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Alignment of weakly magnetic metals during solidification in a strong magnetic field

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ABSTRACT

Systematic understanding on the magnetic alignment and adjustment on mechanical properties of a weakly magnetic metal were carried out. The application of a sufficiently strong magnetic field modifies the nature of solidification by means of the magnetic anisotropic property of weak magnetic crystals. With a range of characterization techniques, the effects of different factors, i.e. magnetic flux density, copper/eutectic content, on the magnetic alignment were considered. Lotgering factor and magnetic energy were further introduced to evaluate the magnetic alignment and the alignment mechanisms. The magnetic alignment process for primary phase in the present case tends to be prompt. Subsequently, magnetic field effect on the anisotropic properties of the Al_2Cu phase was checked together with understanding its crystallography. The present research provides a better understanding of the strong magnetic field effects on solidification and also a potential method for Al–Cu structural materials preparation.
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1. Introduction

For aluminum alloys, most of the desirable physical properties are developed via alloying, solidification control or heat treatment resulting in heterogeneous microstructures [1]. Among these alloys, Al–Cu alloys exhibit promising natures as structural or electronic materials. The addition of copper which has a relative high solubility in aluminum contributes to increase the strength, hardness and/or creep resistance [2] or increase the electro-migration performance [3]. The presence of θ-Al_2Cu intermetallic phase is believed to play an important role [4]. Besides of the commercial Al–Cu alloys, the preparation of Al (Cu) based metal matrix composites [5,6] and Al–Cu based thin films or coatings [3,7] have also been intensively investigated. In the materials, the morphologies and distribution of the θ-Al_2Cu phase are important in determining the physical properties. In order to control the growth/precipitation behavior of θ-Al_2Cu, various approaches have been developed together with the unidirectional solidification [8]. For instance, laser surface alloying [9], friction stir processing [10], severe plastic deformation [11] and reaction sintering [5,12] are frequently used to decrease the θ-Al_2Cu phase size and/or reach a certain distribution in the material. To obtain a better performance, heat treatment is often applied [1]. The influence of different processing parameters on the growth, properties of Al–Cu eutectic and θ-Al_2Cu phases has been a common scientific issue. If a strong magnetic field is further integrated [8,13,14], the thermodynamic properties of the alloy and the concomitant crystal growth on both micro- and meso- scales [15] may be influenced.

By applying a proper magnetic field, strong magnetic field effects are readily observed even for weak magnetic materials [13,16,17]. In earlier research, the solidification/phase transformation of metals with higher magnetic susceptibilities such as iron/steel [18] and Bi-based alloys [14] have been widely investigated. Both the phase transformation temperature and phase morphology are influenced by the applied magnetic field. It provides direct evidence that the magnetic field contributes to not only a thermodynamic effect, but also a meso-scale effect on the crystal growth [19]. Under a magnetic field, additional anisotropic properties can therefore be expected after the magnetic alignment of crystals [20]. Although aluminum and copper are both weak magnetic materials (with very low magnetic susceptibilities), the magnetic alignment of θ-Al_2Cu phase could be reached [17,21,22] in a proper magnetic field. The [001] crystallographic direction could be aligned by a strong magnetic field of 12 T [22]. During the process of unidirectional solidification, the growth of Al and θ-Al_2Cu phases were both modified and for the θ-Al_2Cu phase there is a competition between the preferred growth direction and the magnetic alignment direction [17]. The eutectic microstructure then becomes irregular causing a large number of defects in the crystals which may influence the mechanical properties of the Al–Cu alloy. At the same time, in a sufficiently strong magnetic field, the nucleation [13], melt convection [23] and even the diffusion of atoms as demonstrated by related work with diffusion couples [24] can be influenced. Therefore, the effect of a strong magnetic field on alignment/growth during solidification presents itself with a large degree of complexity.

