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Quantitative Determination on Hot Tearing in Mg-Al Binary Alloys

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Abstract

Hot tearing, or hot cracking, is one of the most severe solidification defects commonly encountered during casting. It is such a complicated phenomenon that a full understanding is still not yet achieved, though it has been extensively investigated for decades. Most contributions are still based on qualitative characterisations. The purpose of this work is to develop a method that can quantitatively evaluate and investigate hot tearing behaviour. The principle is based on contraction stress/force measurements. The measured contraction force has been proven to be able to evaluate the hot tearing susceptibility as a more straightforward and quantitative index. By analyzing the contraction force curve, information can be obtained for both the initiation and the propagation of the hot tear. With this method, the influence of mould temperature and Al content on hot tearing behaviour of Mg-Al binary alloys has been investigated. The contraction force curves also indicate that the liquid refilling plays an important role during the hot crack propagation. With a lower cooling rate and higher onset temperature of hot tear, the remaining liquid is more favourable to refill the initiated hot crack, and consequently interrupts the propagation of cracks or possibly completely heals the cracks.

Introduction

Hot tearing (or hot cracking) is one of the most severe solidification defects commonly encountered during casting. It is such a complicated phenomenon that a full understanding is still not yet achieved, though it has been extensively investigated for decades. Most contributions are still based on qualitative characterizations [1-3]. Two experimental methods, i.e. constrained rod casting (CRC) and ring mould casting (RMC) are popularly employed. Either the total crack length/crack width, the critical rod length (CRC) or the critical ring diameter (RMC) at which no crack can be observed, are normally used as a qualitative assessment index for the hot tearing susceptibility [2]. Meanwhile, computational modelling has been introduced to predict the hot tearing, and a number of criteria had been developed [4-8]. Unfortunately, the results are not satisfying. Suyitno et al [9] evaluated eight criteria of hot tearing proposed in the previous literature by implementing them into a FE simulation of the Al-Cu DC casting process. They concluded that only one criterion is in qualitative accordance with the casting practice. The lack of quantitative knowledge suggests a need for more fundamental experimental studies on hot tearing, particularly on a quantitative basis.

So far, investigations on hot tearing are mainly focused on the steels and aluminium alloys. In contrast, only limited work had been done for magnesium alloys [10-19]. Recently, magnesium alloys have increasingly attracted interest, particularly in the automotive industry, due to magnesium's low density and high strength to weight ratio. However, the poor creep resistance at elevated temperature of commercial magnesium cast alloys, such as AZ91, has prevented their extensive applications in major powertrain components. In order to overcome this problem, the AS, AE, and MRI series were developed by modifying the AZ series with adding Si, rare earth elements (RE) or Ca [20,21]. The addition of these alloying elements, however, deteriorates castability, in particular the susceptibility to hot tearing [13,14,19,21]. In addition, expanding the range of magnesium alloy applications encourages the development of new wrought magnesium alloys with good workability. The high quality of wrought alloys, with less casting defects, is an important prerequisite for the secondary processing of these alloys. In these alloys, hot tearing behaviour, including the mechanism of formation and how to suppress the formation of tears, was also not understood. Investigations on the hot tearing of magnesium alloys are therefore highly desirable. The present work investigates the hot tearing behaviour of Mg-Al binary alloys in a quantitative way.

