Wang, Z.; Huang, Y.; Srinivasan, A.; Liu, Z.; Beckmann, F.; Kainer, K.U.; Hort, N.:

Experimental and numerical analysis of hot tearing susceptibility for Mg–Y alloys

In: Journal of Materials Science (2013) Springer

DOI: 10.1007/s10853-013-7712-z

Experimental and numerical analysis of hot tearing susceptibility for Mg-Y alloys

Zhi Wang[1,2], Yuanding Huang[1], Amirthalingam Srinivasan[1,3], Zheng Liu[2], Felix Beckmann[4], Karl Ulrich Kainer[1], Norbert Hort[1]

1 MagIC-Magnesium Innovation Centre, Helmholtz-Zentrum Geesthacht, Max-Planck-Str. 1, 21502 Geesthacht, Germany

2 School of Materials Science and Engineering, Shenyang University of Technology, Shenyang 110870, China

3 National Institute for Interdisciplinary Science and Technology (CSIR), Trivandrum 695019, India

4 Institute of Materials Research, Helmholtz-Zentrum Geesthacht, Max-Planck-Str. 1, 21502 Geesthacht, Germany

Abstract: The influences of Y content and initial mold temperatures on the hot tearing susceptibility (HTS) of binary Mg-Y alloys were investigated using a constrained rod casting (CRC) apparatus, which is equipped with a load cell and data acquisition systems. The hot crack formation was monitored during CRC experiments. The experimental results show that HTS first increases with increase in the Y content, reaches the maximum at about 1.5 wt.% Y and then decreases with further increase in the content of Y. The severest of hot tearing is found in Mg-1.5 wt.% Y alloy which is due to its large columnar grain structure, wide solidification range and small amount of eutectic. The resistance to hot tearing is apparently improved by increasing the initial mold temperature. ProCAST simulation software was used to predict the hot tearing of Mg-Y alloys in CRC. The simulation results show a good agreement with the experimental measurements. The numerical simulations will be helpful and valuable to optimize the alloy composition and casting parameters to minimize the hot tearing defects.

Keywords: Mg-Y alloys, Microstructure, solidification, Hot tearing

1 Introduction

Hot tearing, also known as hot cracking or solidification cracking, is often a major defect in alloy castings [1]. Hot tearing occurs due to the obstructed contraction of solidifying material, often at a location of stress concentration associated with a sudden change in the transverse cross section. Hot tearing has been investigated extensively by various methods [2-5]. So far, the investigations on hot tearing are mainly focused on steels and Al alloys [6-7]. Recently, Eskin et al. reviewed the hot tearing behavior in Al alloys [8]. In contrast, only few works were reported on the hot tearing of Mg alloys.

For the hot tearing of Mg alloys, most of previous studies were carried out only on Mg-Al and Mg-Zn series. Cao et al. [9] performed a detailed work on the HTS of Mg-Al alloys with the content of Al from 0.25 to 8 wt.% Al (using CRC) in a steel mold. The maximum cracking susceptibility was found to be around Mg-1Al. They also surveyed the effects of alloying elements such as Ca on the HTS of Mg-Al alloys [4]. Their results demonstrated that the HTS decreases significantly with increasing Ca content due to the improved castability. The hot cracking mechanism of Sr addition to Mg-6Al-0.5Mn alloy was studied by Li et al. [10]. They showed that the HTS of Mg-6Al-0.5Mn alloy decreases with an increasing Sr content. The reason is that the addition of Sr not only decreases the eutectic temperature and depresses the tendency of divorce eutectic but also refines the grain and improves the filling capacity. Zhou et al. [11] used thermodynamic calculations and quantitative methods to evaluate the hot tearing of Mg-Zn alloys. They found that the hot tearing of these alloys is largely influenced by the content of Zn and mold temperature. The influence of Zn content on the HTS follows the "λ" shape. The increment in the mold temperature alleviates the hot tearing.

The theoretical predictions of hot tearing mainly include a hot tearing indicator (HTI) [12] and a viscoplastic deformation model [13]. Zhu et al. developed a hot tearing indicator based on the accumulated plastic strain at the last stage of solidification. This model has been integrated in commercial software ProCAST [12]. They predicted the HTS of Mg-Al alloys using this model and their predictions agreed well with the experimental results.

Considering the fact that the element Y plays a very important role in modifying the properties of Mg alloys [14-16], the investigations on the effects of Y on HTS of Mg alloys should be very interesting. The purpose of the present study is to assess the HTS of Mg-Y alloys with respect to Y content and mold temperatures. In addition, the HTS of Mg-Y is predicted using HTI in ProCAST software. The predicted results are validated with the experimental measurements.

2 Experimental procedures

2.1 Hot tearing tests

The system to evaluate the hot tearing based on the measurement of contraction force was developed by Zhen et al. [5]. The details about the apparatus are given elsewhere [17]. In the present investigation, three binary Mg-Y alloys containing 0.2, 1.5 and 4 wt.% Y were melted. 350 g of pure Mg alloy was molten in a mild steel crucible under a protective gas mixture of high pure Ar+0.2% SF_6. Pure Y was added to the melt at 700 °C. The molten metal was stirred at 80 rpm for 2 min and holding for 5 min before poured into the CRC mold at a melt temperature of 750 °C, which was coated with a thin layer of boron nitride. The mold was preheated to temperature (T_{mold}) of 250 and 450 °C. The castings were removed from the mold after complete solidification and cooling, and then examined for cracks. The geometry of the cast component is shown in Fig. 1. The actual chemical compositions of the casting were analysed using optical emission spectroscopy (OES) (Spectroflame, Spectro, Kleve, Germany) (Table 1). Each hot tearing test was repeated for three times. During solidification, the cooling curve and the force as a function of time were recorded by the computer. They were processed to obtain the important information such as the critical temperature at which the hot tearing occurred [5, 11]. The corresponding solid fraction was calculated using Pandat thermodynamic software with Scheil solidification model.

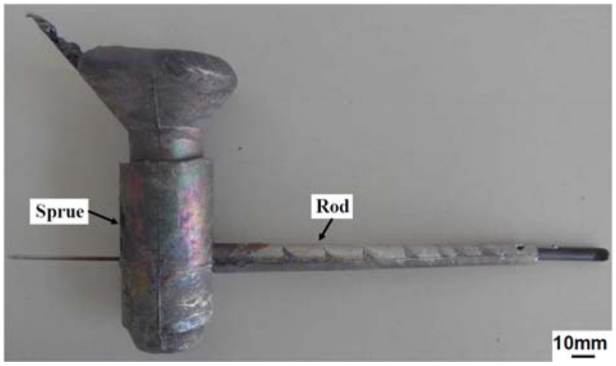


Fig. 1 Photograph showing the casting for HTS studies.

Table 1 Actual chemical compositions of experimental alloys (wt.%)

Alloy	Y	Mn	Si	Fe	Mg
Mg-0.2Y	0.22	0.034	0.018	<0.01	Bal.
Mg-1.5Y	1.44	0.032	0.107	<0.01	Bal.
Mg-4Y	3.58	0.030	0.007	<0.01	Bal.

