6]. It is of interest to understand how the static magnetic field suppresses the oscillation and to discuss the application of the levitation method for measuring the thermophysical properties.

The solidified structure can be significantly influenced by the melt flow. If one can control the intensity of the oscillation and the convection in the levitated melts, the experimental technique is a powerful tool to understand how the melt convection influences the solidified structures. Thus, from a fundamental aspect, it is also of interest to study the effect of the magnetic field on the microstructure solidified from the undercooled melts by using the levitation method.

First, this paper presents the influence of the static magnetic field on the oscillation of the levitated melt. Second, the effect of the static magnetic field on the solidified structure of some alloys is presented.

1. Experiments. The levitation of metallic melts was performed by the simultaneous imposition of the alternating and the static magnetic fields [4]. An RF generator (200 kHz, 20 kW) was connected to the levitation coil. The static magnetic field was imposed by using a cryogen-free superconducting magnet (Maximum field: 10 T, bore size: 100 mm). Melts were levitated in Ar atmosphere and

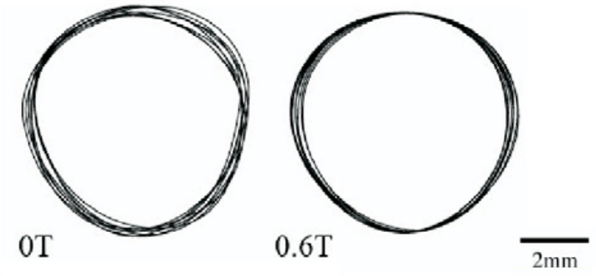

Fig. 1. Shape of the levitated copper melts.

were cooled by He-5% H_2 gas. The temperature was measured by a two-color pyrometer and the melt was observed by a CCD camera (250 frames/s). Pure Cu and conventional middle carbon steel were used. The typical weight of the sample was 1 g and diameters of the levitated melt were approximately 6 mm. Inclusions on the levitated melt were traced to examine the melt flow.

2. Oscillation. Fig. 1 shows shape of the levitated cooper melts. The observation was performed in the horizontal direction. The ratio of the diameter in the horizontal direction to that in the vertical direction was 0.98. Traces of the melt levitated at a magnetic field of 0 T showed that the distortion resulted in the split and the shift of the fundamental frequencies ($l = 2$, $|m| = 0, 1, 2$) occurred. As the magnetic field increased, the amplitude of the oscillation decreased. At a magnetic field of 0.6 T, the horizontal length periodically changed and the vertical length was constant. The melt shape change observed at 0.6 T corresponded to the oscillation of the $l = 2$, $|m| = 2$ mode [5]. Thus, the static magnetic field preferably suppressed the $|m| = 0.1$ modes and the single mode oscillation ($|m| = 2$) was achieved at 0.6 T.

Fig. 2 shows the spectra obtained by Fourier transformation of the horizontal length. Several peaks corresponding to the fundamental frequencies were observed at a static magnetic field of 0 T. In contrast, only a single peak of the $|m| = 2$ mode was observed at 0.6 T. At a magnetic field exceeding 0.75 T, no peak was detected.

Suppression of the oscillation depended on the oscillation modes. The present result showed that only the oscillation of the $l = 2$, $|m| = 2$ mode was agitated at an optimum static magnetic field. The selective suppression of the oscillation mode can be used to measure the surface tension.

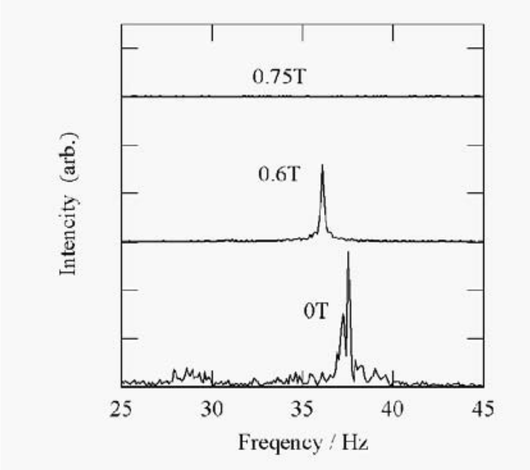

Fig. 2. Spectra obtained by the Fourier transformation of the horizontal length.

