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EVALUATION OF HORIZONTAL AND VERTICAL CONSTRAINED ROD CASTING MOLD ON HOT TEARING SUSCEPTIBILITY OF Al-Cu ALLOYS

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Abstract

This research aims to evaluate horizontal and vertical constrained rod casting (CRC) molds on hot tearing susceptibility (HTS) of Al-xCu casting alloys with 2.2, 3.6, 7.5, and 12.5 percent Cu. The hot tears on the casting product were observed using a macroscopic approach. In addition, the hot tearing susceptibility of each casting product prepared using these molds was evaluated using the HTS formula. The results show that the vertical CRC mold has a higher HTS value than the horizontal CRC mold. The rod

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length is a significant factor in causing hot tearing. Longer rods are more susceptible to hot tearing. The horizontal CRC mold provides a clearer effect of rod length and Cu composition on the average HTS value. In the vertical CRC mold, the effect of Cu composition on the average HTS value is less clear. Therefore, it is highly recommended to use horizontal CRC mold for HTS testing of aluminum casting alloys.

Keywords: *hot tearing susceptibility, constrained rod casting (CRC), horizontal CRC mold, vertical CRC mold, Al-Cu alloys, casting*

Introduction

Hot tearing, or interchangeably known as hot tears, hot cracking or hot shortness,[1,2] has been recognized as one of the most critical issues encountered during the casting process as it causes severe and irreversible defects.[3] The occurrence of hot tearing decreases casting productivity due to the rejected products. Hot tearing occurs in the late stages of solidification when the volume fraction of the solid is above 85–95%[4] and it propagates in the interdendritic liquid film during the solidification process.[4]

Hot tearing is a complex phenomenon[5] since several mechanisms can be responsible for the formation of hot tearing. The previous research reported that hot tearing occurs due to shrinkage.[6] In permanent mold casting the hot tearing occurs as a result of contraction stresses. The principle of action and reaction between the expanding mold and the contracting solid metal leads to the generation of tensile stresses in the solid metal and compressive stresses in the mold.[7] This stress concentration is imposed by the mold geometry like corners, sharpness, junctions of the bars to the gating, etc. Several experimental methods for assessing the hot tearing susceptibility (HTS) of aluminum alloys have been developed over the years. All of these methods aim to investigate the severity of the formation of hot tears. Recently, various methods have been developed for the hot tearing test such as:

i. Visual rating methods i.e. ring mold testing,[8] constrained-rod casting (CRC),[9–13] cylindrical rod, ball rod, and "*U*" shape casting test[1]
ii. Mechanical testing techniques i.e. stress and strain measurements[4]
iii. Physical properties testing i.e. resistivity and acoustic emission testing.[8]

Almost all the studied alloys are prone to hot tearing and are torn in the CRC molds with different severity.

The constrained rod casting (CRC) mold is the most commonly used mold for investigating the phenomenon of hot tearing.[1,2,4,6] A CRC mold with different rod lengths is an effective method for evaluating the hot tearing susceptibility of various alloys.[14] The CRC mold is divided into two types: a horizontal CRC mold and a vertical CRC mold. Several previous studies have been recognized for evaluating the hot tearing susceptibility using vertical and horizontal CRC molds on various aluminum alloys.[9,10,13–20] Some researchers predominantly employ vertical CRC molds with four rods.[9,10,13–16,19,21,22]

Several researchers have investigated the assessment of hot tearing using various molds, shapes and alloy compositions. The aluminum alloys employed in the previous studies vary from each other, making it challenging to pinpoint the cause of hot tearing in aluminum alloys using CRC molds. Accordingly, our research is dedicated to exploring and evaluating the impact of mold type while keeping casting process parameters and alloys consistent for both molds on hot tearing susceptibility. Notably, the assessment of hot tearing using vertical and horizontal CRC has not been carried out with the same alloys and casting parameters in previous studies. The evaluation of hot tearing using vertical and horizontal CRC is never evaluated in similar alloys and casting parameters. This research aims to evaluate the hot tearing susceptibility of Al-xCu alloys using horizontal and vertical CRC molds for similar alloys and casting parameters. The hot tearing susceptibility (HTS) equation was used to evaluate the hot tearing tendency of metal depending on rod length, tear categories and tear location.

Experimental

Figures 1a and b show the horizontal and vertical CRC mold, respectively. These molds were designed with six constrained rods A, B, C, D, E, and F with different lengths. The number of constrained rods in the vertical CRC mold is adapted from Cao[5] and Novikov[23] CRC mold. These molds were made of gray cast iron and

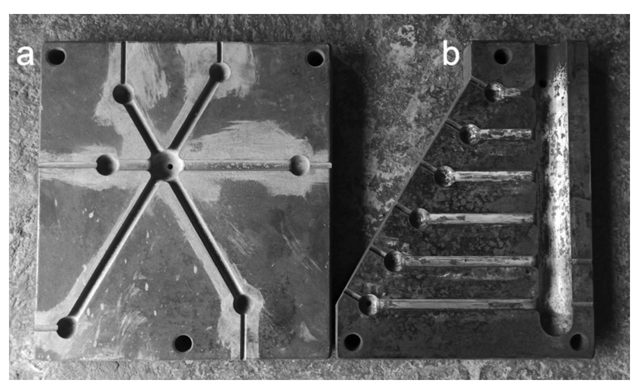

Figure 1. The half side of mold for the constrained rod casting (CRC) used in this research; (a) horizontal, (b) vertical mold.

consisted of two partitioned halves. The number of cylindrical constrained rods for both the horizontal and vertical CRC molds was identical. The dimensions of all constrained rods and sprue in both the horizontal and vertical molds are shown in Figures 2a and b respectively. Both the horizontal and vertical CRC molds were designed with identical dimensions. A spherical cast cavity or a ball end was positioned at the end of each rod, serving as an anchor to prevent unrestricted contraction caused by solidification shrinkage.

