MEASUREMENT OF THE ONSET OF HOT CRACKING IN DC CAST BILLETS

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Abstract

Hot tearing is a major cause of production loss during DC casting. Billet material is most vulnerable to center cracks at start-up or at excessive casting speed. The present work aims at contributing to the understanding of the mechanisms involved and therefore focus on the steady state regime of casting. Casting experiments were performed to determine the speed at which a crack forms or when crack propagation stops. After the start-up phase it is verified that a sound billet was cast. Subsequently the casting speed was gradually increased until a crack was detected by means of ultrasonic inspection. Next the procedure is reversed by gradually decreasing the speed until the billet is sound again, all casting parameters being recorded. After casting, the location of the start and end of the crack was determined by US-testing with greater precision. Numerous samples are cut from the regions of interest and characterized by metallography. Experiments have been performed varying the alloy class (3003 vs. 5182), chemical composition, grain refinement and hydrogen content. Numerical analyses will be necessary to translate the casting parameters into more intrinsic hot tearing parameters, like the mushy zone thickness.

Introduction

The established casting recipes result from trial and error based on the experience of the casthouse people. For new products this knowledge is lacking. A long quest for better understanding aluminum DC-casting defects has driven many research efforts like in the earlier EMPACT[1] project. The present VIRCAST[2] project focuses on building a process chain model in particular by relating as-cast and homogenized structure to downstream processing investigated in the VIRFAB and VIRFORM projects[2].

One of the goals of the VIRCAST project is to further understand and ultimately prevent hot tearing. Our approach is the development of mathematical simulation tools that relate process parameters to material properties to predict the susceptibility to hot tearing. Academic[3] work needs industrial scale trials performed by the industrial partners[4]. Experimental results will firstly be used to increase background knowledge. Ultimately they will serve to validate the newly developed simulation tools [1-4].

This paper describes a set of industrial scale castings performed at the pilot caster at ALDEL (Corus Primary Aluminum) in Delfzijl in The Netherlands and at the research facilities of Pechiney in Voreppe, France. We used the same approach made of analytical model to conceive the best set of experiments, then to apply a rigorous casting procedure using in line US control and finally characterizing the final billets. The two VIRCAST alloys 3003 and 5182 have been cast, one by each partner.

Background

Hot cracking occurs at the last stage of solidification at high solid fraction. In the vulnerable region, between 85% and 99% solid fraction, the mushy material has low ductility [5], which originates from the presence of intragranular liquid films [6]. Excessive stresses exerted on such a structure will result in a crack when metal feeding is no longer possible. Metal feeding through the porous mush is governed by alloy composition, grain morphology and gas content.

Composition is a key factor. Alloying elements influence the solidification path, which is one factor governing permeability evolution. Alloys having the longest solidification interval with the smallest eutectic fractions are the more problematic as regards hot tearing. For binary alloys, elements with high tearing sensitivity are in decreasing order: Sn, Si, Cu and Mg [5]. The most vulnerable alloys are 7xxx [7], 2xxx and 6xxx [8]. Alloys 5xxx and 3xxx are not so crack sensitive and have not been fully explored, but some work exists on 5xxx [9].

From a process point of view, the casting speed is the principal factor because it directly governs the strain applied to the mush and the liquid pressure drop. Foundrymen distinguish between two casting speeds [10]: the speed at crack initiation (IS) differs from the speed at which the crack heals (HS). The experimental observation is that IS > HS. Apparently it takes more energy to initiate a tear than to propagate it. Casting temperature, grain refining and hydrogen level have a direct effect on cracking [10].