2.2 Microstructural observations

The morphologies of grains and cracks of the castings were observed on the samples taken from the regions near the hot spot. The samples were ground and polished, and then chemically etched in a solution of 8 g picric acid, 5 ml acetic acid, 10 ml distilled water and 100 ml ethanol. Their microstructures were observed using Reichert-Jung MeF3 optical microscope with a digital camera attachment. A Zeiss Ultra 55 (Carl Zeiss GmbH, Oberkochen, Germany) Scanning Electron Microscope (SEM) equipped with Electron Dispersive Spectrometer (EDS) was also used to observe the fracture surfaces and the crack propagations.

The HTS were characterized by the measurements of crack volume using X-ray micro-tomography with an X-ray tube-based high resolution tomography (*nanotom® s* - phoenix, GE Measurement & Control Solutions, Germany). X-ray micro-tomography is a non destructive and three-dimensional characterization method that has been applied to a number of fields within materials science [18-19]. The technique allows imaging the internal microstructural features by measuring variations in intensity of a transmitted X-ray beam through a rotating specimen. The principle is to obtain a sequence of X-ray projections of the sample containing crack as it rotates around an axis perpendicular to the beam of the X-ray radiation. By using *datos|x2.0 reconstruction* software (phoenix, GE Measurement & Control Solutions, Germany), three dimensional volume of the sample can be reconstructed from these two dimensional projections. The resolution achieved after reconstruction of the volume in the region of interest was of about 20 µm. The advantage of this method is that the crack volume can be measured accurately. The two samples for each alloy were evaluated and average crack volume is presented.

3 Results

3.1 Hot tearing curves

Fig. 2 shows the experimental hot tearing curves of Mg-Y alloys with different contents of Y at different mold temperatures. The force drop on the force curve is observed near the solidus temperature. It corresponds to the occurrence of hot tearing. The detailed characterization of hot tearing curves, including the definition of hot tearing initiation and crack propagation, can be found elsewhere [11, 20]. As shown in Fig. 2, for all hot tearing tests, when the pouring starts, the temperature increases suddenly and the force drops slightly. This may be caused by the molten melt pressure that hit the stud which was connected to the load cell as the melt entered from sprue into the rod relatively fast, due to the sudden change in the cross sections.

The hot tearing initiation temperatures depend on the alloy composition. For Mg-0.2 wt.% Y alloy at a mold temperature of 250 °C, the hot crack initiates at 605.8 °C which corresponds to a solid fraction of 0.997 (Fig. 2 (a)). However, no force drop occurred in the force curve of Mg-1.5 wt.% Y alloy. In this case, according to Huang et al [21], the initiation of hot tearing can be identified by locating the point on the force curve at which the force as a function time changes from linear increment to non-linear. Hence the initiation temperature of hot tearing for Mg-1.5 wt.% Y alloy is found to be 616.6 °C. This temperature corresponds to a solid fraction of 0.956. This result is in line with the well established knowledge that hot tearing normally occurs at the latest stage of solidification when an approximation of 5% liquid is left [22]. Likewise, the initiation temperature of hot tearing for Mg-4 wt.% Y alloy is also determined using the above mentioned method and its corresponding solid fraction is 0.918.

The force drop stage on the hot tearing curves can be regarded as the hot crack propagation for all castings [5, 11]. Compared with the tests with low mold temperature, the force drops are not so apparent at high mold temperature (450 °C). For example, the force curve of Mg-1.5 wt.% Y alloy does not show an apparent force drop at high mold temperature (Fig. 2 (d)), indicating that no visible hot cracks occurred. This is in good agreement with the microstructural observation (discussed later).

