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MODIFICATION OF CONSTRAINED ROD CASTING MOLD FOR NEW HOT TEARING MEASUREMENT

Hot tearing severity was evaluated in this experiment by introducing a new apparatus called Constrained Rod Casting Modified Horizontal (CRCM-Horizontal). Six constraint bars with different lengths can produce hot tearing on the cast sample. Mold position was modified from vertical to horizontal and the shape was changed from a harp shape to a star shape, which allows for the liquid metal to feed into each rod cavity simultaneously. Hot tearing development was recorded along the bars by a digital camera. A new Hot Tearing Susceptibility (*HTS*) formula was developed for quantitative investigation of hot tearing on a cast sample. The parameters of the *HTS* formula are bar length of cast sample (*Li*), tear severity (*Ci*) and location of hot tear (*Pi*). Footprint charts and hot tear scales are used to illustrate hot tearing severity. The experiment was conducted with Al-1.36Zn-1.19Si and Al-5.9Cu-1.9Mg alloys to investigate the sensibility of the apparatus and modification its operation.

Keywords: Hot tearing, CRCM-Horizontal, *HTS* formula, casting

1. Introduction

The present study introduces a new apparatus that allows for the quantitative analysis of the severity of hot tearing of cast alloys. Techniques for investigating and assessing hot tearing susceptibility have been widely studied. Various apparatuses have been designed to resist the shrinkage and thermal contraction that cause cracks during solidification. Hot tearing can be divided into three categories: hot tear observations after solidification, measurement of load (stress) or dislocation during solidification, and a test on physical properties [1-2]. The ring mold is the most commonly used to observe hot tearing because it is easy to implement in an experimental setting. The liquid metal is poured into a cavity between the ring and core. Shrinkage and thermal contraction occur in the liquid metal during solidification. Stress formed in the cast alloy results from solidification shrinkage and thermal contraction. When the stress on the alloy exceeds the strength of the material, hot tearing occurs [3-5].

Hot spots develop from the force generated from the bar constraint at the end, and mechanical loading forms orthogonally from the dendritic growth. Hot spots may be one or more, caused by thermal contact between liquid metal and mold. Hot tearing frequently forms in hotspot areas [12,13]. The Permanent Star-Shaped Steel Mold (PSM) with "Dog Bone" shaped was developed to study on hot tearing susceptibility [6]. I-beam casting was developed to test cracking during the solidification of metal alloys. The susceptibility to cracking was evaluated by measuring the maximum restraint length reached before cracking developed [8].

The T-Shaped mold has been used to study hot tearing in the sand mold. The mold geometry allows for unrestrained contraction of the cast during solidification. The T-Shaped cavity has a steel bolt (hook) on the end of both arms, which constrains the liquid metal, so it cannot free a movement cause by metal contracted. Load solidification is transferred from the bolt to the load cell. The bolt's fix restrained of liquid metal from free a movement due to contraction in casting, which concentrates the strain in the mushy zone, and hot tearing will occur [9-11]. The Crickacier Hot Tearing Test design apparatus is applied to represent deformation and cooling rates. Furthermore, it allows mechanical loading of the mushy zone with a real casting structure when the material is vulnerable to hot tearing. The middle section of a sample is made larger to create a hot spot. The critical area is located just below the feeder [12,13].

The Cast Hot Tearing rig (CHT rig) test was developed to observe hot tearing on alloys. The apparatus is divided into two bar sections. One of the bar sections is typically fully restrained. The other side is connected to a thermocouple and a load cell (one end fixed to the load cell). The hot spot location is found in the center of the bar section [14-17]. The horizontal bar permanent steel mold was designed to observe hot tearing on the alloy. Molten was poured from a down sprue to the horizontal bar, and the cast solidified from the end of the horizontal restraint bar down towards the sprue. Hot tearing formed near the down sprue as a result of stress-induced strain from the axial contraction of the horizontal bar. The hot tears form when the stress exceeds the alloy's semi-solid strength or ductility [18-21].