Figure 2a shows the detailed dimension of the horizontal CRC mold. The length of the constrained rods varied from the shortest to the longest at 51 mm (rod A), 75 mm (rod B), 95 mm (rod C), 121 mm (rod D), 143 mm (rod E) and 165 mm (rod F), respectively. The constrained rods of the horizontal CRC mold have a typical diameter of 9.5 mm. Additionally, the cylindrical rods were spaced apart from each other at a 60° angle. A ball end with a diameter of 19 mm is provided at the end of each rod. The sprue of the horizontal CRC mold has a diameter of 29 mm. In addition, a 4 mm diameter air vent was affixed to the ball end of each constrained rod. Figure 2b shows the dimensions of the vertical CRC mold. The length of the constrained rods from the shortest to the longest was the same as those of the horizontal CRC mold. The distance between each rod was 38 mm. The diameter of the constrained rods, ball end, sprue and air vent were also typical with horizontal CRC mold. All the details of the geometry of the two molds are displayed in Figure 2c.

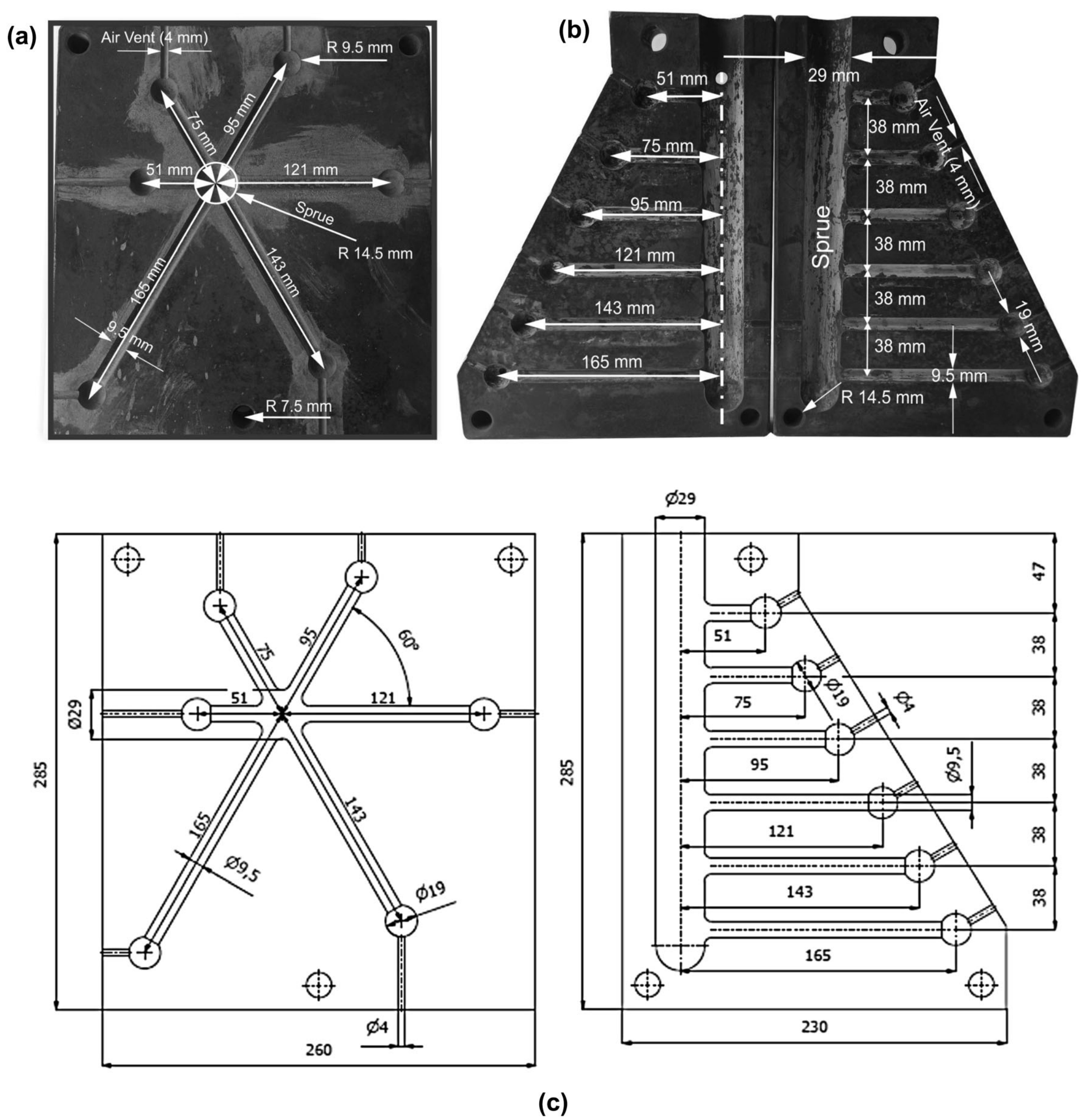

Figure 2. Dimensions of the CRC mold (a) horizontal mold, (b) vertical mold and (c) the details of the geometry of the two molds in mm.

A pure aluminum ingot and master alloys of Al-40 wt% Cu were used as raw materials. For each alloy composition, the master alloying elements were added to pure aluminum using a calculated amount of the corresponding master alloys to achieve the desired addition levels. The melting temperature was maintained at 750 ± 5 °C. The actual composition of all the Al-xCu alloys was determined by Optical Emission Spectroscopy (OES) (ARL easySpark™ Metal Analyzer, Switzerland). Table 1. shows the varied Cu content in Al-xCu which were 2.2, 3.6, 7.5, and 12.5 percent.

Both CRC horizontal and vertical mold cavities were cleaned before the experiment and the molds were coated with boron nitride to minimize friction between the mold wall and the casting during solidification. The lower section of the horizontal CRC mold was affixed to a precisely leveled table, and the upper part was manually assembled. Because hot tearing is a complex phenomenon involving many variables, the best possible efforts were made to control the casting process. The earlier works have conducted experiments to determine the effect of mold temperature on hot tearing susceptibility in aluminum alloys.[21–26] Based on the previous works, the molds were preheated to a temperature of 387 °C to ensure their readiness for pouring. In this experiment, the pouring temperature for each alloy was set at 700 °C. In this research, a grain refiner was not employed for the alloys. The vertical CRC mold was poured in a vertical position with a tilt angle of 17.5 degrees while the horizontal CRC mold was poured in a horizontal position. The molten material was introduced into the horizontal CRC mold via a vertical channel with a height of 60 mm and a diameter of 29 mm. The horizontal and vertical CRC molds were poured at the same alloys and melt velocity. The pouring time for each mold was approximately 8–10 seconds. Each casting product was removed from each mold approximately 2 minutes after the pouring process. Each process was repeated four times for each alloy on each mold with the same casting parameters process. During the experiments, the melt, the pouring, and the mold temperature were monitored using a K type thermocouple (WRN-M6K, Japan). All the cast rods were visually checked to evaluate the hot tearing using a digital camera with a magnification up to 10 times.