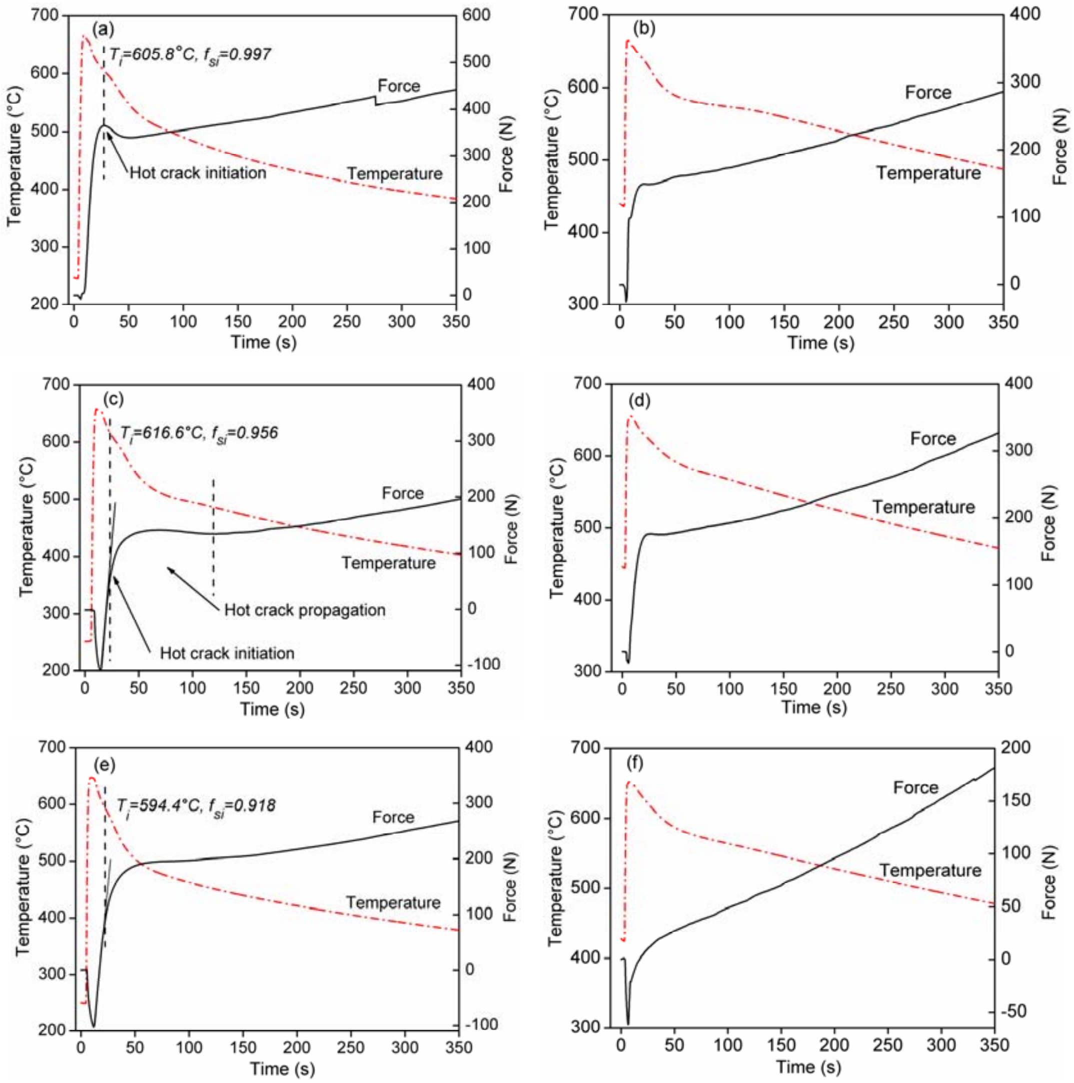


Fig. 2 Contraction force and temperature as a function of time for Mg-Y alloys at different mold temperatures: (a) Mg-0.2 wt.% Y, T_{mold}=250 °C; (b) Mg-0.2 wt.% Y, T_{mold}=450 °C; (c) Mg-1.5 wt.% Y, T_{mold}=250 °C; (d) Mg-1.5 wt.% Y, T_{mold}=450 °C; (e) Mg-4 wt.% Y, T_{mold}=250 °C; (f) Mg-4 wt.% Y, T_{mold}=250 °C.

3.2 Microstructure and crack morphology

Fig. 3 shows the optical microstructures of binary Mg-Y alloys taken from the region near the junction of the sprue and the horizontal rod at different mold temperatures. At low mold temperature, the microstructure changes from columnar grains to equiaxed grains with increasing the content of Y. Mg-1.5 wt.% Y alloy exhibits both columnar grain and coarse equiaxed grains (Fig. 3 b). Equiaxed grains are dominant in Mg-4 wt.% Y alloy (Fig. 3 c). The grain sizes of Mg-0.2 wt.% Y and Mg-1.5 wt.% Y alloys decrease as the mold temperature increases from 250 to 450 °C. At low contents of Y, cellular or/and columnar grains dominate. Whereas Mg-4 wt.% Y alloy exhibits a coarse equiaxed grain due to the low cooling rate and the high solute content. Compared with low mold temperature, the primary cellular grain sizes decreases with increasing in the mold temperature at low contents of Y.

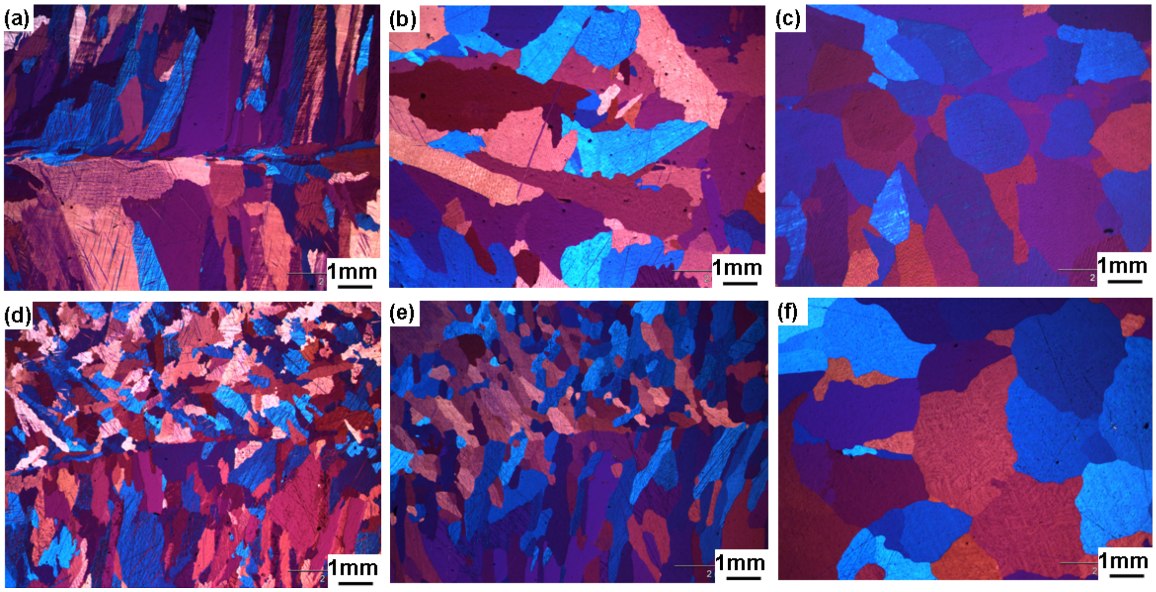


Fig. 3 Optical microstructures of binary Mg-Y alloys showing the grain structures at different mold temperatures: (a) Mg-0.2 wt.% Y, T_{mold}=250 °C; (b) Mg-1.5 wt.% Y, T_{mold}=250 °C; (c) Mg-4 wt.% Y, T_{mold}=250 °C; (d) Mg-0.2 wt.% Y, T_{mold}=450 °C; (e) Mg-1.5 wt.% Y, T_{mold}=450 °C; (f) Mg-4 wt.% Y, T_{mold}=450 °C.

Fig. 4 shows calculated slices through the reconstructed volume obtained by X-ray tomography. The alignment of the slices is chosen to represent the crack morphology at the longitudinal cross sections of the samples near the sprue-rod junction of Mg-Y alloys castings.

No cracks are observed in Mg-0.2 wt.% Y alloy at low mold temperature. However, there are severe cracks can be found in Mg-1.5 wt.% Y alloy. In this sample, the initiation of hot cracks at the junctions can clearly be traced down towards the center of the rod, in a direction almost perpendicular to the main axis of the rod. Compared with Mg-1.5 wt.% Y alloy, the amount of cracks decreases in Mg-4 wt.% Y alloy. In this alloy, few white river patterns are noticed along with tears. These river patterns are due to the high X-ray absorption compared to the Mg matrix. EDS analysis indicates that these regions are eutectic phases with high content of Y (Fig. 5). In Mg-4wt.%Y alloys, the content of Y in the white region can reach to 31.81wt.%. Another interesting phenomenon is that with increasing the Y content the amount of white river patterns increases. They are normally observed near the main cracks. Moreover, most of the hot cracks locate near the surface. At the higher mold temperature few small cracks are observed. The results reconfirm that increasing in the initial mold temperature decreases the HTS.