Experimental Setup

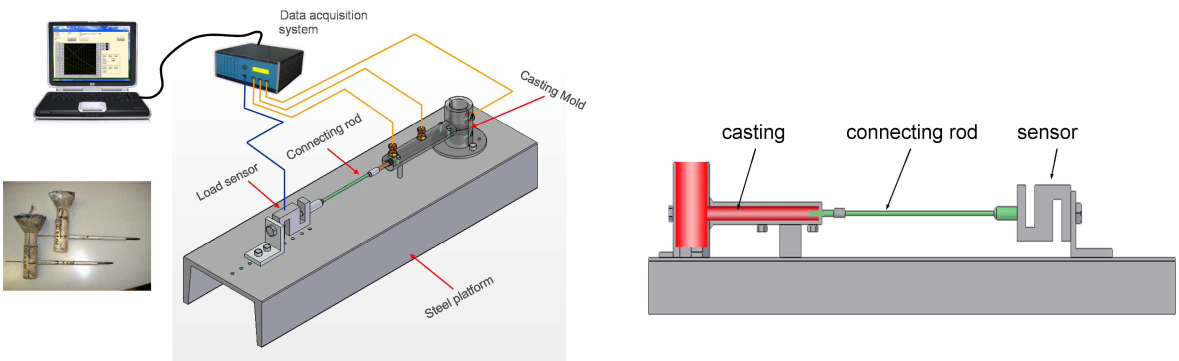
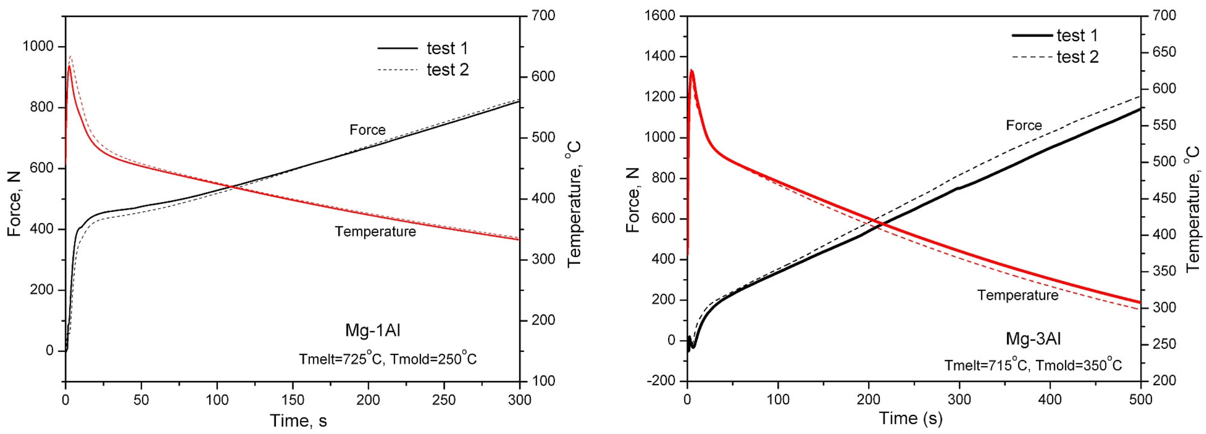


Figure 1. Schematic of the experimental setup.

Figure 1 shows a schematic of the experimental setup developed in this study. The principle of the setup is to monitor the evolution of hot tearing using the measurement of the contraction stress induced by the solidification and thermal shrinkages. When a hot tear occurs during solidification, the induced contraction stress is accordingly released. A sudden drop can be observed on the force curve. The behaviour of hot tearing can then be investigated by analyzing force development. This includes the initiation of hot tearing, the evolution and the final size of the hot crack and so on.



(a) (b)

Figure 2. Reproducibility of the new developed hot tearing susceptibility assessment process. (a) Mg-1wt.%Al, cast at 725°C with a mould temperature of 250°C; (b) Mg-3wt.%Al, cast at 715°C with a mould temperature of 350°C.

The whole system consists of a constrained rod casting mould made of steel, a contraction force measurement system with a load cell, and a data acquisition system. A similar design can be found in the works by Wang et al [22] and Cao et al [14,23]. However, in practice the friction between the solidifying casting and the inner wall of the mould will become a challenge on truly measuring the contraction stress. This friction can result in unrepeatable and confusing data. The present evaluation system successfully eliminates the influence of friction between the mould and casting rod. This makes the main difference from Wang and Cao´s apparatus. The details of the apparatus setup and the design are given elsewhere [24]. Figure 2 gives two example tests, which show very consistent results, not only the trend of the curves, but also the onset temperature of hot tearing. For instance, the onset temperatures of hot tearing for test 1 and 2 of Mg-3wt.%Al are 623.1°C and 622.4°C, respectively (Fig. 2(b)).