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The N-tech mold for hot tearing tests consists of five Dog Bone rods of different lengths. Hot spots occurs along the bar. This test could be categorized as qualitative and semi-quantitative for measuring hot tearing. The hot tearing index is obtained by recording the total number of cracks that occur along the Dog Bone rods [2]. Design of the steel mold for constrained rod casting is meant for evaluating hot tearing. An anchor is used to restrain the rod from free movement due to contraction during solidification. A load cell was used for recording load data during solidification. The thermocouple was positioned near the sprue at the bottom of the rod for measuring temperature near the hot spot [22-29]. The hot tear usually occurred at the junction of the sprue and horizontal bar. The temperature at the hot spot is recorded during solidification with thermocouples. The loading rate (force vs. time) and cooling rate (temperature vs. time) were used for analyzing the hot tearing phenomenon.

The purpose of this study was to modify the CRC mold casting from the vertical to horizontal position and alter the bar design from the harp shape into the star shape with the sprue in the middle of the mold. The star shape allows the liquid metal to feed all the rod cavities simultaneously. Heat will be released from the liquid metal of the bars through the steel mold and into the ambient air, it will affecting the other rods. The experiment was performed on Al-1.36Zn-1.19Si and Al-5.9Cu-1.9Mg alloys to investigate the effectiveness of this modified apparatus. A motivation to modify the CRC mold due to observe the hot tears' phenomenon, as a result of thermal contraction. The position of CRC mold was in vertical, so when the molten is fed into bar cavities that will not fill in the same time, while the rod at top and bottom positions will receive heat only from one side. So it needs a new mold development, that is modifying the CRC mold from a vertical position to a horizontal, it was assumed the molten will be feeding simultaneously into the bar cavity. Star-shaped has been modified in order that heat released from the liquid metal will effect on each bar.

2. Material and method

2.1. Melting and casting

The experimental setup, shown in Fig. 1, consists of a steel mold, the thermocouple, and the alloy preparation and casting system. For sample 1 (Al-1.36Zn-1.19Si), the ingot of ADC12 was added to pure aluminum at a pouring temperature of 670°C. For sample 2 (Al-5.9Cu-1.9Mg), the aluminum bar of Al-2024 was re-melted at a pouring temperature of 788°C. Table 1 shows the chemical composition of the cast-samples obtained from Metal-standard spectroscopy. The mold temperature was kept constant at 220°C for both alloys. The temperature was monitored with a K-type thermocouple during casting. The top of the sprue was widened into a funnel-shaped cup to facilitate pouring. The sample was etched using solutions and microstructures of the samples were observed by an optical microscope (OM) Olympus and SEM images using JOEL JSM – 5800.

2.2. Hot-tear Susceptibility Test

A schematic of the steel mold for observing the hot tearing susceptibility was designed and used in this study as shown in Fig. 2. The mold was modified from the instrument CRC to the CRCM-Horizontal. Previously, the CRC mold was vertical and molten was poured through a vertical sprue that then fed the longest rod at the bottom position, then to the shortest at the top bar respectively. In this experiment, the steel mold was changed from a vertical position to a horizontal position. Therefore, when the molten metal was poured through the sprue vertically, it fed all of the rod cavities simultaneously. The temperature of each bar will influence each other during solidification (via temperature release) due to star-shaped of the mold. The mold has cavities

TABLE 1

Chemical composition (wt%) of cast samples

Si	Fe	Cu	Mn	Mg	Ti	Cr	Pb	Sn	Ni	Zn	Al
1.1900	0.6236	0.3030	0.0608	0.0083	0.0161	0.0065	0.0700	0.0002	0.0093	1.3692	Bal.
0.1597	0.2531	5.9311	0.7332	1.9359	0.0143	0.0118	—	—	0.0122	0.1835	Bal.