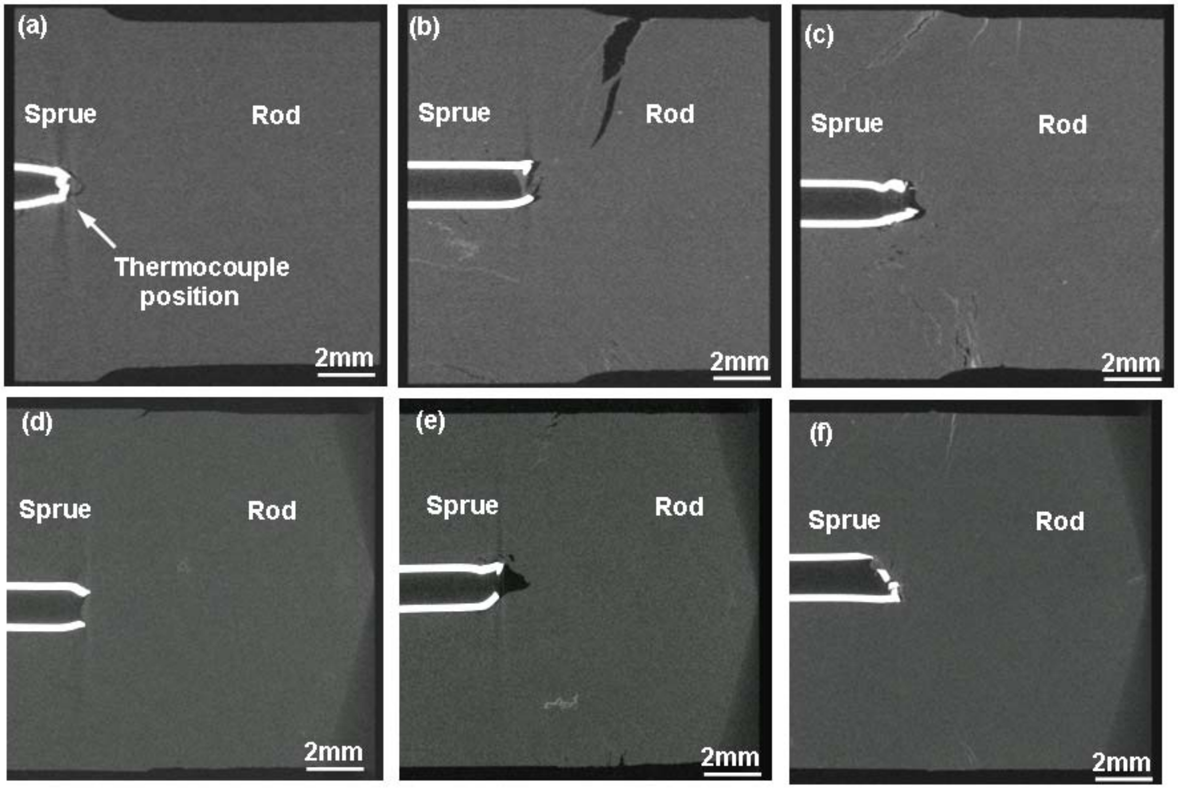
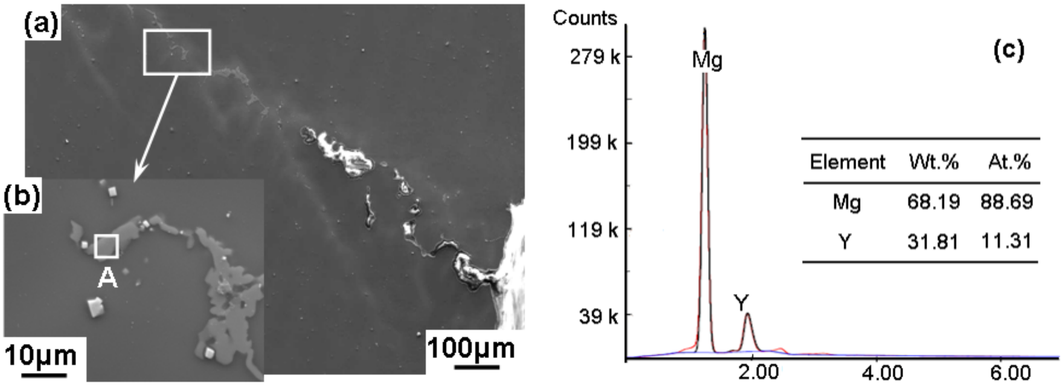


Fig. 4 X-ray photographs of Mg-Y alloys showing crack morphologies at different mold temperatures: (a) Mg-0.2 wt.% Y, T_{mold}=250 °C; (b) Mg-1.5 wt.% Y, T_{mold}=250 °C; (c) Mg-4 wt.% Y, T_{mold}=250 °C; (d) Mg-0.2 wt.% Y, T_{mold}=450 °C; (e) Mg-1.5 wt.% Y, T_{mold}=450 °C; (f) Mg-4 wt.% Y, T_{mold}=450 °C.



Element	Wt.%	At.%
Mg	68.19	88.69
Y	31.81	11.31

Fig. 5 As-cast microstructure of Mg-4 wt.% Y alloy at a mold temperature of 450 °C: (a) SEM image, (b) magnified view of second phase and (c) EDS analysis for the point A in (b).

3.3 Quantitative measurement of hot tearing

The HTS is usually assessed by the length and width of open cracks observed on the surfaces of casting [4, 9]. The disadvantage of this method is that the closed cracks inside the casting cannot be counted. Thus, the measured values are not so accurate. To overcome this shortness, in the present study, the HTS of alloys is characterized using the total volume of cracks measured by X-ray tomography. Table 2 shows the results for Mg-Y alloys at mold temperatures of 250 and 450 °C. The total crack volume depends on the content of Y and mold temperatures. For both mold temperatures, the crack volumes increase with the increment in the content of Y, reaches to a maximum at about 1.5 wt.% Y and then reduces with further increasing in the content of Y. The crack volume of Mg-0.2 wt.% Y alloy is 0.42 mm^3 at a mold temperature of 250 °C. When the content of Y increase to 1.5 wt.% Y, the crack volume is 18.11 mm^3. Further increasing Y content to 4 wt.% Y, decreases again to 3.16 mm^3. Table 2 also suggests that the volume of hot cracks decrease with increasing in the initial mold temperature. For example, the crack volume of Mg-1.5 wt.% Y alloy decreases from 18.11 to 1.18 mm^3 as the mold temperature increases from 250 to 450 °C. This is due to the fact that the cooling rate becomes slower, and then leads to a smaller thermal gradient at higher mold temperatures.

Table 2 Total crack volumes measured by X-ray micro-tomography for Mg-Y alloys at different mold temperatures.

Alloys	Mold temperature (°C)	Crack volume (mm^3)
Mg-0.2 wt.% Y	250	0.42
	450	0.15
Mg-1.5 wt.% Y	250	18.11

	450	1.18
Mg-4 wt.% Y	250	3.16
	450	0.07

4 Numerical description

4.1 Hot tearing indicator

The HTI is a strain-driven model based upon the total strain which develops during the solidification. The model is computing the elastic and plastic strains at a given node when the fraction of solid is between the critical solid fraction (usually 50%) and 99%. It was proposed based on Gurson's constitutive model [23], which was developed for studying the progressive micro-rupture through nucleation and growth of micro-voids in the material of ductile and porous solids. In order to describe the material behavior in the semi-solid state, a modified Gurson's constitutive model was used for the HTI [12, 23-26]. After assuming that the casting is isotropic (although at the final stage of the solidification, the castings may exhibit localized anisotropic behavior), the HTI (e_{ht}) was estimated as follows:

$$e_{ht} = \bar{\varepsilon}_{ht}^{p} = \int_{t_c}^{t} \sqrt{\frac{2}{3}\dot{\varepsilon}^{p} : \dot{\varepsilon}^{p}}\, d\tau \,, \qquad t_C \le t \le t_S \tag{1}$$

where $\bar{\varepsilon}_{ht}^{p}$ is the critical accumulated effective plastic strain for the initiation of hot tearing, $\dot{\varepsilon}^{p}$ is the effective plastic strain rate, t_C represents the time when the coherency temperature is reached, and t_S denotes the time when the solidus temperature is reached. In fact, as shown by Equation (1), HTI is the accumulated plastic strain in the semi-solid region that corresponds to the void nucleation. Therefore, it should provide a good indication for the susceptibility of the hot tearing occurred during solidification.