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[1] EC funded project BE 1112 “EMPACT” Brite Euram programme, contract no. BRPR-CT95-0112, 1/2/96 – 31/1/00
[2] EC funded project GRD1-10921 “VIRCAST” Growth programme, contract no. G5RD-CT00-0153, 1/3/00 – 29/2/04. VIRCAST, VIRFAB (transformation) and VIRFORM (forming) are joint projects gathered in VIR[*] cluster program.
[3] Scientific partners in VIRCAST-WP1 “Hot Tearing” are SINTEF, INPG, IFE, NTNU, EPFL and CALCOM. SINTEF leads this work package. Industrial partner CALCOM implements the knowledge in software tools.
[4] Industrial partners in VIRCAST-WP5 “Large Scale Experiments” are former Algroup (now ALCAN), ELKEM, CORUS, PECHINEY, HYDRO and former VAW (now HYDRO). CORUS leads this work package.

Experimental procedure

In these experiments a billet of 10" (ca. 250 mm) diameter is cast with Wagstaff Hot Top AirSlip™ tooling in a dual mould set-up. Two billets can be cast in parallel from the same melt. One of the billets may also be shut-off, which allows performing a second experiment shortly after the first one. Once the cast is in the stationary phase, absence of center crack (and porosity) is verified by ultrasonic (US) testing in the pit during casting. After this, the casting speed is ramped-up gradually to a pre-set maximum speed or until a crack is detected by US testing. Next the casting speed is ramped down again to the original starting speed. Cooling water flow rate and metal temperature are kept constant as far as possible within the experimental and equipment limitations. After casting the cold billet is inspected with US with a better precision than is possible "in-situ" to find the crack start and end. In fact it is still unclear at that moment if the observed evolution of the US signals is really caused by cracks, but this is confirmed later by sectioning of the billet. In the case of dual billet casting the duplicate billet serves to prove the reproducibility of the experiment, i.e. to prove that differences between the individual moulds or cooling water flows have only minor effects on cracking (as long as they are in good working condition).

Design Of Experiments

The main cause of difference between the experiments performed is found in the selected alloy systems, being the 3000 series in Corus and the 5000 series in Pechiney. The selected variations in chemical composition have been set-up by use of Design of Experiment method.

Analytical Hot tearing susceptibility. The solid fractions of designated compositions as function of temperature have been calculated beforehand with Alstruc[5] to verify the influence of composition on the solidification interval. Back diffusion and a cooling rate of 3 °C/s have been used in the microsegregation computation. The solidification paths were used to compute the Hot Crack Susceptibility (HCS) by the Rappaz-Drezet-Gremaud approach [2], which returns two integral terms A and B associated with the pressure drop and the feeding deficiency[6]. The larger A and B, the more crack sensitive the alloy.

3003. Table I presents the DOE composition for 3003. This plan is dedicated to Si, Fe and grain refiner effects and secondly on Cu and Mg. Mn is kept constant. Ti has no direct influence on the solidification path but it affects the microstructure morphology via grain refining phenomenon. Also, Table I reports the values of the integrals A and B of the RDG criteria and the solidification characteristics given by Alstruc. Variants 2 and 5 are high because of higher Si, variant 8 is high because of higher Cu and Mg, whereas variant 9 is low because of lower Cu and Mg.

[5] ALSTRUC – results made available by A-L. Dons, SINTEF. Courtesy of ELKEM, HYDRO and SINTEF.
[6] Integrals made available by JM. Drezet, EPFL/Calcom.

Table I: 3003 DOE and HCS integrals
Mn is equal to 1.0 wt%

ar	Si	Fe	Cu	Mg	Ti	GR kg/t	A	B
0	0.15	0.30	0.50	0.25	0.005	0	2448	27267
1	0.15	0.15	0.50	0.25	0.005	0	2459	27524
2	0.30	0.30	0.50	0.25	0.005	0	2612	31092
3	0.15	0.30	0.50	0.25	0.013	1.5	2442	27146
4	0.15	0.15	0.50	0.25	0.013	1.5	2451	27342
5	0.30	0.30	0.50	0.25	0.013	1.5	2606	30941
6	0.15	0.30	0.50	0.25	0.020	1.5	2431	26906
7	0.15	0.15	0.50	0.25	0.020	1.5	2440	27102
8	0.15	0.30	0.70	0.30	0.005	0	2662	32216
9	0.15	0.30	0.30	0.20	0.005	0	2217	22390

5182. The most sensitive elements have been chosen for designing 5182 experiments. The decision was based on the same analytical procedure as before. Terms A and B of the HCS criterion are gathered in table II. The reference is the standard 5182. Only one element was changed at a time, in addition or subtraction. Si and Cu were the most sensitive elements with respect to their small composition variations, but Mg and Cu had the largest effects to HCS. The 5182 DOE was designed to be a square factorial in Cu and Mg, other elements were kept constant.