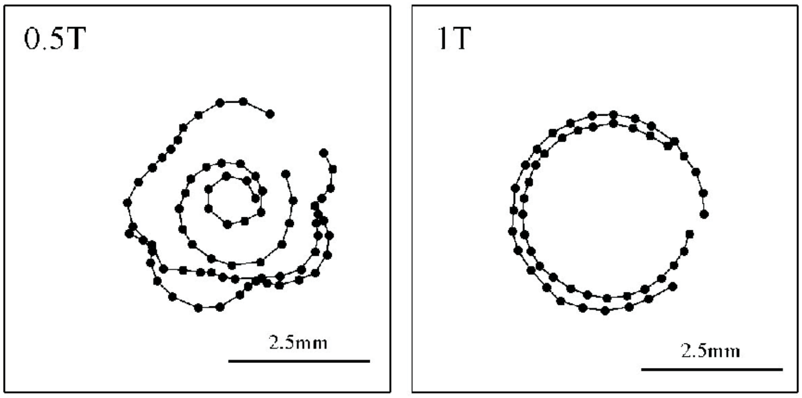

Fig. 3. Traces of the inclusions on the levitated copper melts. The interval between the positions was 1/250 s.

3. Melt flow and solidification. Fig. 3 shows traces of the inclusions floating on the levitated copper melts. The inclusions randomly moved in the levitated melts at 0 T. The random motion indicated that the electromagnetic force stirred the melt. At a static magnetic field of 0.5 T, rotation of the melt was clearly observed, although the random movement was still observed. At a static magnetic field exceeding 1 T, the traces indicated the inclusions and exhibited the circular motion and the inclusions had the same angular velocity. Although the oscillation and the convection originate in nature of the fluids, the rotations is not associated with the melt flow. The imposition of the magnetic fields exceeding 1 T achieved the melt levitation in which the melt flow was significantly reduced.

The solidified structure of the middle carbon steel was shown in Fig. 4. When the static magnetic field was not imposed, the equiaxed grains were obtained. In contrast, the coarse columnar grains were formed when a static magnetic field of 10 T was imposed. Reduction of the convection by the static magnetic field resulted in the morphological transition from the equiaxed grains to the columnar grains. A similar transition was observed for Cu–Ag, Fe–Ni alloys [7].

In the Ni–Cu system, the morphological transition from the equiaxed grains to the columnar grains occurred at the lower critical undercooling, and other tran-

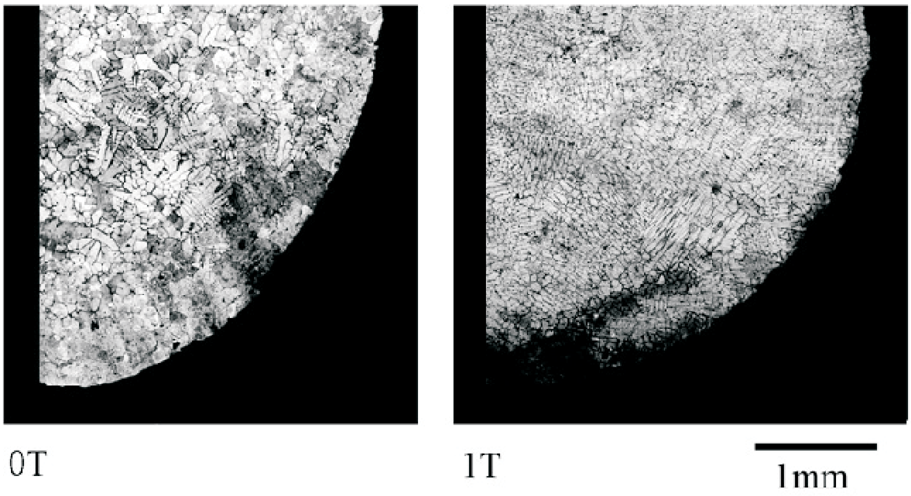

Fig. 4. Solidified structure of the middle carbon steel.

sition from the columnar grains to the equiaxed grains occurred at the higher critical undercooling [2]. They explained the transition by considering the fragmentation of the dendrites during the period following the recalescence on the basis of the model [8]. The estimated morphology was qualitatively agreed with the experimental results. However, they also pointed out that the lower critical undercooling was a relatively poor agreement with the experimentally obtained value and the melt flow might result in the poor agreement. The present results showed that the equiaxed grains were not obtained when the melt flow was reduced. The present results proved that the melt flow dominantly promoted the fragmentation and consequently resulted in the equiaxed grains in the lower undercooling region. Since the solidification in the lower undercooling region is not far from that in the conventional casting processes, the results provide useful information for the microstructure control by solidification process.

4. Conclusions. The influence of the static magnetic field on the oscillation of the levitated melts was examined by levitation using the alternating and the static magnetic fields. Reduction of the oscillation depended on the oscillation modes. Only the oscillation of the $l = 1$, $|m| = 2$ mode was observed at an optimum static magnetic field (typically 0.4–0.6 T). The melt flow was not detected at a magnetic field exceeding 1 T. The morphological transition from the equiaxed grains to the columnar grains occurred when the static magnetic field was imposed. The result proved that the melt flow dominantly resulted in formation of the equiaxed grains in conventional solidification processes.

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