Experimental Procedure

A cylindrical mild steel crucible coated with BN was used for melting in an electrical resistance furnace. High purity Ar +0.2% SF_6 mixed protective gas was used for melt protection. Pure magnesium (99.9 wt.%) and aluminium (99.6 wt.%) were used as raw materials. Mg-Al binary alloys with 1, 3 and 9 % Al (nominal concentration in weight percentage) were prepared. The casting temperature was set at 80°C above the liquidus temperature for each alloy. The mould was coated with a thin layer of BN, and preheated to a temperature between 250°C and 500°C. Once the casting started the force measurement system was activated. The force, temperatures of the mould at different positions and the temperature at the hot spot area were recorded by the data acquisition system during casting [24].

Traditionally, the size of a hot crack (either the total size or the width of crack) was normally used as the index of hot tearing susceptibility. However, large errors are normally inevitable due to the fact that the depth of crack was not taken into account and also the complexity of the crack pattern. In the present work, the volume of total cracks is used to quantify the crack size. The volume of cracks was measured by a wax penetration method. The detailed procedure can be found elsewhere [25]. It is noted that only the volume of the opened cracks can be measured with this method.

The morphologies of hot tears were investigated using scanning electron microscopy (SEM) ZEISS Ultra 55. The surface of hot cracks was scanned by the detector of energy dispersive analysis (EDX). The compositions were analyzed in these areas.

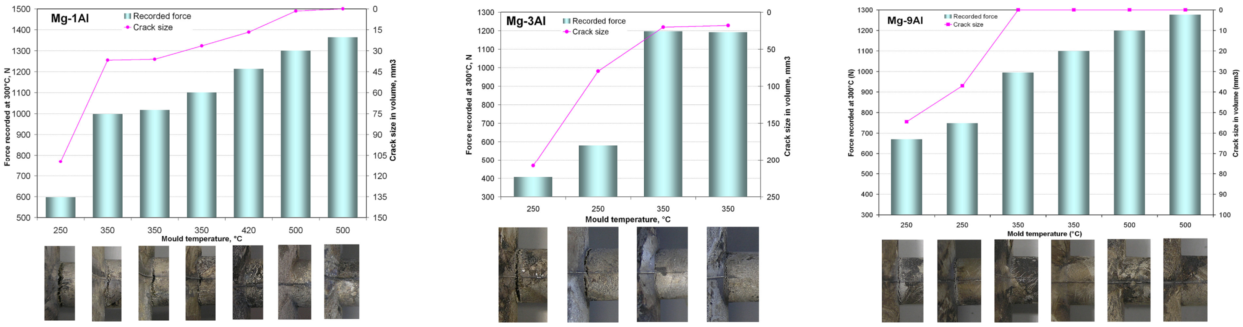
Results and Discussions

Assessment of Hot Tearing Susceptibility

The size of a hot crack has normally been used as the index of hot tearing susceptibility. The released force caused by the formation of hot tearing depends on the size of the formed crack. The larger the crack size is, the more stress is released. Therefore, it can be expected that the final force recorded after the solidification completed can inversely reflect the size of hot cracks and consequently the hot tearing susceptibility.

Figure 3 shows the results of the recorded force as the castings solidified down to 300°C for Mg-1wt.%Al, Mg-3wt.% and Mg-9wt.%Al alloys with different mould temperatures. For comparison purpose, the volume of each crack was measured by using the wax penetration method. The results are shown in Figure 3 together with a macro picture of the cracks. The results in all alloys show good correlations between the crack size and the recorded force. The small force corresponds to a big crack, while the large force corresponds to the small crack. This confirms that by using the developed setup the recorded contraction force can be used for the assessment of hot tearing susceptibility. Compared with the measurement of crack length/width, it is more straightforward and also offers more reliable quantitative data.