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So far, the mechanisms of the strong magnetic field effects on solidification are still not fully understood and the relationship between a strong magnetic field treatment and mechanical properties is still unclear. Therefore, the objectives of this paper are in line with (i) Strong magnetic field effect (SMFE) on the behavior of primary θ-Al_2Cu phase; (ii) SMFE on the subsequent primary crystal growth; (iii) SMFE on the eutectic growth; (iv) Mechanical properties of the primary θ-Al_2Cu phase. With a better understanding on the nature of strong magnetic field effect, technologies of field-manipulation of weak magnetic materials may be integrated.

2. Experimental

2.1. Materials and apparatus

The materials used in the experiments are hypereutectic Al–Cu alloys with copper contents of 50 wt.% (Affilips N.V., Belgium,>99% purity) and 38 wt.% (Halcor S.A., Greece,>99% purity). Cylindrical samples were prepared from crushed Al–Cu alloy powders by using an induction furnace under Ar gas atmosphere. The cylindrical sample was cut and placed in a high purity corundum crucible which was sealed with refractory mortar (Hongyuan Co. Ltd., China,>30 wt.% Al_2O_3). After fixing the crucible in a stainless steel sample holder, it was mounted into a tube furnace which was placed in a vertical strong magnetic field up to 12 T induced by a vertical superconducting magnet (Oxford Instruments, UK). The temperature of the furnace can reach 900 °C and was controlled to a precision of ±1 °C. A water cooling system is installed to keep the inner wall of the magnet at a temperature below 40 °C. The experimental apparatus has been schematically presented in [25]. The magnetic field distribution together with the field gradient along the vertical direction was measured with a magnetic fluxmeter (HT700SP, Shanghai YAHAO). The furnace consisting of non-magnetic materials has negligible influence on the magnetic field distribution [17]. There were mainly two procedures for the experiments: (i) The alloy was first heated to 700 °C at a rate of 5 °C/min in or outside the strong magnetic field and kept for around 30 min to ensure full melting of the sample; (ii) The sample was cooled down in the furnace (at −10 °C/min, the cooling rate however was noticed slower below ∼500 °C) to room temperature in or outside the superconducting magnet.

The phase diagram is shown in Fig. 1. During the experiments, the Al–Cu alloy with 50 wt.% copper is used to investigate the strong magnetic field effect on the morphology of the θ-Al_2Cu phase. The presence of a small amount of eutectic phase makes it easier to observe the magnetic field effects. At an increased Al content, the influence of the eutectic on the behavior of primary θ-Al_2Cu phase becomes stronger. In order to obtain detailed information of the strong magnetic field effects on solidification, a 38 wt.% copper alloy is used and the magnetic field effect on eutectic growth, together with the phase is examined.

2.2. Materials characterizations

The specimens (9 mm in diameter and 12 mm in height) were cut along the longitudinal or transverse direction with respect to the magnetic field. After polishing, the specimens were analyzed by scanning electron microscopy (SEM, XL30-FEG, FEI, the Netherlands) with energy dispersed X-ray detector. X-ray diffraction (XRD, Seifert 3003T/T, Germany) and electron back-scattered diffraction (EBSD, EDAX, the Netherlands) were used to evaluate the texture and microstructure of the sample. To investigate the mechanical properties, the Vickers micro-hardness (HV0.3) of the θ-Al_2Cu phase was measured (Model FV = 700, Future-Tech Corp., Japan) on carefully polished sample surfaces with an indentation load of 0.3 kg.