Table 1. Chemical Compositions (in wt%) of Al-xCu Alloys Prepared for the Hot Tearing Test

Element (wt%)	Cu	Fe	Si	Mn	Al
Alloy A	2.20	0.18	0.09	0.02	97.43
Alloy B	3.59	0.13	0.06	0.02	96.10
Alloy C	7.49	0.13	0.06	0.02	92.15
Alloy D	12.58	0.13	0.05	0.02	86.98

In this research, the hot tearing sensitivity or HTS value for a sample was calculated using Eq. (1).[12]

$$\mathrm{HTS} = \sum \left(F_{\mathrm{length}} x F_{\mathrm{location}} x F_{\mathrm{crack}} \right) \qquad \text{Eqn. 1}$$

where the F_{length} is the rod length factor as shown in Figure 3a, F_{location} is the crack location factor as shown in Figure 3b, and F_{crack} is the crack factor. The values for each factor are shown in Table 2. The factor is used to rate the severity of the hot tearing on the rod. For F_{length} value, the shorter rods were given a lower rating than the longer rods because they were less prone to hot tearing. The F_{location} values were determined by the location of the crack at the rod as shown in Figure 4. The sprue end, ball end, and the middle of the rod have the factor location value 1, 2, and 3, respectively. The reason for defining the factor location value is based on the severity of each location to hot tearing. The lowest value of factor location indicates that the location is more prone to hot tearing and vice versa.

The (F_{crack}) values were determined as follows:

1. If there is no hot tearing visible on the surface of the rod, (F_{crack}) then the value was 0.
2. If a hairline tear formed is a surface tear that extends up to half the circumference of the rod then the value was 1.
3. If a large hairline tear formed extends the length of the rod, then the value was 2.
4. If a major tear formed on the entire circumference and depth of the rod then the value was 3
5. If the fracture occurred then the value was 4

A summary of the hot tearing severity of the samples can be seen in Table 2.

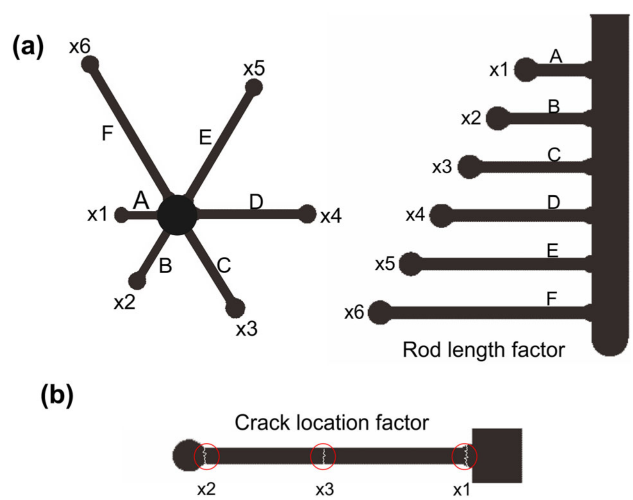

Figure 3. Illustrations of the susceptibility criteria for hot tearing of horizontal and vertical CRC mold are as follows: (a) rod length factor and (b) crack location factor.

Table 2. Hot Tearing Susceptibility Rating System

Rod Name	Rod length (mm)	F_{length}	Hot tearing category	F_{crack}	Hot tearing location	$F_{location}$
A	51	1	No tearing	0	Sprue end	1
B	75	2	Hairline tear	1	Middle rod	3
C	95	3	Large hairline tear	2	Ball end	2
D	121	4	Major tear	3		
E	143	5	Fracture	4		
F	165	6				

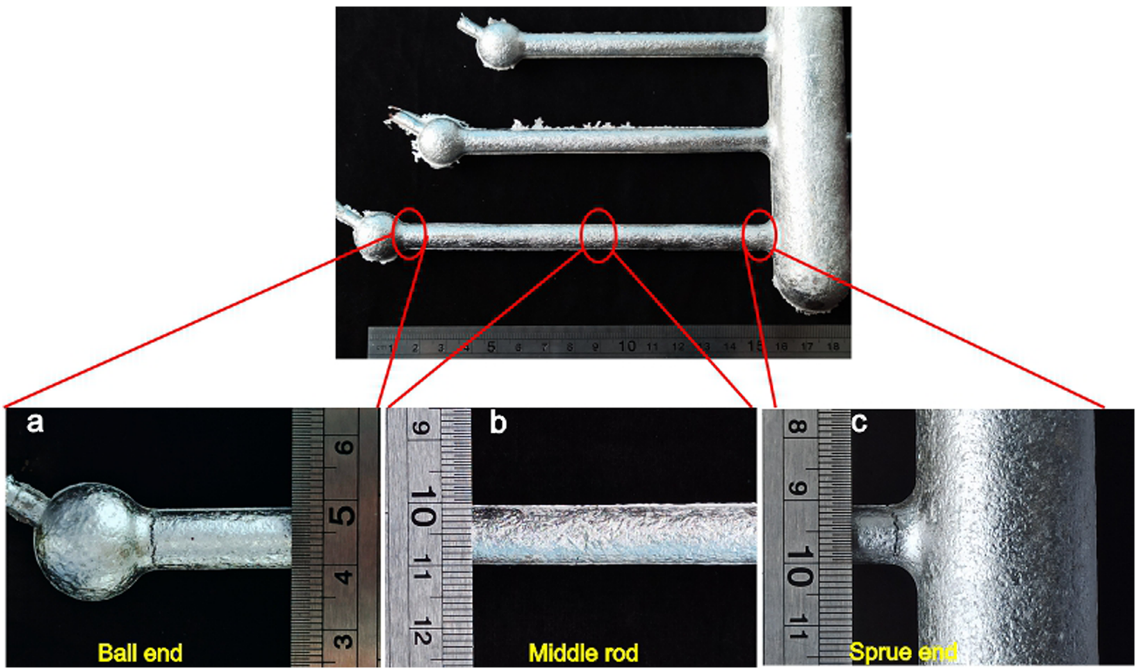

Figure 4. Location of the hot tearing on horizontal and vertical mold; (a) ball end, (b) middle rod, and (c) sprue end.