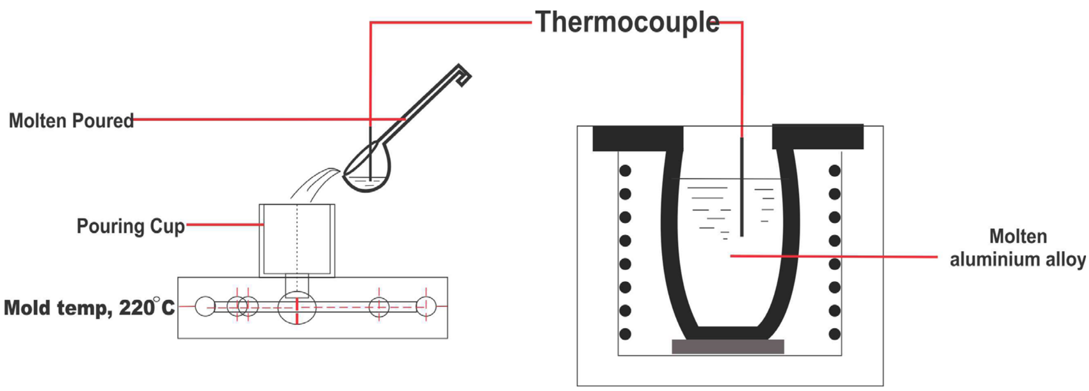

Fig. 1. A schematic diagram of the apparatus and setup

with six different bar lengths: 51 (bar A), 73.8 (bar B), 96.6 (bar C), 119.4 (bar D), 142.2 (bar E), and 165 mm (bar F) with all rod diameters measuring at 9.5 mm. The rods are constrained at the end of the bars by spherical cavities (with 19 mm diameters). The cylindrical rods are separated from each other at an angle 60 degrees. The melt is fed to the rods through the vertical sprue with a height of 60 mm and a diameter of 29 mm.

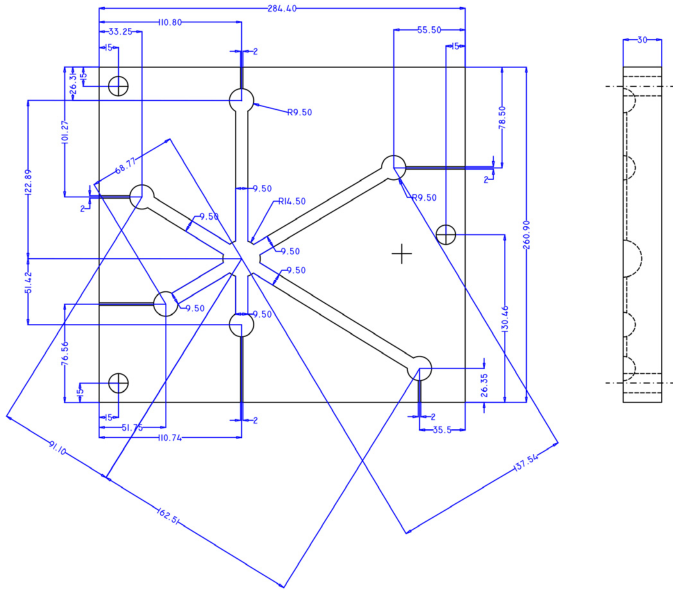

Fig. 2. The details of CRCM-Horizontal steel mold for evaluating hot tearing susceptibility (*HTS*). The dimension is in mm [30]

2.3. Hot-Tear Index

The hot tear severity of the alloys was qualified using the *HTS* rating. The rating method is based on three different parameters: length of bars, tear severity, and location of the tear in the casting. The severity was classified into five categories: no tear, hairline, light tear, severe tear, and complete tear. Hot tear severities observed in casting are shown in Fig. 3. Each of the six-rod lengths was given a rating between 1 and 6 (1 represents a high rating/high tear severity). The rating is proposed to reflect the severity of the hot tearing on the rod. The shorter rods were given a higher rating than the longer rod because they were less likely to hot tear. If hot tearing was observed in the shorter rod, that would reflect the severity of the hot tearing problem on the alloys. The most severe will receive the highest rating value.