4.2 Geometry and mesh

The model includes four assembled parts: mold, casting, steel rod and graphite stopper. The geometry used in the simulation including the thermocouple (TC1) location is shown in Fig. 6. The figure showing dimensions is a mid-plane view of the casting. All dimensions are given in mm. The overall dimensions are:

- Length=252.5 mm
- Width=80 mm
- Height=140 mm

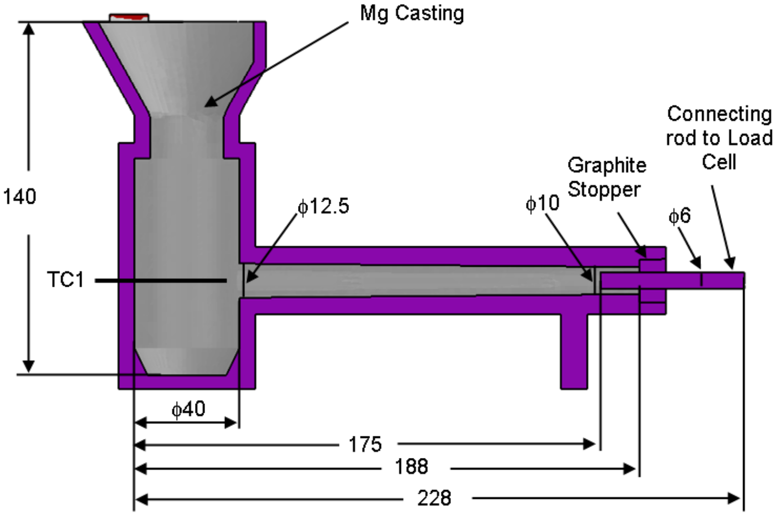


Fig. 6 Geometry of casting mold. TC means the thermocouple.

The mesh generator MeshCAST was used to construct the computational grid of the casting and mold. Construction of this mesh is an important stage in solving the subsequent problems, since it determines the accuracy of the computations and the time required for calculations. Fig. 7 shows the computational meshing of the casting and mold. Four node tetrahedron elements were chosen for meshing both the casting and mold. A finite-element mesh was chosen for the casting to increase the accuracy of the calculations. However, the mesh density was comparatively lower for the mold. The computational mesh of casting and mold consisted of 168,627 elements and 35708 nodes.

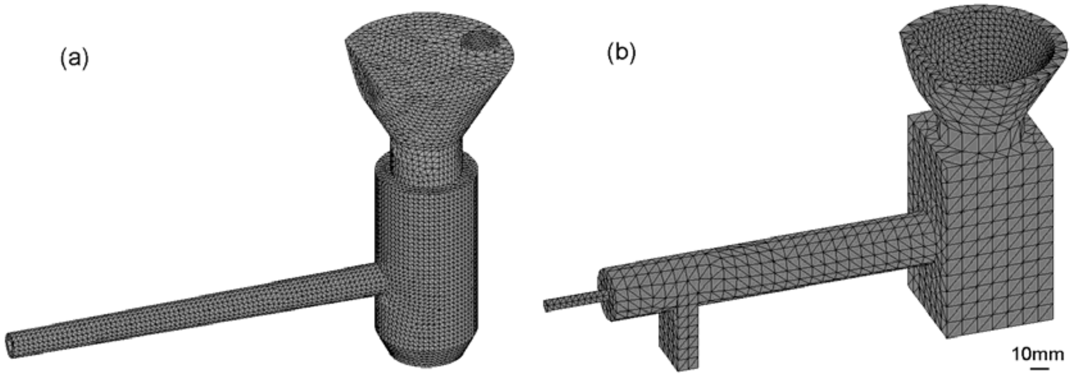


Fig. 7 Computational meshing of the casting and mold: (a) casting; (b) mold.

4.3 Material properties

The alloy composition, casting geometry, cooling history and mechanical properties of alloys influence the formation of hot tearing. In order to predict the formation of hot tearing, it is critical to have accurate data of thermophysical and mechanical properties, especially for the mushy zone, as input for complex solidification processes. ProCAST has a thermodynamic database to calculate these properties. Thus, it is possible to compute the enthalpy curve, density, viscosity and thermal conductivity based upon the chemical composition. Typical calculated thermophysical and thermodynamic properties for Mg-1.5 wt.% Y alloy are shown in Fig. 8 and Fig. 9, respectively. All these properties were function of temperature. The solidification path was obtained using Scheil solidification model in Pandat. During the simulation using ProCAST, the castings were assumed to be solid undergoing elasto-plastic deformation.

In the assembly of model, the mold and steel rod were assigned steel_H13 and stopper was assigned graphite. The material properties of steel_H13 and graphite were taken from the materials database in ProCAST. The models Rigid and Vacant were used for the mold. An elasto-plastic stress model was used for the casting.

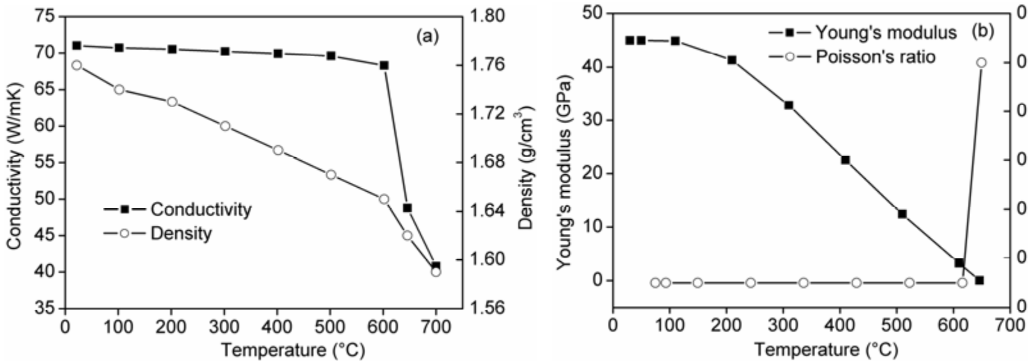


Fig. 8 Thermophysical properties of the Mg-1.5 wt.% Y alloy: (a) thermal conductivity and density, (b) Young's modulus and Poisson's ratio.