Results

Figure 4 displays the cast produced from the vertical CRC mold. It can be observed that the tear occurs at three different locations on the longest rod (*F*-rod) from the vertical CRC mold. It occurs in the ball end, in the middle of the rod, and in the sprue end. It is in accordance as stated in Refs..[5,9,10,17,18,21] The crack location as shown in Figure 4 correlates to the crack location factor ($F_{location}$) as shown in Figure 3 where each value is stated in Table 2. The crack locations depend on each alloy, each rod length, and each mold, thus it will affect the HTS value.

Figure 5 shows the crack formed in the rod that was processed using vertical CRC mold. Figure 5a shows that the tear is not formed in the sample. Figure 5b–d show that a tear is formed in the sample where the tear characteristic is a hairline tear, large hairline tear, major tear, and fracture, respectively. Each crack characteristic correlates to the crack factor (F_{crack}), and it is used to define the crack factor (F_{crack}) value as stated in Table 2. It is also used for evaluating the F_{crack} value for the horizontal CRC mold.

Figures 6a and b depict the sample cast products that were cast using horizontal and vertical CRC mold for Al-12.5Cu respectively.

Figures 7a and b shows the hot tear locations of all Al-xCu alloy cast products that are prepared using horizontal and vertical CRC molds. The yellow circles indicate the tears that occur in the rod of each mold. Figure 7a displays a close-up of cracks in each alloy composition for horizontal CRC mold. According to the experimental results and the analysis of crack locations in the horizontal CRC mold, for all Al-xCu alloys, sixty-eight percent of hot tearing occurs at the sprue end, while thirty-two percent occurs at the ball

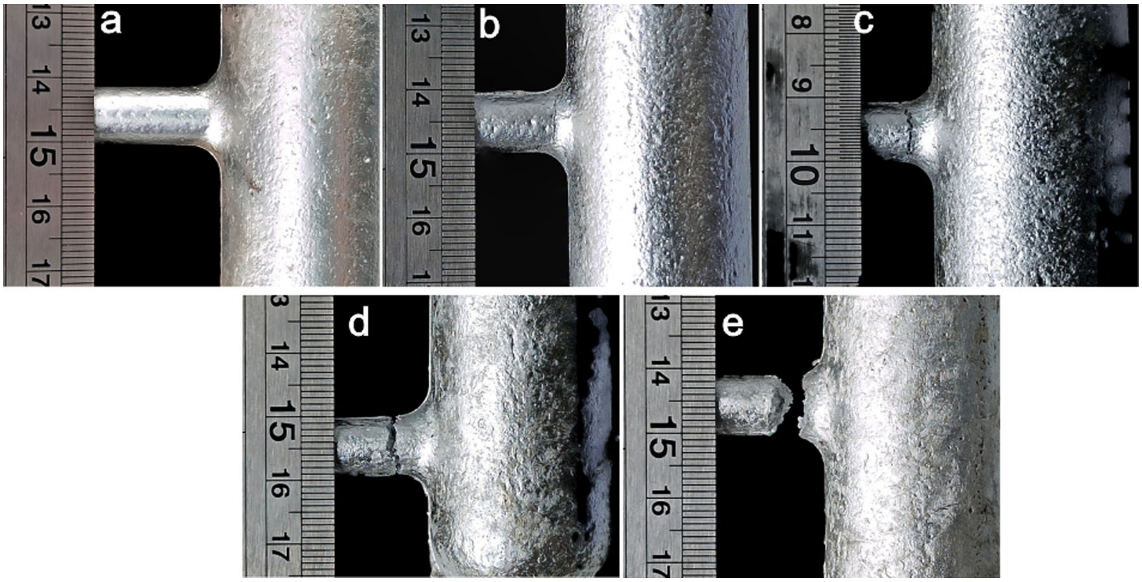

Figure 5. Typical hot tearing defects with different levels of severity: (a) no crack, (b) hairline, (c) large hairline, (d) major, and (e) fracture.

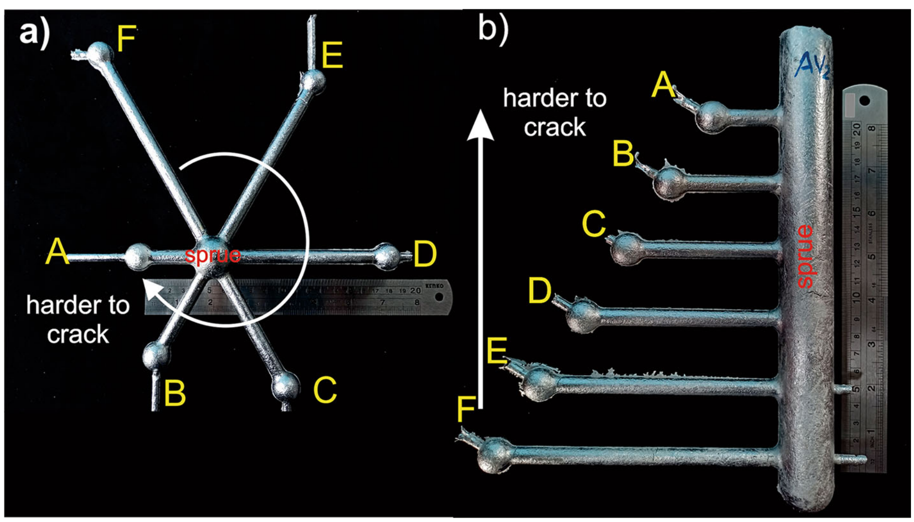

Figure 6.. The sample cast products made from Al-12.5Cu that were produced using (a) horizontal CRC mold and (b) vertical CRC mold.

end. Notably, hot tearing in the middle of the rods was not observed in any alloys of Al-xCu processed using the horizontal CRC mold. Considering the length factor (F_{length}), tears occur in all rods cast using the horizontal CRC mold for all Al-xCu alloys, except in the shortest rod. Specifically, hot tearing at the B and C rods occurs only at the sprue end, whereas tears at the D, E, and F rods manifest at both the sprue end and the ball end. In the vertical CRC mold such as shown in Figure 7b, tears are observed in all rods. For all Al-xCu alloys, sixty percent of hot tearing takes place at the sprue end, thirty-nine percent at the ball end, and one percent at the middle of the rod. A tear in the middle of the rod only occurs in the longest rod. Specifically, hot tearing at the A, B, and C rods occurs solely at the sprue end, while at the D, E, and F rods, tears occur at both the sprue end and ball end.