Figure 3 (a) shows that for Mg-1wt.%Al alloy increasing the mould temperature decreases the crack size and when the mould temperature reaches 500°C, no crack was found at all. It indicates that the hot tearing susceptibility decreases with increasing mould temperature. The same trend is also found for Mg-3wt.%Al and Mg-9wt.%Al alloys. But for Mg-3wt.%Al alloy no crack was found when the mould temperature is above 350°C while for Mg-9wt.%Al no crack was found when the mould temperature is above 250°C. Different mould temperature can lead to different cooling rate in the casting. Hot tearing is a defect normally formed in the hot spot areas, where the lattermost solidification proceeds. For an irregular shape casting, a higher cooling rate generates larger temperature gradients, and thus results in more severe hot spots. Meanwhile, the larger temperature gradient leads to the higher thermal stresses in the casting [2]. Therefore, the hot tearing susceptibility is higher with a higher cooling rate, i.e. a lower mould temperature, and vice versa.



(a) (b) (c)

Figure 3. Contraction force vs hot crack size at different mould temperatures for (a) Mg-1wt.%Al, (b) Mg-3wt.%Al and (c) Mg-9wt.%Al.

Monitoring the Formation of Hot Tearing

<u>Initiation of hot tearing</u>

Fig. 4-6 show the experimental curves for all three alloys with different mould temperatures respectively. Clear drops were recorded in almost all force curves. The peak point of the drop indicates the initiation of hot tearing. Fig. 6 (b) shows an exception, where a rather constant force was recorded for a short time from 578°C. This suggests a force relaxation taking place during the solidification due to the rearrangement of the solid grains and the remaining liquid under the imposed solidification stress.

Table 1. Information about the initiation and propagation of hot tearing for Mg-Al binary alloys at different mould temperatures.

		Mg-1wt.%Al				Mg-3wt.%Al		Mg-9wt.%Al	
Mould temperature		250°C	350°C	420°C	500°C	250°C	350°C	250°C	350°C
Hot crack initiation	T_i (°C)	620.6	621.2	632.2	633.8	604.4	621.1	549.1	-
	f_{s-i}	0.93	0.92	0.85	0.82	0.79	0.60	0.64	-
Hot crack propagation	F_r (N)	14.4	68.3	47.5	22.7	24.9	33.8	8.4	0
	t_p (s)	0.8	1.4	2.2	7.3	1.0	2.3	1.0	-
	v_p (N/s)	18	48.79	21.59	3.11	24.9	14.7	8.4	0

$\boldsymbol{T_i}$: hot crack initiation temperature; $\boldsymbol{f_{s-i}}$: hot crack initiation solid fraction
$\boldsymbol{F_r}$: force released during crack propagation; $\boldsymbol{t_p}$: crack propagation time
$\boldsymbol{v_p}$: force release rate, which is proportional to crack propagation rate

The results show that the mould temperature, i.e. cooling rate, influences the onset temperature of hot tear (Table 1). For Mg-1wt.%Al alloy with the mould temperature of 250°C, the hot tear initiated at 620.6°C. This corresponds to a solid fraction of 0.928, according to the solidification calculation using thermodynamic software Pandat by applying the widely used Scheil model. This value is very close to the well established knowledge that hot tearing normally occurs at the latest stage of solidification when an approximate 5% liquid is left [3]. However, with the mould temperature increasing to 500°C, the onset temperature increases to 633.8°C. This corresponds to a solid fraction of only 0.82. For Mg-3wt.%Al and Mg-9wt.%Al alloys, the result shows the same trend, but even lower solid fraction. A higher mould temperature results in a lower cooling rate. As a consequence, the solidification microstructure becomes coarser with larger dendrite arm spaces. This leads to an increased coherent temperature, at which the dendrites start to touch with each other to form a solid network. Thus with higher mould temperature, the thermal stress will start to build up on the solid skeleton and possibly initiate a hot crack at a higher temperature/lower solid fraction.