The tear surface is created by tensile stress along the gage length of the specimen (sprue end to ball end). Hot tears are frequently found at the sprue end of the rod. However, cracking at the ball-end or in the middle of the rods, which is more difficult due to solidification stage, sometimes occurred. The overall hot tears were given as the summation of the individual hot-tear ratings of the six bars. A modified *HTS* parameter to assess the severity of tearing following Eq. (1) is shown in Fig. 4.

$$HTS = \Sigma(Ci) \times (Li) \times (Pi) \tag{1}$$

where *HTS* is overall hot tear susceptibility of the alloy casting, *Ci* is a numerical value used to present the degree or level of

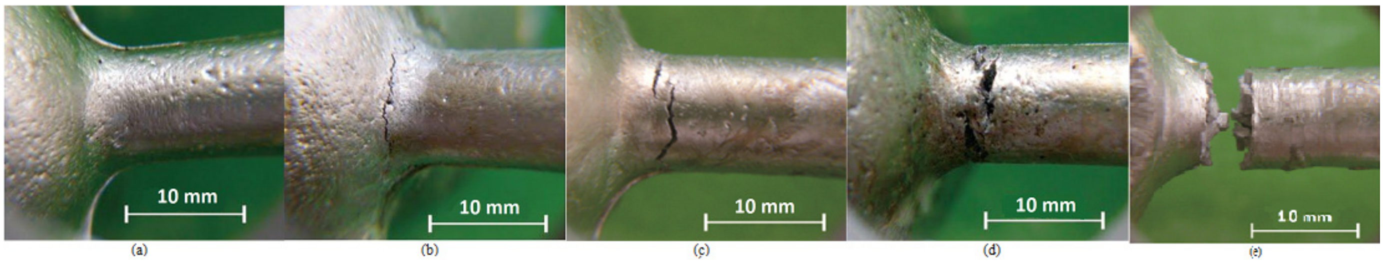

Fig. 3. Typical hot-tearing defects on the casting surface with different levels of severity: (a) no crack, (b) hairline, (c) light, (d) severe and (e) complete tear [31]

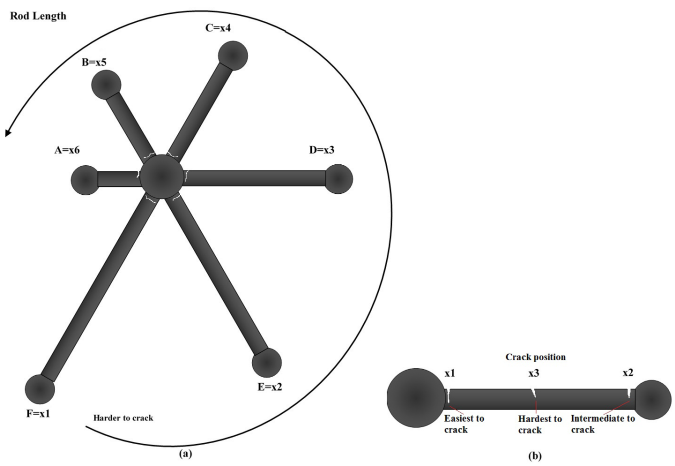

Fig. 4. Determining crack susceptibility from measured widths of crack in CRCM: (a) rod length and (b) crack position [31]

hot tear severity in the bar, *Li* is the length rating of each hot tear, and *Pi* is the position of the tear (see Table 2). Eq. (1) was modified from Eq. (2-4) to make it appropriate with the CRCM Horizontal steel mold.

TABLE 2

HTS rating system [31]

Bar length (mm)	L_i	Hot-tear Category	C_i	Hot-tear Position	P_i
51.0	6	No crack	0	Sprue end	1
73.8	5	Hairline	1	Middle rod	3
96.6	4	Light	2	Ball end	2
119.4	3	Medium	3		
142.2	2	Complete	4		
165.0	1				

Tear categories and their hot tearing severity value (*C*): a) No crack, no tear that appears on the surface of the bar; b) Hairline, a hairline tear located on the surface and that extends to a maximum of half the circumference of the bar; c) Light tear, a hairline tear that extends over the entire circumference of the bar; d) Medium tear, a tear that extends over the entire circumference of the bar and in depth; e) Complete tear, a complete or almost complete separation of the bar.