Considering the crack factor (F_{crack}) as shown in Figure 7a, for Al-xCu alloys that were processed using horizontal CRC mold, for Al-2.2Cu and Al-3.6Cu alloys, most of the cracks have major tear characteristics. Two tears might occur in the same rod at the same period and occur at the sprue end and ball end. These tears only occur at the D, E, and F rods of Al-2.2Cu alloys. For Al-7.5Cu and Al-12.5 Cu, most of the tears have large hairline and hairline tears respectively. These hairline tears are mostly found at the sprue end area of the rod. On the other hand, for Al-xCu alloys that are processed using vertical CRC mold, for Al-2.2Cu and Al-3.6Cu alloys, most of the tears have a

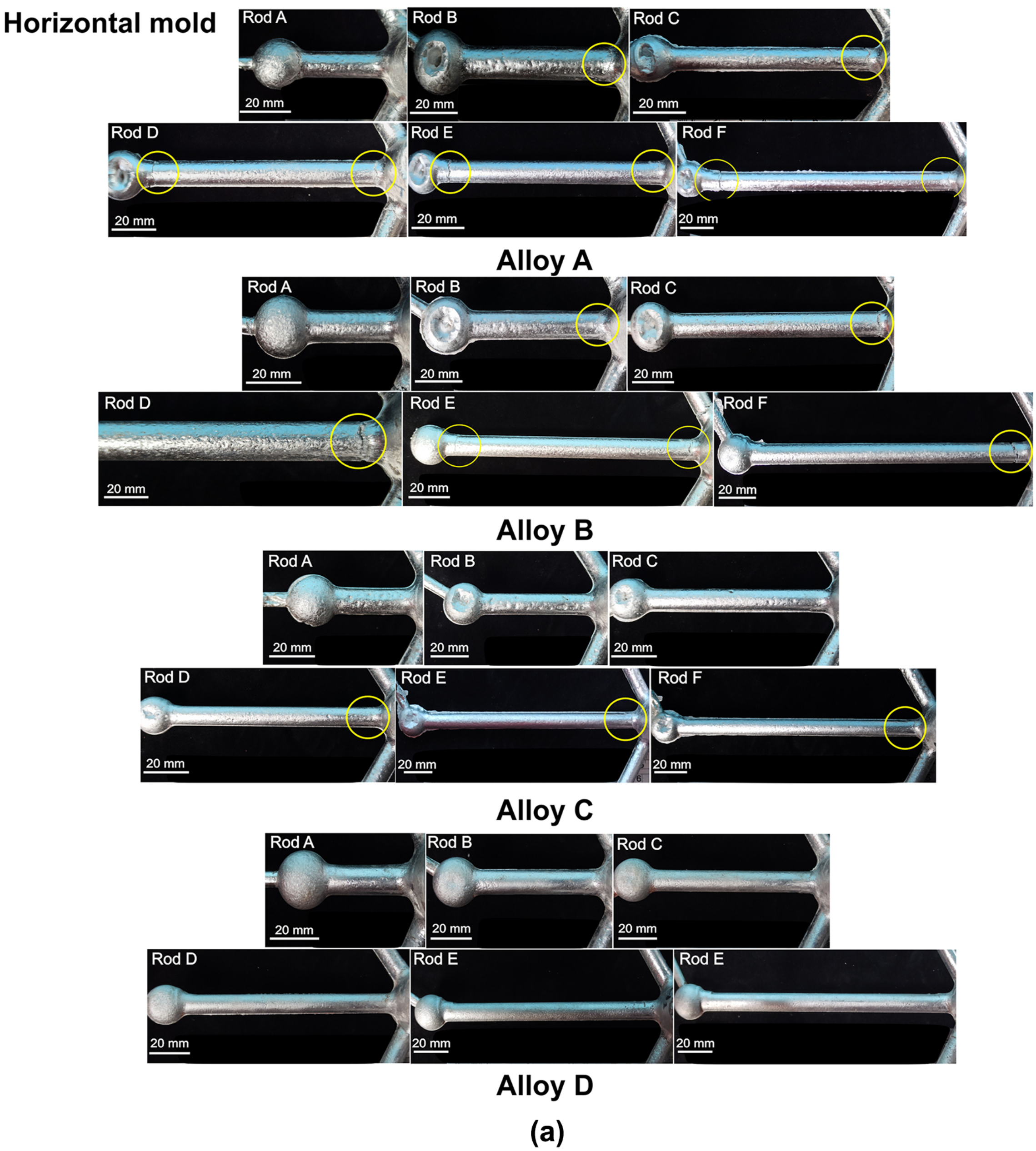

Figure 7. The enlarged images of the cracks in each alloy composition were prepared in a) horizontal and b) vertical CRC molds.