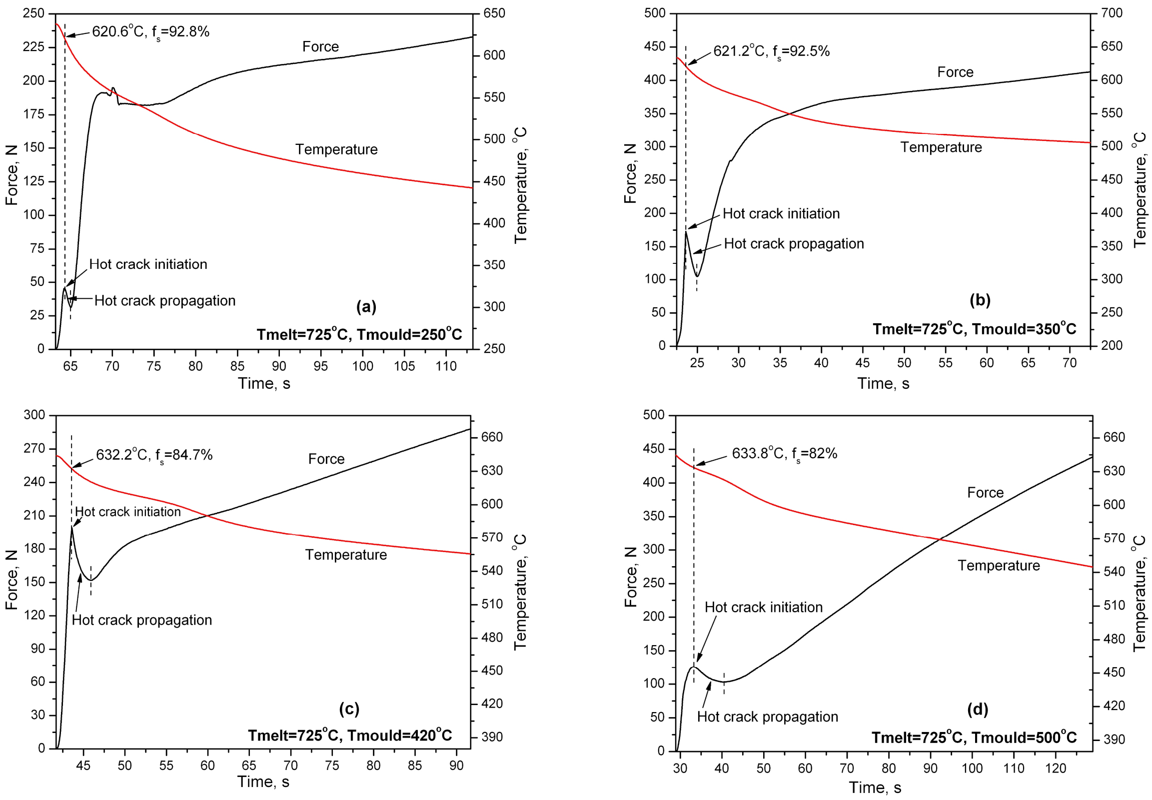


Figure 4. Contraction force and temperature as a function of time for Mg-1wt.%Al alloy cast at 725°C with mould temperature of (a) 250°C, (b)350°C, (c)420°C, and (d)500°C.

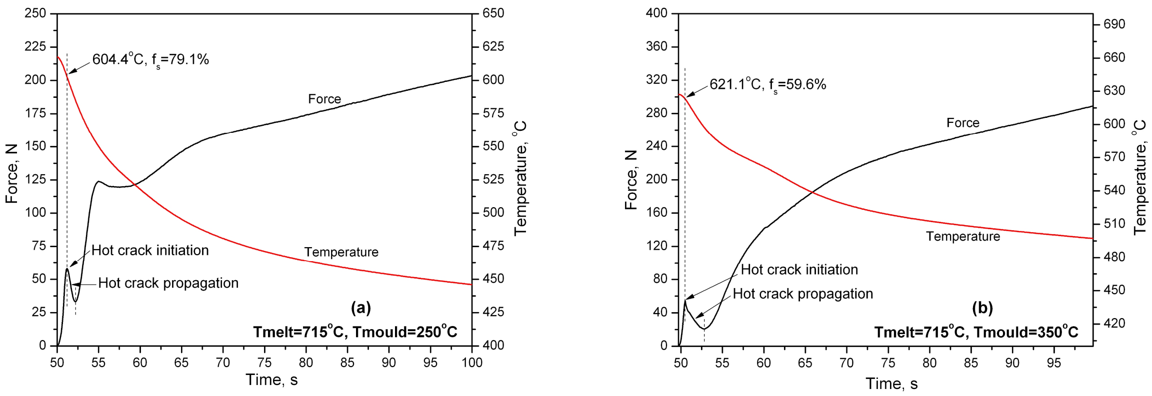


Figure 5. Contraction force and temperature as a function of time for Mg-3wt.%Al alloy cast at 715°C with mould temperature of (a) 250°C, (b)350°C.