Recently many formulas have been used to evaluate the hot tearing susceptibility of the CRC apparatus. According to Agro *et al*., the formula (in Cao and Kou [22]) for Hot Cracking Susceptibility (*HSC*) is as follows:

$$HCS' = \sum f_{crack} \times f_{length} \times f_{location} \tag{2}$$

in Eq. (2), the value of the cracking width factor (f_{crack}) is 1 for short hairline, 2 for full hair line, 3 for crack, and 4 for half broken rod. The value of the crack length factor (f_{length}) is 4 for the longest rod, 8 for the second longest rod, 16 for the third longest rod, and 32 for the shortest rod. The value of the crack location factor ($f_{location}$) is 1 for cracking at the sprue end, 2 at the ball end, and 3 in the middle of the rod.

The formula modified by Cao and Kou [22], Lin et al. [25], and Nabawi et al. [29] for the hot-tear occurs. In the Kamga et al. [28], the *HTS* parameter was decided to evaluate the *C/L* ratio.

3. Results and Discussion

Fig. 5 shows the result of the Al-1.36Zn-1.19Si cast alloy in the CRCM-Horizontal steel mold. Cracks occurred in same parts, generally in the sprue area. Cracks that occurred in the sample were quantified using the parameters listed in Fig. 4 and Table 2 through Eq. (1). Bars A and B in the sample did not develop any visible cracks. In bar C, cracks of the medium tear category were visible on the sample with a crack position at about 0.4 mm from the sprue end. In bar D, a complete separation crack was found at a position of about 1.2 mm from the sprue end. Bar F exhibits a visible crack of the medium category with a crack location of about 138 mm measured from the sprue to the ball end. A summary of hot tearing severity of the samples can be seen in Table 3.

TABLE 3

Hot tearing calculated on Al-1.36Zn-1.19Si cast-sample

Bar	L_i	Category	C_i	Position	P_i	$HTS = \Sigma(L_i \cdot C_i \cdot P_i)$
A	6	No crack	0		0	0
B	5	No crack	0		0	0
C	4	Medium crack	3	Sprue end	1	12
D	3	Complete separated	4	Sprue end	1	12
E	2	Medium crack	3	Sprue end	1	6
F	1	Medium crack	3	Ball end	2	6
Total index *HTS*						36