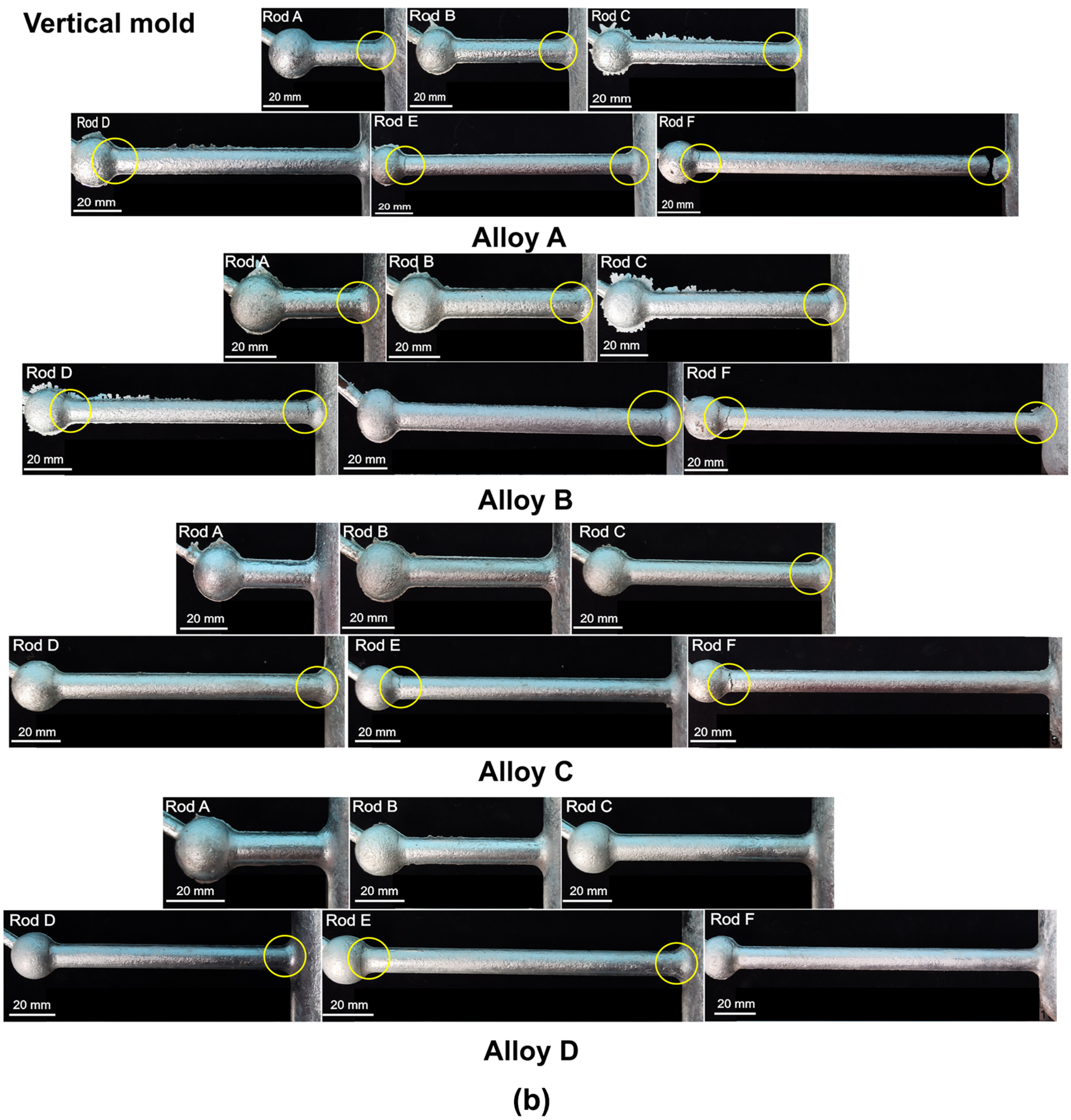

Figure 7. continued

hairline tear and major tear characteristics respectively. Some of the rods of the casted sample are found fractured or separated. This thing happened at the sprue end and ball end area of E and F rods as shown in Figure 7b. These fracture rods can be seen directly during the dismantling of the cast sample from the mold cavity of the vertical CRC mold. Two tears that occurred in the same rod were also found in the vertical CRC mold. These tears only occur at D, E, and F rods of Al-2.2Cu and Al-3.6Cu alloys. For Al-7.5Cu and Al-12.5 Cu, most of the tears have a major tear and hairline tear respectively.

Figure 8 shows the correlation between Cu composition to the average value of Hot Tearing Susceptibility (HTS) for horizontal and vertical CRC mold. For Al-(2.2, 3.6, 7.5)Cu, the vertical mold has a higher HTS value than the horizontal mold except for Al-12.5Cu alloys. The highest HTS values of horizontal and vertical CRC mold were 91 and 104 on Al-2.2Cu respectively. Generally, the HTS value decreased with the increasing copper contents for both horizontal and vertical CRC mold.

Figure 9 shows the effect of rod length of horizontal CRC mold and Cu composition of Al-(2.2-12.5)Cu alloys on the average of HTS value. It shows that the HTS value increased with rod length for Al-(2.2-7.5)Cu alloys, and it did not change significantly for Al-12.5Cu alloys in all varied rod lengths. In the shortest rod length (51 mm) for all alloys Al-(2.2-12.5)Cu, the average HTS values were zero which indicated that the hot tearing was not formed. The average HTS value increased gradually with Cu content when the rod length was more than 51 mm, and it

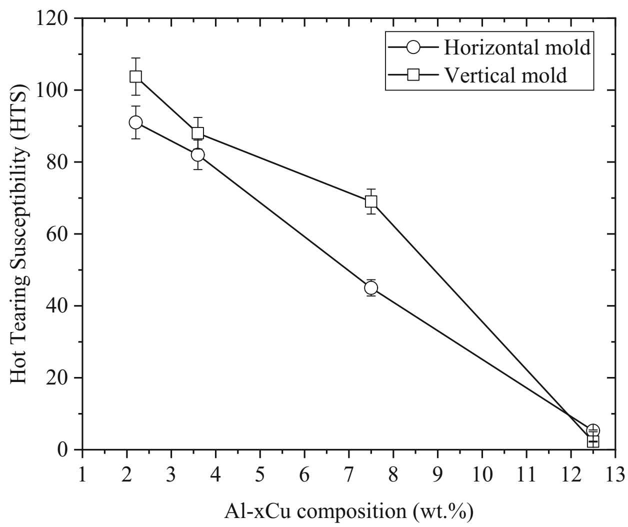

Figure 8. The effect of alloy compositions in the Al-Cu system on the HTS values in both horizontal and vertical CRC molds.

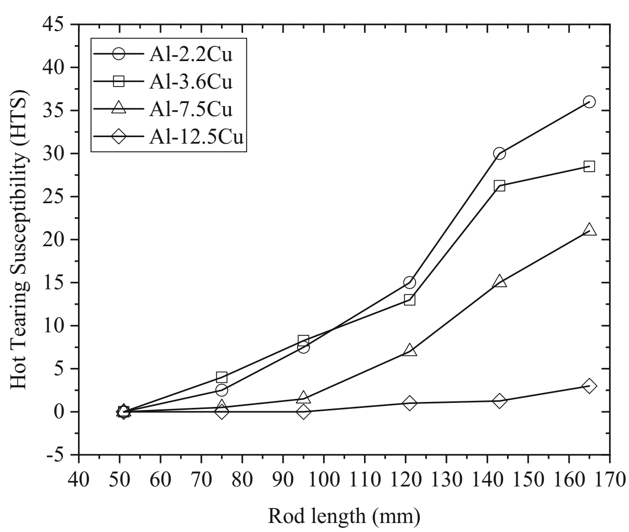

Figure 9. The correlation between the length and HTS value in the horizontal CRC mold.

happened on all Al-(2.2-12.5Cu) alloys. In the horizontal CRC mold, it was noticed that the average HTS value increased with rod length only in some specific ranges of Cu content in Al-xCu alloys.