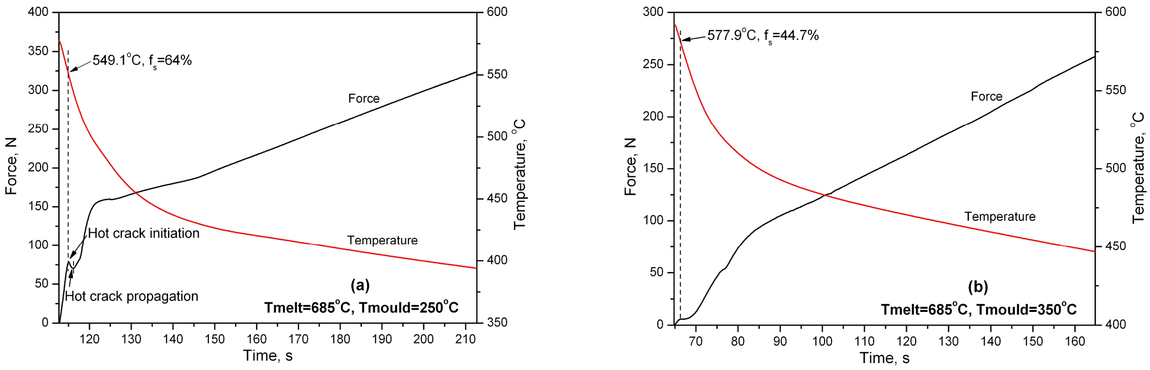


Figure 6. Contraction force and temperature as a function of time for Mg-9wt.%Al alloy cast at 715°C with mould temperature of (a) 250°C, (b)350°C.

The concentration of Al was also found to have an influence on the onset of hot tearing. The increment in the content of Al reduces the critical solid fraction. Currently, the responsible reasons are still unclear and further investigations are required.

Propagation of hot tearing

Hot tearing is defined as a crack that occurs as a tensile failure during solidification [3]. It evolves in a way of nucleation/initiation and then growth/propagation. Besides the initiation, the propagation of the hot tear can also be investigated by further analyzing the experimental curves. During the propagation of the hot crack, the stress or force will be continuously released. Therefore, the force release part on the curves, as marked in Fig. 4 and 5, reflects the crack propagation. Tab. 1 lists the data derived from the experimental curves. It is shown that with mould temperature increase, the force released during the hot crack propagation becomes smaller. This is in good agreement with the results on crack size and final recorded force reported in Fig. 3. However, it is noted that with a mould temperature of 250°C, the value of F_r is smaller than it is expected. This is because at this condition, two force drops were observed in the experimental curves (Fig. 4 (a) and Fig. 5 (a)), which indicates that the crack further propagated at a lower temperature. The data in Tab. 1 only suggested the first one.

The results shown in Fig. 4 suggest that hot cracking initiated at all mould temperatures for Mg-1wt.%Al alloy. However, the macro picture of the casting (Fig. 3 (a)) indicates that no crack was observed with the mould temperature of 500°C, while only a very tiny crack was found with the mould temperature of 420°C. One explanation for this inconsistence is that under higher mould temperature the initiated crack had been partially or completely healed, by the refilling of the remaining liquid. When a new crack formed, its subsequent propagation will locally generate negative pressure. This negative pressure will drive the remaining liquid to fill the crack opening. Farup et al [26] simulated the interaction between hot tear and the remaining liquid with in-situ observation of succinonitrile-acetone organic alloy. They found that the remaining liquid can readily refill the crack opening. In the present work, with the higher mould temperature there is more liquid left at the onset temperature of the hot crack (Tab. 1). Therefore, the possibility of crack refilling is high. Tab.1 also gives the force release rate at different mould temperatures. It is believed to be proportional to the crack propagation rate. At higher mould temperature, the crack propagates more slowly compared to lower mould temperature. As a consequence, the remaining liquid has a longer time to refill the crack. Besides that, the refilling channels and fluidity of the liquid can also influence the liquid refilling. Under the higher mould temperature, the remaining liquid exists in a thicker and more continuous form due to the coarser microstructure. This favors a better flow channel. Additionally, the lower cooling rate leads to a higher crack onset temperature. The viscosity of the liquid is lower. When the liquid refills in the crack opening, the localized stress will be largely decreased due to the surface tension of the liquid. As a result, the crack propagation is interrupted or even completely stopped. In this way, the crack can be healed.