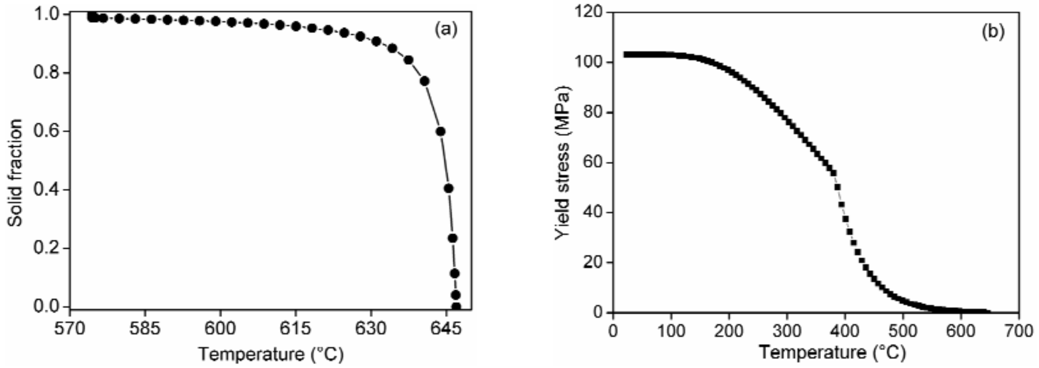


Fig. 9 Thermodynamic and thermophysical properties of the Mg-1.5 wt.% Y alloy: (a) solidification path, (b) yield stress as a function of temperature.

4.4 Boundary and initial conditions

The following boundary and initial conditions were assigned:

- All components of the model, except the casting, were assigned as constrained by applying zero displacements in all directions. Zero displacement in the y direction was assigned to the rod end of the casting.
- Heat transfer coefficient of 500 W/(m^2*K) was applied in the casting-mold interface.
- Air cooling by convection of 10 W/(m^2*K) was applied to all surfaces which were in touch with the surrounding air. The ambient temperature of the surrounding air was assumed 20°C.
- The preheated mold temperature was assigned as 250 or 450°C.
- A gravity of 9.8 m/s^2 was applied to the casting which kept the bottom surface in contact with the mold.

4.5 Run of the calculation and viewing of results

ProCAST allows a unique coupling between thermal, flow and stress calculations. In the present simulation, the full analysis is performed simultaneously on the same mesh. The results of temperature, solid fraction and HTI fields are viewed or exported into the post-processor Visual-CAST after computation. These results are used to analysis the hot tearing formation.

5 Numerical results

5.1 Temperature field

Fig. 10 shows the temperature fields for the casting of Mg-1.5 wt.% Y alloy with an initial mold temperature of 250 °C. The shown view is a mid-plane slice of the casting in the X-direction. Results are shown at the following times: (a) immediately after filling, (b) at a total solid fraction of 0.6, (c) at a total solid fraction of 1, and (d) at the end of the simulation. These results show that over time the casting cools down until it completely solidifies. The temperature continuously decreases till the end of the simulation. A relatively large temperature gradient is observed near the junction between the sprue and horizontal rod. The sprue and rod are fairly isothermal, but the temperature of sprue is consistently higher than that of the rod. These differences in temperatures at the junction between the sprue and rod lead to large thermal strains, and hence, the formation of hot tear occurs.

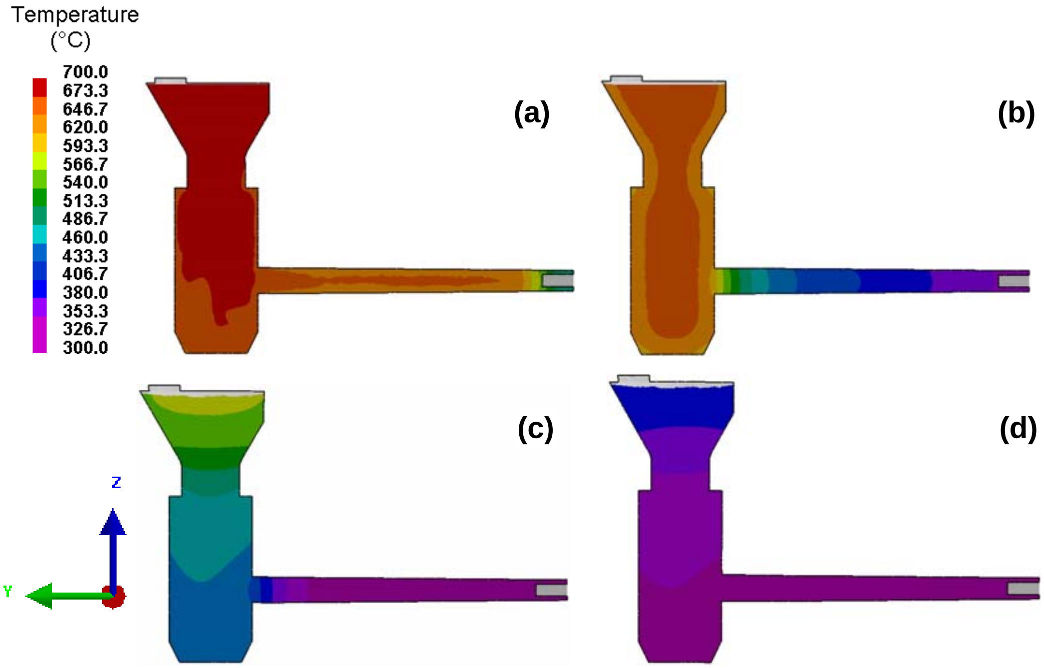


Fig. 10 Temperature field for the Mg-1.5 wt.% Y alloy with an initial mold temperature of 250 °C: (a) Immediately after filling, (b) At a total solid fraction of 0.6, (c) At a total solid of 1, (d) At the end of the simulation

5.2 Hot tearing indicator

Fig. 11 shows a comparison between the predicted HTI and the observed cracks on the surfaces of Mg-Y alloys at different initial mold temperatures. The observations of cracks indicate that the hot tearing normally occurs at the sprue-rod junction. Both the location and severity of hot tearing obtained from simulations match well with the experimental results. The value of HTI increases when the content of Y increases from 0.2 to 1.5 wt.%, and then decreases with further increase in the content of Y. In addition, for the alloys with same composition, HTI reduces with the increment in mold temperature.