Figure 10 shows the effect of the rod length of vertical CRC mold and Cu composition of Al-xCu alloys on the average HTS value. It shows that the HTS value increased with rod length for Al-(2.2-7.5)Cu alloys, and it did not change significantly for Al-12.5Cu alloys in all varied rod lengths. In the shortest rod length (51 mm) for Al-(2.2-12.5)Cu alloys, the average HTS values are 0 which indicates no hot tearing is observed. The observed phenomenon was consistent with horizontal CRC mold as mentioned earlier. For Al-(2.2-3.6)Cu alloys, the average HTS value increased gradually when the rod length was more than 51 mm. Meanwhile, the average HTS value increased

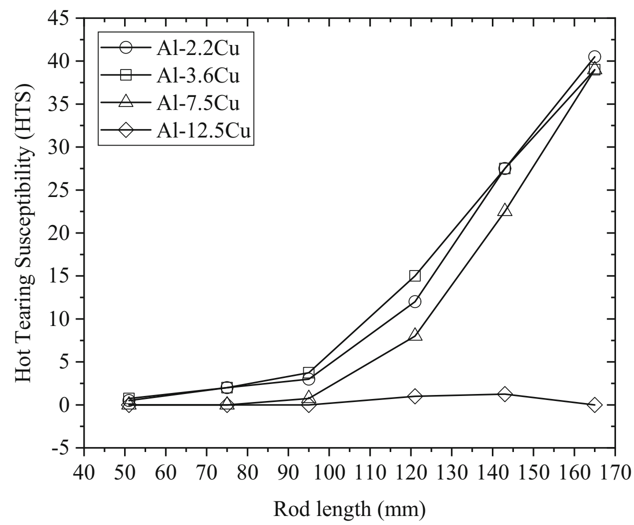

Figure 10. The correlation between the rod length and HTS value in the vertical CRC mold.

gradually when the rod length was more than 75 mm for Al-7.5Cu alloys. The average HTS value increased dramatically on Al-(2.2-7.5)Cu alloys when the rod length was more than 75 mm. In the vertical CRC mold, the effect of Cu content was not as clear as in the case of the horizontal CRC mold.

Discussion

In this research, the hot tearing susceptibility of Al-xCu alloys was evaluated by using horizontal and vertical constraint rod casting (CRC) molds. A hot tearing susceptibility (HTS) equation was also used to evaluate the hot tearing tendency of the alloys depending on the rod lengths, tear categories as well as tear locations.

Basically, the hot tearing phenomenon occurred more often at the sprue-end and ball-end of a rod because of two casualties. Firstly, it happened due to the much larger size of the sprue compared to the rod which resulted in a faster solidification of the molten metal in the rod. The sprue end near the rod constituted the last place for the molten metal to solidify. Secondly, the hot tearing occurred due to the abrupt change of the sectional area from the sprue to the rod, which led to stress concentration at the sprue end near the rod.[5] Conversely, hot tearing was minimal in the middle of the rod because there was a lack of stress concentration.[5]

The hot tear in the sprue end of a horizontal CRC mold occurred more frequently than that in a vertical CRC mold. This was attributed to the more uniform temperature in the sprue of the horizontal CRC mold than the vertical one. Once poured into a cavity of a vertical CRC mold, the molten metal would first fill the longest rod followed by the filling to the nearest rod, causing a less uniform temperature in the sprue (see Figure 2b). Meanwhile, the molten metal would fill all the rod cavities simultaneously once poured into the cavity of the horizontal CRC mold. As a result, the temperature of the molten metal at the sprue in such a horizontal CRC mold was more uniform (see Figure 2a). However, the uniform temperature distribution at the sprue would lead to a higher possibility of hot tearing in the location near the sprue end of the horizontal CRC mold. In this case, the sprue contained a larger volume of liquid metal than in the rod. As a consequence, this molten metal solidified much slower in the sprue than that in the rod. The larger the solidifying temperature range between the sprue and the rod resulted in a higher susceptibility for hot tearing.[5]

As indicated in Figures 9 and 10, it is noted that crack was harder to occur in shorter rods. This finding is confirmed by Ref.,[16] which showed that a higher HTS value could be found in the longer rods. Confirming the earlier works,[16,17] which showed that hot tearing was prone to occur in a longer rod because of a larger thermal contraction and shrinkage. According to the findings in this experiment, the hot tear that occurred in the middle of the rod within the vertical CRC mold was attributed to the surface friction within the rod cavity. This friction hindered the movement of the molten metal in its semi-solid state. As the length of the rod increased, the wall surface area enlarged and consequently the wall friction was greater and resisted the flow of the molten metal. In the end, this led to the formation of hotspots and tears in the middle of the rod.[2,26,27]

One of the factors contributing to the severity of hot tears is attributed to the final stage of solidification, which is considered the most susceptible phase to hot tearing.[28,29] During the pouring of the molten metal into the vertical mold, the liquid metal first filled the area of the longest rod and lastly filled the shortest rod near the top sprue. The assumption was that the top of the sprue, near the shortest rod in the vertical mold, being last to solidify, resulted in exacerbated hot tearing near the sprue. This was evidenced by the fact that in vertical molds, hot tears still occurred in the shortest rod for copper content of 2.2–3.6. On the other hand, in a horizontal mold, the flow of molten metal into the mold cavity was distributed uniformly to each rod and the final solidification point of the last molten metal was in the sprue area exactly in the center of the mold. This resulted in an increase in temperature in the sprue area of the horizontal mold. The assumption earlier states that the severity of hot tearing in the area near the sprue in the horizontal mold would also increase. However, the assumption mentioned earlier contradicts the observed facts in the horizontal mold. This is supported by observations of several cast products from horizontal molds; hot tears did not occur in the shortest rods (rod A) under various copper content variations. This indicates that, in horizontal molds, the increase in temperature at the specific hotspot areas and the last stage of the solidification region did not significantly affect hot tearing formation. Consequently, it can be inferred that the primary factor contributing to hot tearing is the length of the rod, with longer rods exhibiting a greater tendency for hot tearing.