Fracture Surface Morphology

Fig. 7 shows the morphologies of hot tear surfaces for Mg-Al alloys prepared under the same mould temperature. For Mg-1wt.%Al alloy (Fig. 7 (a)), the surface of hot tear is very smooth and clean with some evidence of fractured grain bridges. In contrast, a thin layer of material with a fluvial pattern is observed on the fracture surface of Mg-9wt.%Al alloy (Fig. 7 (b)). The EDX result (Fig. 7 (c)) shows an apparently higher Al content than the matrix in these areas, which can be related to the eutectic composition. This indicates that some liquid exists on the crack surface of Mg-9wt.%Al alloy. They are either locally remaining or later refilled. The thermodynamic calculation shows that with increasing Al content, the fraction of eutectic liquid increases [27]. For Mg-1wt.%Al and Mg-3wt.%Al alloys, the eutectic fraction are only 0.005 and 0.03 respectively, while for Mg-9wt.%Al it is 0.15. This explains why the evidence of liquid was only found in high Al containing Mg-Al alloys.

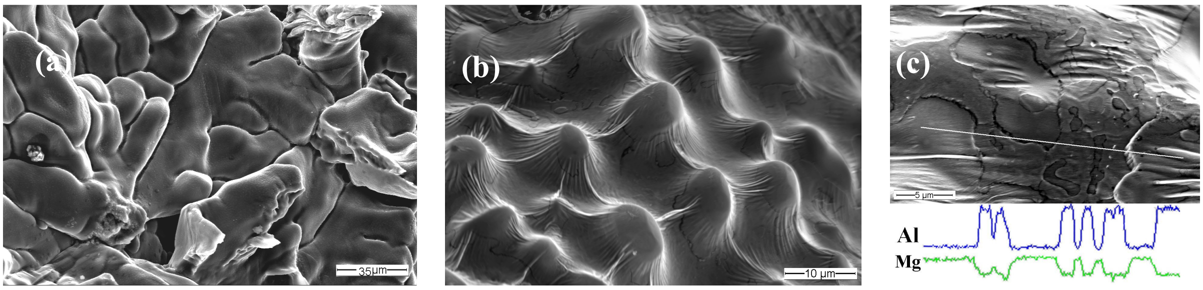


Figure 7. Morphologies of hot tear surfaces of (a) Mg-1wt.%Al, (b) Mg-9wt.%Al cast with a mould temperature of 250°C, and (c) EDX line scan for sample (b).

Conclusions

A quantitative method to investigate the hot tearing behavior was developed. The new method is based on the measurement of the contraction force. The results demonstrate a good repeatability and reliability. The contraction force is able to evaluate the susceptibility of hot tearing as a more straightforward and quantitative index. The increment in the mould temperature reduces the susceptibility of hot tearing for the binary Mg-Al alloys, meanwhile increasing the initiation temperature of hot tearing. Furthermore, by analyzing the curve of the recorded contraction force, useful information can be obtained for not only the initiation of the hot tear, but also its propagation. In the alloys under investigation, the liquid refilling plays an important role during the propagation of the hot tearing. With a higher mould temperature, a lower propagation rate for the initiated hot crack is detected. This is because the remaining liquid is favored to refill the initiated hot crack, and consequently interrupts the propagation of cracks or possibly completely heals the cracks.

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