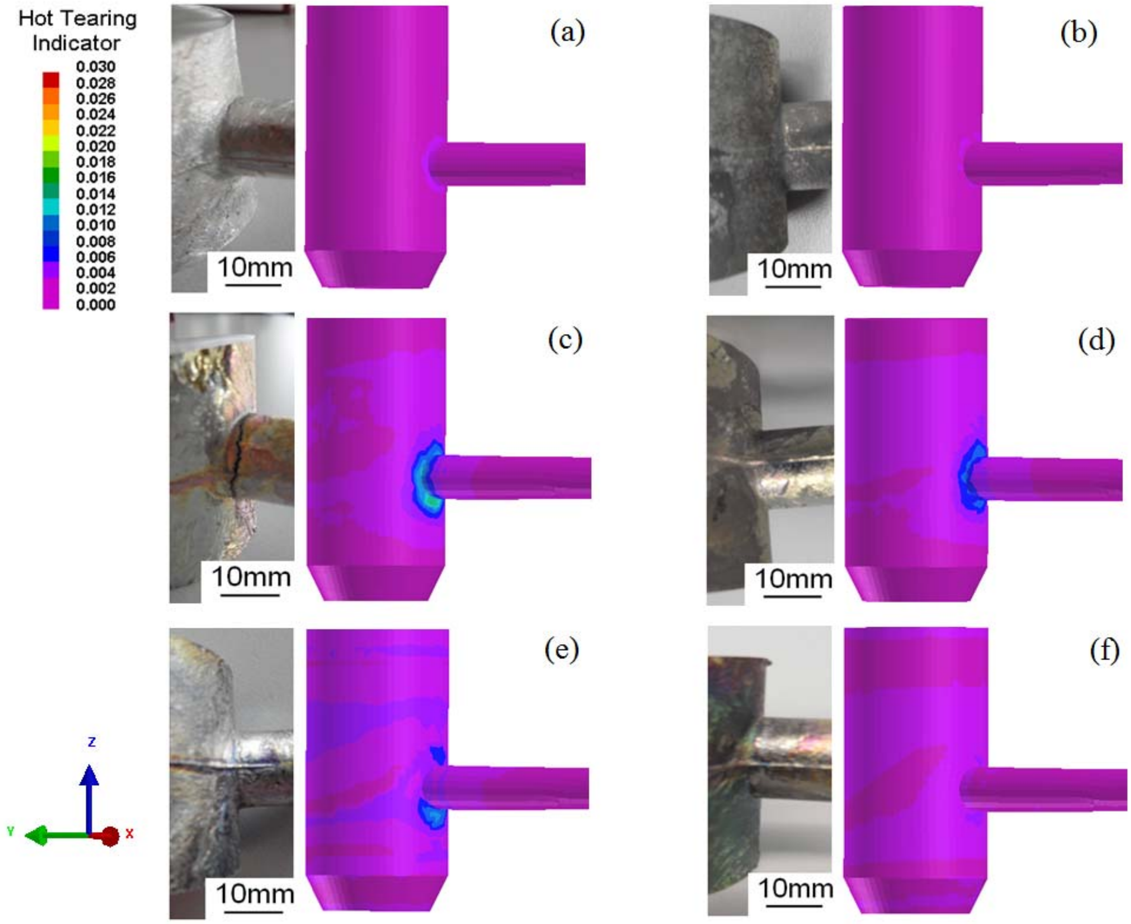


Fig. 11 Comparison between the simulated HTI and observed cracks on the surfaces of Mg-Y alloys at difference mold temperatures: (a) Mg-0.2 wt.% Y, T_{mold}=250°C; (b) Mg-0.2 wt.% Y, T_{mold}=450°C; (c) Mg-1.5 wt.% Y, T_{mold}=250°C; (d) Mg-1.5 wt.% Y, T_{mold}=450°C; (e) Mg-4 wt.% Y, T_{mold}=250°C; (f) Mg-4 wt.% Y, T_{mold}=250°C.

6 Discussion

6.1 Influences of Y content on HTS

The HTS of Mg-Y alloys is influenced by the content of Y in two ways: solidification range and microstructure. Clyne and Davies' thermodynamic model is useful tool to predict the HTS for binary systems [27]. Their prediction is based on the critical solidification time during which the alloy is vulnerable to cracking. The alloy with a wide solidification range has a high hot tearing tendency because it spends a longer time in the vulnerable zone. Normally, the HTS is proportional to the solidification range, especially the vulnerable solidification region which is defined as the temperature range ΔT between the temperatures at which the solid fraction is 0.90 ($T_{0.9}$) and 0.99 ($T_{0.99}$):

$$\Delta T = T_{0.9} - T_{0.99} \quad (2)$$

The larger the value of ΔT, the higher the HTS. Fig. 12 shows the “solid fraction as a function of the temperature” f_s/T in the range of solid fraction from 0.7 to 1.0 for Mg-Y alloys. Mg-1.5 wt.% Y alloy has a much higher ΔT than other alloys (Fig. 12). Hence based on the Clyne and Davies’ model, it has a higher HTS, which matches well with the experimental results.

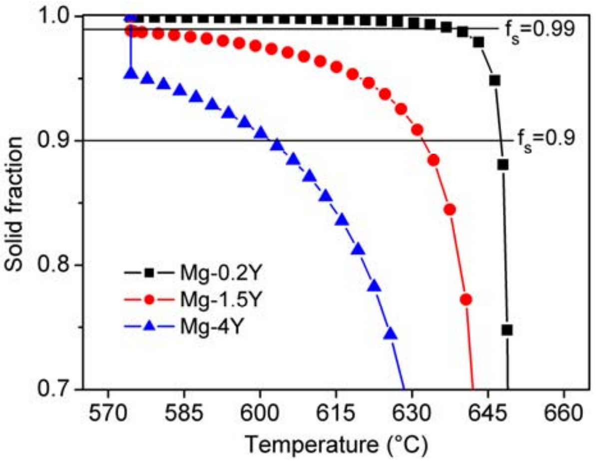


Fig. 12 Solid fraction vs. temperature for Mg-Y alloys calculated using Scheil’s model.

The critical solid fraction at which the hot tearing initiates depends on the content of Y (Fig. 2). It decreases from 0.997 to 0.918 with increasing the content of Y from 0.2 to 4 wt.%. As shown in Fig. 12, the solid fraction increases sharply at the beginning of solidification, and slows down near the solidus temperature. For the alloys with low contents of Y, like Mg-0.2 wt.% Y alloy, the solid fraction increases rapidly below its liquidus temperature. In that case, the strains due to thermal contraction build up and impose on the casting at a high solid fraction. When the accumulated strain exceeds the critical value, the cracking is induced. In contrast, the solid fraction of alloys with high Y content increases relatively slowly. The solid fraction at which the hot tearing initiates is well below 1 (0.918 for Mg-4Y alloy).

The grain morphology is regarded as one of the most important factors to influence the initiation of hot tearing [28, 29]. The addition of Y in Mg affects its grain morphology. The high HTS of Mg-1.5Y alloy is related to its coarse and columnar grains. Normally, the large grains with a columnar shape promote the formation of hot tearing. Mg-1.5 wt.% Y alloy casting exhibits severe open crack across the rod (Fig. 4 (b)). Conversely, a fine grain with equiaxed structure enhances the feeding ability of liquid metal. The thermal strain can be accommodated, and hence the initiation of hot tearing is avoided [28].