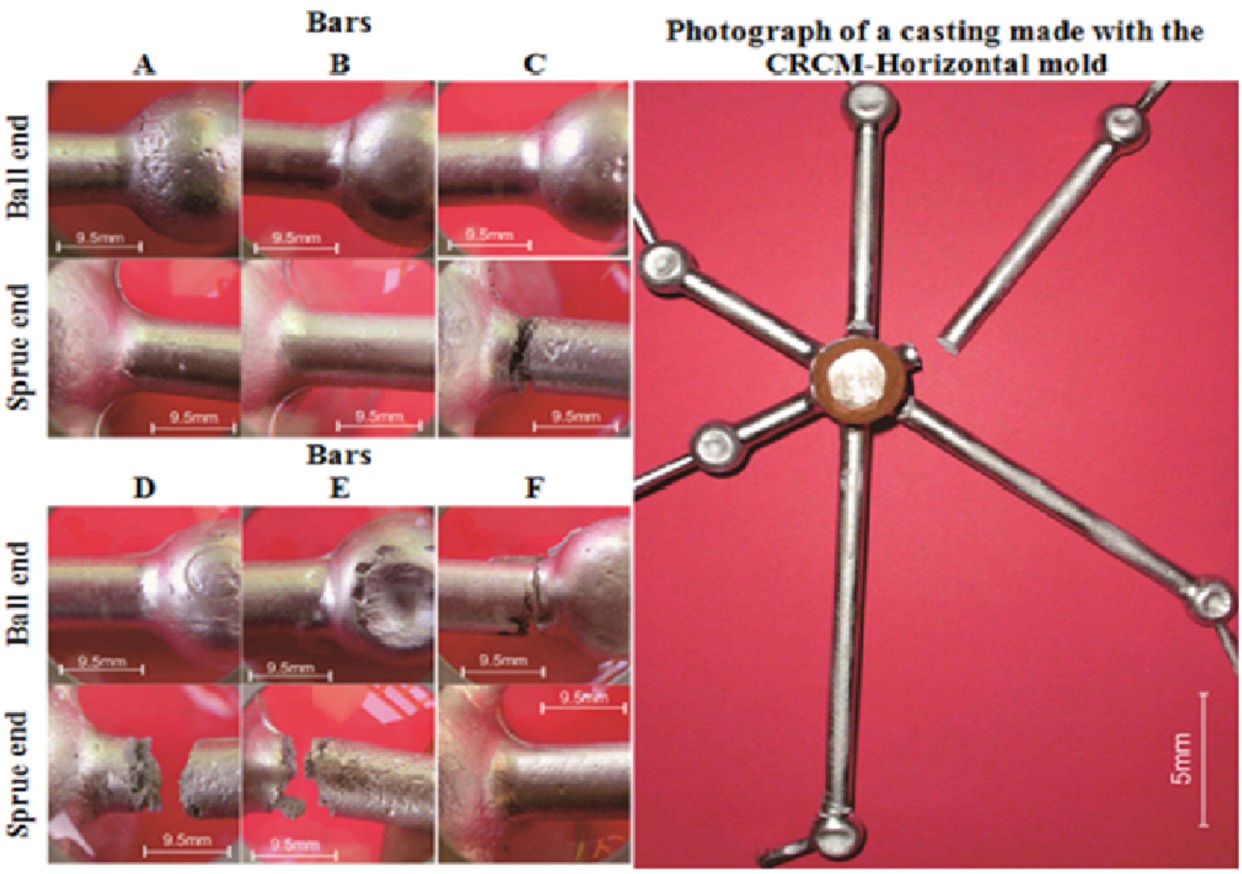

Fig. 5. Photograph of Al-1.36Zn-1.19Si cast-sample made with the CRCM-Horizontal (at sprue end – ball end)

Fig. 6 shows the hot tear cast-sample for Al-5.9Cu-1.9Mg. No cracks were found in Bar A and B, while cracks did develop on Bar C, D, E, and F, F demonstrating a crack in the complete separation category. Generally, tears are found in the sprue area. Tears generally formed more readily on the longest sample-arm. This is caused by the longest-arm developing greater stress during solidification. Shrinkage of the metal alloy produces thermal contraction, so that the longest arm generates the greatest pressure [31]. The remaining liquid feeding the mold also plays an important role in the arm because the longer arm needs more molten to feed it.

Hot tearing in the sprue area is caused by two mechanisms: (a) the sprue area is the location of last freeze, because it is in the middle of the steel mold and has different dimensions (larger) than the arms. Freezing starts from an edge of the metal-mold (from the ball to arm to sprue). When the dendrite networks are closed (bridging), then the feeding of the liquid into less-filled and unfilled areas is obstructed. Tears begin to form and grow due to stress on the arms. (b) Metal freezing in the sample arms restricts the free movement of the arms due to shrinkage. Movement is restrained by the sprue and the ball at the end of the bars.

TABLE 4

Hot tearing detection on Al-5.9Cu-1.9Mg cast-sample

Bar	L_i	Category	C_i	Position	P_i	$HTS = \Sigma(L_i \cdot C_i \cdot P_i)$
A	6	No crack	0		0	0
B	5	No crack	0		0	0
C	4	Complete separation	4	Sprue end	1	16
D	3	Complete separated	4	Sprue end	1	12
E	2	Complete separated	4	Sprue end	1	8
F	1	Complete separated	4	Sprue end	1	4
Total index *HTS*						40

Footprint charts were developed from the *HTS* values of the cast samples. Each axis on the footprint chart reflects one of the bars, the value shown on each axis is a result of $Ci \times Li \times Pi$. Fig. 7a and Table 3 show the maximum hot tear on bars C and D,