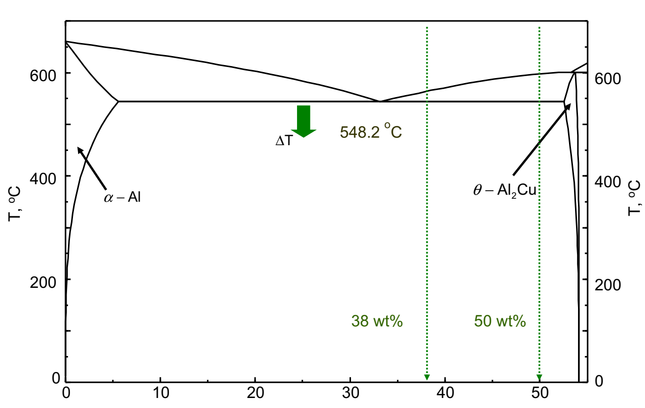

Fig. 1. Phase diagram of Al–Al_2Cu (obtained via Factsage software). During the experiments, two compositions, 38 wt.% and 50 wt.% Cu, were selected to investigate the strong magnetic field effect on the solidification behavior of θ-Al_2Cu phase. T indicates temperature and ΔT is the undercooling with respect to the eutectic temperature.

3. Results and discussion

3.1. Effect of magnetic flux density on alignment of Al_2Cu phase in a strong magnetic field

During the solidification of a hypereutectic Al–Cu alloy, the θ-Al_2Cu phase precipitates from the liquid bulk as the primary solid phase. Since the nucleation and growth are both energy dependent [13], the behavior of primary θ-Al_2Cu phase during solidification can be influenced by an external magnetic field. Subsequently, the eutectic (Al and θ-Al_2Cu) formation may also be modified. To illustrate the strong magnetic field effects on the θ-Al_2Cu phase, Al-50 wt.% Cu alloy samples were solidified under different magnetic fields. Fig. 2 provides the representative back-scattered electron images of the samples solidified in different magnetic fields. With increasing magnetic flux density, a clear alignment of the θ-Al_2Cu phase is observed. Without a magnetic field, the θ phase (bright area in Fig. 2(a)) exhibits a chessboard-like morphology and a full-developed facet structure. The θ phase as well as the eutectic distributes randomly through the sample and the facet morphology of the θ phase may make the material brittle. In a magnetic field of 1 T, no clear alignment can be observed and the morphology difference is not obvious when compared with the sample solidified outside the magnetic field (Fig. 2(a) and (b)). Even in a magnetic field of 5 T, the alignment cannot be easily distinguished by morphological comparison (Fig. 2(c)). When the magnetic field reaches 12 T, the magnetic field alignment becomes very obvious morphologically and parallel stripes of θ phase and eutectic are observed (Fig. 2(d)). However, these results cannot give a full image of the magnetic field induced alignment since the magnetic alignment depends significantly on the crystallography of the Al_2Cu phase. In order to perform a further evaluation on the alignment, the X-ray diffraction (XRD) patterns of cross-sections of samples were measured after different magnetic field treatment (Fig. 3).

3.2. Morphological and crystallographic alignment of Al_2Cu phase

As shown in Fig. 3, the intensities of the 1 1 0 and 2 2 0 peaks become stronger by increasing the magnetic flux density which is in line with the literature [21,26] where the *c*-axis of the θ-Al_2Cu is found to be aligned parallel to the magnetic field. In order to have an overview of the magnetic alignment, the XRD patterns of different cross-sections were checked for the sample treated in a 12 T magnetic field and are given in Fig. 4. It indicates that all $hk0$, $h00$ and $0k0$ peaks are expected for a longitudinal cross-section when the *c*-axis is aligned. In the cross section 1 and cross section 2, this conclusion can be emphasized and the XRD pattern is related to the specific cross section. In the vertical cross section, $00l$ is almost the only detectable peak indicating *c*-axis of the θ-Al_2Cu crystal is well aligned. If we further compare Fig. 3 and Fig. 4, the cross section dependence of the XRD pattern is more obviously viewed. For instance, in the XRD patterns of Fig. 3, the 2 0 0 peak becomes invisible for the sample treated in 5 and 12 T magnetic fields. Mainly two reasons can be provided based on the above analyses:

(i) The XRD patterns are dependent on the cross-section of the sample (cross-sections taken in Fig. 4 are different from the cross-sections in Fig. 3); a remarkable difference is observed between different longitudinal cross-sections.

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