6.2 Influences of mold temperatures on HTS

As aforementioned, the HTS of Mg-Y alloys is also influenced by the initial mold temperatures. The HTS decreases with increasing the mold temperature from 250 to 450 °C. This reduction may be attributed to a number of factors as follows. The low mold temperature leads to a larger thermal gradient and high contraction stress imposed on the solidifying casting. Based on the strain theory proposed by Pellini [30-31], the initiation of hot tearing depends on the strain rate developed in the liquid film regions. Generally, the hot tearing resistance decreases with increasing the strain contraction rate. Thus, an elevated mold temperature reduces the HTS by lowering the strain contraction rate. The lower strain rate provides an opportunity for the casting to recover for such a strain through microscopic movements of the dendrite cells or liquid metal; however, similar compensation may not be possible at a high strain rate.

Fig. 2 (c) and (d) show the experimental cooling curves of Mg-1.5 wt.% Y alloy at different mold temperatures. The cooling rate was calculated using the whole solidification range divided by the corresponding solidification time. Faster solidification leads to a larger thermal gradient at the sprue-rod junction, which is considered as one important criterion for the initiation of hot tearing. According to the cooling curves, the cooling rates of Mg-1.5 wt.% Y alloy are 4.24 °C/s at a mold temperature of 250 °C and 0.81 °C/s at 450 °C. It is known that the temperature differences between various parts of the casting can cause internal contraction stress. In addition, the temperature difference between the mold and casting can exacerbate the thermal gradient and stress. An elevated mold temperature can effectively reduce the temperature difference between the casting and mold. In that case, the distribution of solute and the solidification are close to equilibrium state. The contraction stress reduces. Therefore, an elevated initial mold temperature can decrease the HTS of alloys by reducing the cooling rate.

On the other hand, the increment in the mold temperature not only significantly reduces the cooling rate but also influences the grain size and its morphology. The changes in the microstructure definitely affect the hot tearing behavior. With elevating the mold temperature, the grain sizes become finer (Fig. 3). In those castings the cracks are minimized.

7 Conclusions

The hot tearing of binary Mg-Y alloys was investigated in an instrumented CRC mold apparatus. Following conclusions are arrived:

(1) The CRC method is successfully used to evaluate the HTS of binary Mg-Y alloys. When a hot tearing initiates, a drop in force is observed on the hot tearing curves. Its corresponding onset temperature and solid fraction can be determined using thermodynamic calculations.

(2) The HTS is affected by the content of Y. It increases with increasing the content of Y, reaches the maximum at 1.5 wt.% Y, and decreases with further additions of Y.

(3) Besides the alloy compositions, the HTS of Mg-Y alloys is also influenced by grain morphology and its size, solidification range and amount of eutectic phases. High susceptibility to hot tearing is found in Mg-1.5 wt.% Y alloy due to its large columnar grain, wide solidification range and small amount of eutectic.

(4) The increment in mold temperature from 250 to 450 °C significantly reduces the HTS of binary Mg-Y alloys. High mold temperature reduces the cooling rate resulting in a small thermal gradient and low strain rate imposed on the solidifying casting.

(5) The predictions of HTS for binary Mg-Y alloys using HTI module in ProCAST software are quite agreement with that obtained by experimental measurements.

Acknowledgements

The authors would like to thank Mr. G. Meister for the technical support, and Mrs. Petra Fischer for SEM observations. Financial supports from China Scholarship Council-Helmholtz scholarship for Wang′ s PhD study in HZG are gratefully acknowledged.

References

[1]Warrington D, McCartney D G (1989) Cast Met 2: 134

[2]Wang Y, Sun B, Wang Q, Zhu Y, Ding W (2002) Mater Lett 53: 35

[3]Suzuki A, Saddock N D, Jones J W, Pollock T M (2005) Acta Mater 53: 2823

[4]Cao G, Kou S (2006) Metall Mater Trans A 37: 3647

[5]Zhen Z S, Hort N, Utke O, Huang Y D, Petri N, Kainer K U (2009) In: Nyberg E A (ed), TMS, San Francisco: 105

[6]Martin G, Yerra S K, Bréchet Y, Véron M, Mithieux J D, Chéhab B, Delannay L, Pardoen T (2012) Acta Mater 60: 4646

[7]Nabawy A M, Samuel A M, Samuel F H, Doty H W (2012) J Mater Sci 47: 4146

[8]Eskin D G, Suyitno, Katgerman L (2004) Prog Mater Sci 49: 629

[9]Cao G, Kou S (2006) Mat Sci Eng A 417: 230

[10]Li S S, Tang B, Jin X Y, Zeng D B (2012) J Mater Sci 47: 2000

[11]Zhou L, Huang Y D, Mao P L, Kainer K U, Liu Z, Hort N (2011) In: Sillekens W H (ed), TMS, San Diego: 125

[12]Zhu J Z, Guo J, Samonds M T (2011) Int. J. Numer. Meth. Eng 87: 289

[13]Marin E B, McDowell DL (1997) Computers and Structures 63: 579

[14]Sandlöbes S, Friák M, Zaefferer S, Dick A, Yi S, Letzig D, Pei Z, Zhu L F, Neugebauer J, Raabe D (2012) Acta Mater 60: 3011

[15]Wu B L, Zhao Y H, Du X H, Zhang Y D, Wagner F, Esling C (2010) Mat Sci Eng A 527: 4334

[16]Peng Q M, Meng J, Li Y, Huang Y D, Hort N (2011) Mat Sci Eng A 528: 2106

[17]Wang Z, Huang Y D, Srinivasan A, Liu Z, Beckmann F, Kainer K U, Hort N (2013) Mater Design 47: 90

[18]Watson I G, Lee P D, Dashwood R J, Young P G (2006) Metall Mater Trans A 37: 551

[19]Alkemper J, Voorhees P W (2001) Acta Mater 49: 897

[20]Zhou L, Huang Y D, Mao P L, Kainer K U, Liu Z, Hort N (2011) Int J Cast Metal Res 24: 170

[21]Huang Y D, Wang Z, Srinivasan A, Kainer K U, Hort N (2012) Acta Phys Pol A 122: 497

[22]Campbell J (2003) Castings, Butterworth-Heinemann, Oxford, United Kingdom

[23]Gurson A L (1997) J Eng Mater-T ASME 99: 2

[24]Tvergaard V, Needleman A (1984) Acta Metal 32: 157

[25]Needleman A, Tvergaard V (1987) J Mech Phys Solids 35: 151

[26]Zhang Z L, Thaulow C, Odegard J (2000) Eng Fract Mechanics 67: 155

[27]Clyne T W, Davies G J (1981) Brit Foundryman 74: 65

[28]Easton M, Grandfield J, StJohn D, Rinderer B (2006) Mater Sci Forum 30: 1675

[29]Dahle A K, Arnberg L (1996) JOM 48: 34

[30]Pellini W S (1952) Foundry 80: 125

[31]Pellini W S, Bishop H F, Ackerlind CG (1952) Trans Amer Foundrym Soc 60: 818