Fig. 6. Photograph of Al-5.9Cu-1.9Mg cast-sample

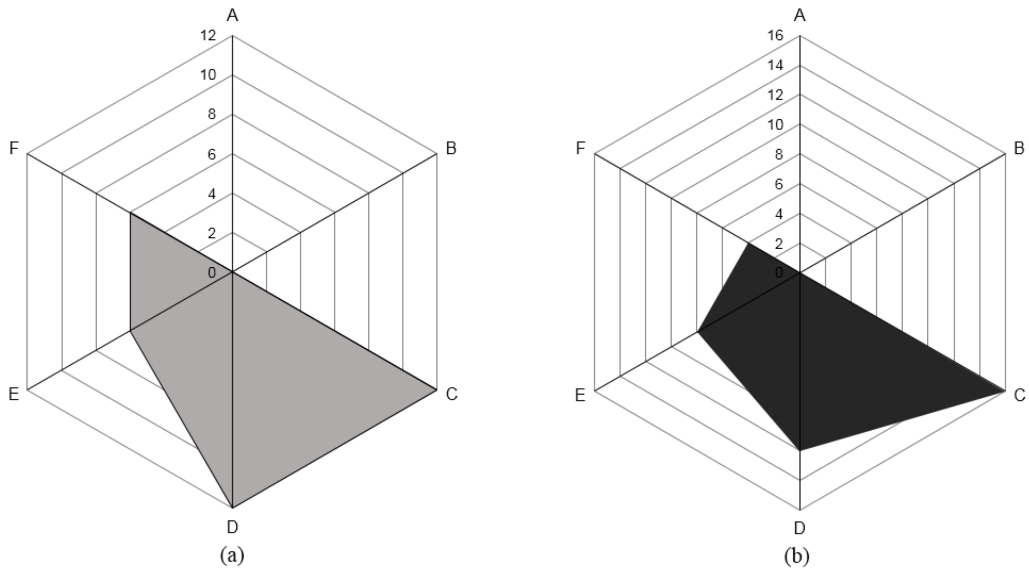

Fig. 7. Footprint charts for sample cast alloys (a) Al-1.36Zn-1.19Si and (b) Al-5.9Cu-1.9Mg

and no tear on bars A and B in the Al-1.36Zn-1.19Si cast-sample. The hot tear index in that sample is 36 *HTS*, which represents the total hot tearing formed from all bars in the sample. Fig. 7b and Table 4 show tear maximums in bars C, D, E, and F in the Al-5.9Cu-1.9Mg cast-sample. Tears did not develop in bars A and B. The hot tear index is 40 *HTS* for that alloy.

The sample for microstructure examination were cut near the sprue end of the rods in the axial direction and cold mounted in epoxy. Fig. 8a shows the optical micrographs of Al-1.36Zn-1.19Si and Fig. 8b for the Al-5.9Cu-1.9Mg cast-sample. Fig. 9 shows an SEM micrograph on the surface of the CRCM-Horizontal sample cast alloy. The image shows that the hot tearing was partially covered by interdendritic liquid and the second phase covering the tear surface. The SEM image of the tear surface shows that the area has tiny second phase covering dendrites, then the same area covered entirely with second phases and no free dendrite surface. The area with free dendrite would initiate hot tearing if that area had not been fed well when the last interdendritic network formed.

4. Conclusions

The conclusions are as follows:

1. The CRCM-Horizontal steel mold was introduced from the modified CRC apparatus for evaluating hot tear development on aluminum alloys with constrained bars and different lengths.