The data presented in Figure 8 indicates that hot tearing susceptibility (HTS) increases as the copper concentration decreases. The aluminum alloys with 2.2–3.6 Cu exhibited the highest susceptibility to hot tearing. This finding is in line with those from several earlier studies[6,13,22,25,26,30,31] which highlighted a significant impact of copper content on the hot tearing susceptibility. In the low copper content the hot tearing is caused by the long freezing range of the Al-2 wt%Cu base alloy[22] that extends the liquid film stage, and also maximizes the degree of solidification shrinkage whereby intensified hot tearing susceptibly is obtained. Suyitno et al.[29] state the decreasing the copper concentration from 3 to 1% causes a decrease in the amount of eutectic observed on the hot tear surface and an increased fraction of solid bridges. Eskin et al.[4] mentioned that solidification shrinkage (the volumetric change attributed to the liquid-solid phase transition) and thermal contraction (the volumetric reduction of solid phase due to the temperature dependence of solid density) are two key factors that are commonly used to assess the overall contraction during solidification, where a small contraction facilitates the hot tearing resistance.

As depicted in Figures 9 and 10, the influence of copper content in the vertical CRC mold was not as significant as that in the case of the horizontal mold. In the later mold, the average HTS values gradually decreased with the increasing copper content and rose with the rod length. This phenomenon was confirmed by the findings in Refs.,[2,13,22,30] which showed a correlation between copper content and HTS values in the horizontal CRC mold. In the case of vertical CRC mold, however, the average HTS value increased with the rod length and the effect of copper content on this value was less obvious. This disparity was attributed to the difference in sprue height, which in the end determined the temperature at the sprue end. Basically, the sprue plays a crucial role in controlling the filling rate of the molten metal and is considered as a critical part of the gating system.[32] In the horizontal CRC mold, each rod had the same sprue height; ensuring a uniform temperature at the sprue end and consistent cooling rates. Conversely, in the vertical CRC mold such as shown in Fig. 6b each rod had a different sprue height; leading to non-uniform temperatures at the sprue end and various cooling rates. In addition, it is important to note that the vertical CRC mold exhibited a higher HTS value compared to the horizontal one.

Considering the effects of gravity, there was a difference in the potential height and pressure of the rods once a vertical CRC mold was used. This phenomenon resulted in variations in the velocity of the molten metal when entering the

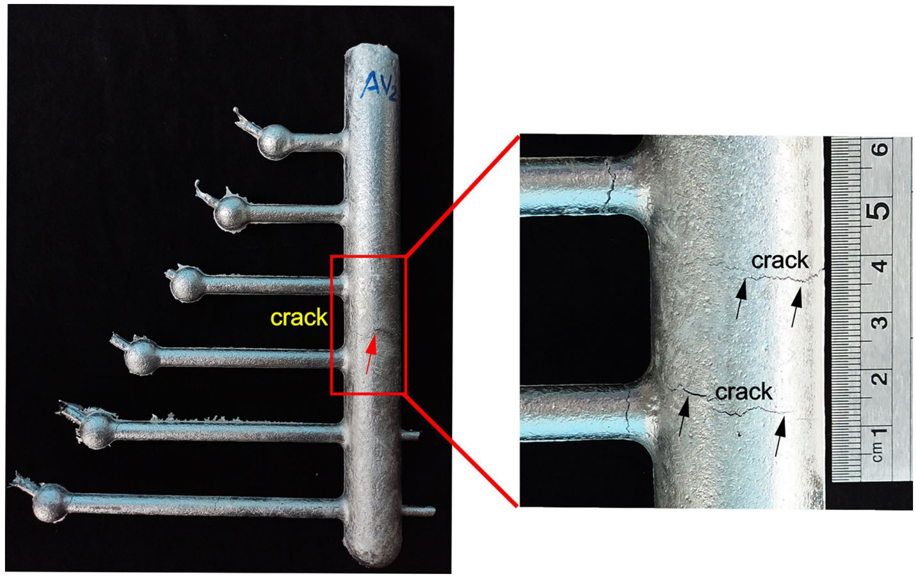

Figure 11. Cracks observed on the sprue of vertical CRC mold.

rods. Consequently, such a difference in the velocity led to the formation of turbulent flow within the rod and sprue cavities, especially in the bottom sprue and in the longest rod. This turbulence flow contributed to the air entrainment[33] and the formation of porosity,[34] which in the end potentially caused the development of hot tearing. Dubey[10] tried to modify the design of the vertical CRC mold to eliminate such a casting defect by improving the fluid flow, equalizing the rod filling times, introducing more uniform temperature gradients, and reducing turbulence within the rods to evaluate the hot tearing tendencies of aluminum alloys. However, the modified vertical CRC mold was still ineffective; some of the constrained rods were still not filled completely and the rod filling times varied from one to another rod. One of the important findings in this research concerns the presence of a crack in the sprue of Al-2.2Cu cast using the vertical CRC mold, such as illustrated in Figure 11. This defect could be observed in all the samples of Al-2.2Cu alloy casting products prepared with such vertical CRC mold. The tear was located in the middle of the sprue, i.e., between the C and D rods in Figure 6b. These findings were confirmed by the earlier research in Ref.[10] As indicated in Table 2 and Figure 5, these cracks could be classified as large hairline tears.

Conclusion

The study on the hot tearing susceptibility (HTS) of Al-Cu alloys using horizontal and vertical constrained rod casting (CRC) molds revealed that the vertical CRC mold generally results in a higher HTS value compared to the horizontal CRC mold. The longer rods are more susceptible to hot tearing. The horizontal CRC mold demonstrates a clearer impact of rod length and copper composition on the average HTS value. In contrast, the effect of copper composition on the average HTS value in the vertical CRC mold is less distinct. Therefore, it is strongly recommended to utilize the horizontal CRC mold for conducting HTS testing on aluminum alloys.

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