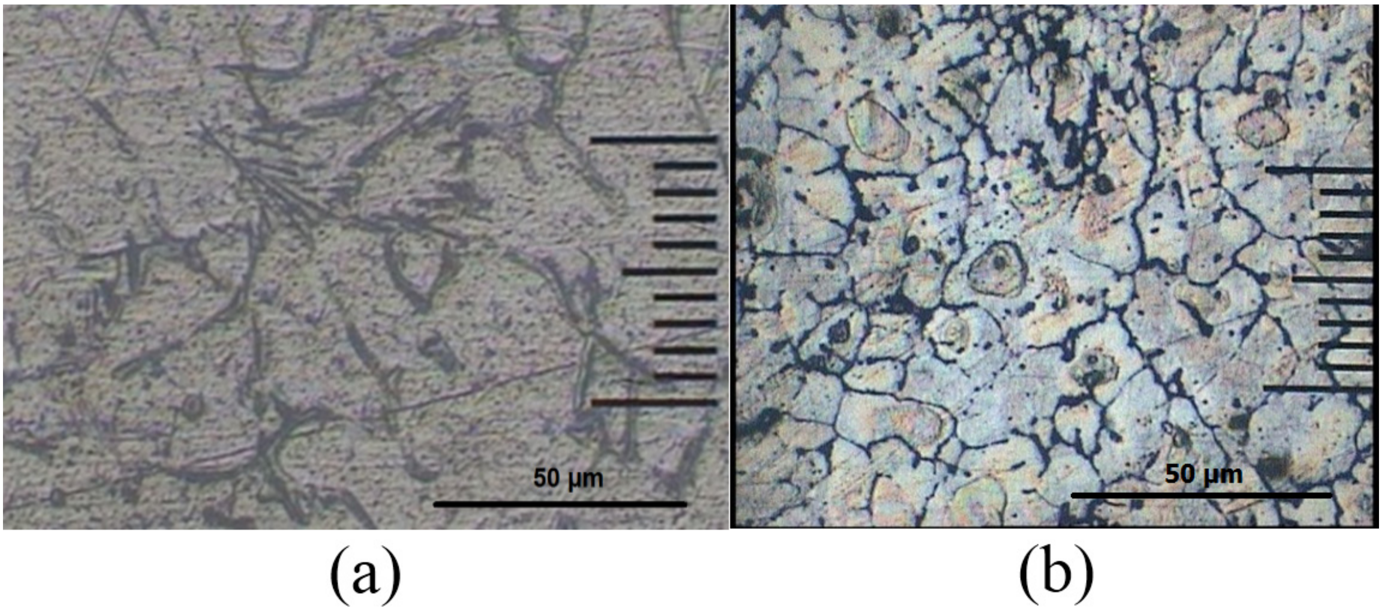

Fig. 8. Microstructures of sample cast alloys (a) Al-1.36Zn-1.19Si and (b) Al-5.9Cu-1.9Mg

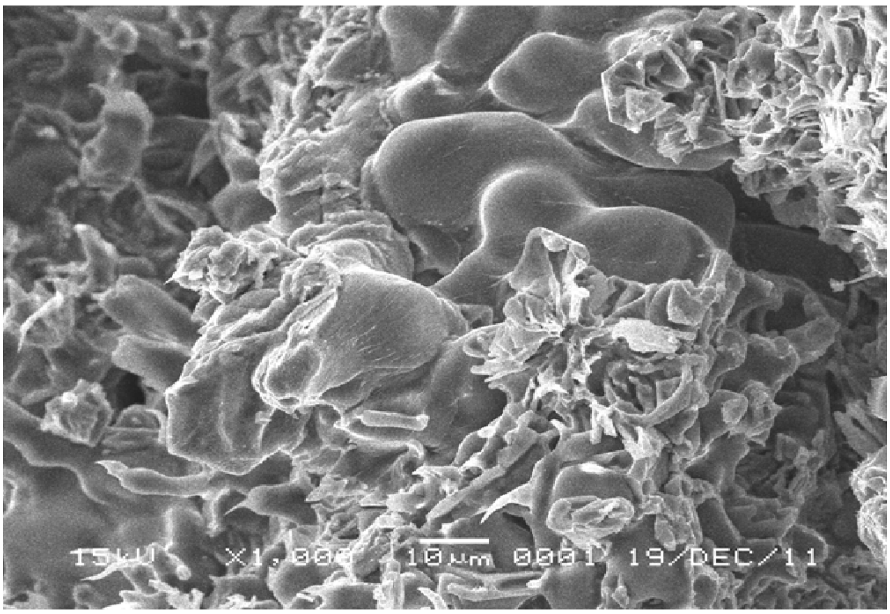

Fig. 9. SEM micrograph was taken from the hot tearing surface on the Al-1.36Zn-1.19Si cast sample

2. The new formula for quantitative investigation of hot tearing susceptibility of cast sample alloys was modified from Agro et al. and Cao and Kou's formulas based on the variation of lengths, categories, and positions.
3. Footprint charts were used to illustrated *HTS* value. The Al-1.36Zn-1.19Si alloy has an *HTS* value of 36 and the Al-5.9Cu-1.9Mg has an *HTS* value of 40.
4. Hot tears generally develop in the sprue area as a result of two factors: last solidification zone and constrained by the sprue and ball.

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