Table II: 5182 DOE and HCS integrals

Var	C_0 wt%	Var. wt%	A	B
5182	**-**	-	**591**	**2830**
Si-	0.10	-0.05	500	2218
Fe-	0.25	-0.20	665	3345
Cu+	0.06	+0.09	401	1671
Mn+	0.35	+0.15	585	2793
Mg+	4.50	+0.50	296	1050

3003 Castings

Experimental procedure

The experiments were performed at the pilot caster of ALDEL, Corus Primary Aluminium in Delfzijl, The Netherlands. The casting pit has a depth of 2.5 m. The furnace capacity of 850 kg allows casting of two full-length billets (ca. 2.3 m) at once. Water flow rate of 6.5 m^3/hr for 2 billets was kept constant. The melt is degassed in the furnace with a rotor prior to casting. In-line filtering with CFF is possible but was not done.

Following a standard start-up casting procedure, soundness was tested in the pit by manually pressing the US-transducer well below the mould and the sump. When absence of crack was confirmed the speed was increased. As the pit was at the time of the experiments not yet fully automated the casting speed was ramped manually, which is of course not very accurate (cf. fig. 1). When the speed was raised so much that a crack was clearly detected by US the procedure was reversed until the crack had vanished. All casting data were captured. Afterwards the cold billets were once more inspected using traditional manual US equipment to determine the start and end positions of the crack. These positions were then related to the captured casting speed at that length.

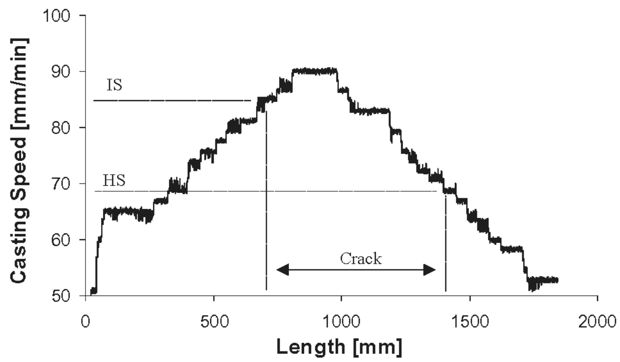

Figure 1: Example of manual speed ramp for 3003 casts

Results

As experimental conditions are not always fully under control some deviations from the target are to be noted. First of all the target chemical composition was not always achieved as may be seen from the actual compositions presented in table III. Several experiments were repeated more than once, hence added subscripts a, b, etc.

Table III: 3003 actually achieved compositions in wt%

Var	Si	Fe	Cu	Mn	Mg	Ti	B
0a	0.16	0.32	0.47	0.97	0.24	0.004	0.0006
0b	0.18	0.28	0.49	1.04	0.32	0.006	0.0005
1a	0.18	0.25	0.56	1.00	0.34	0.006	0.0005
1b	0.14	0.16	0.50	0.92	0.25	0.013	0.0004
2a	0.30	0.32	0.49	0.99	0.25	0.015	0.0007
2b	0.31	0.32	0.50	1.00	0.25	0.015	0.0006
2c	0.30	0.32	0.48	1.09	0.25	0.007	0.0023
3	0.15	0.30	0.56	1.03	0.23	0.012	0.0005
4	0.14	0.16	0.50	0.92	0.25	0.013	0.0004
5	0.30	0.38	0.54	1.07	0.23	0.012	0.0019
6	0.15	0.32	0.59	1.04	0.24	0.013	0.0011
7	0.14	0.14	0.58	1.04	0.35	0.020	0.0005
8a	0.13	0.26	0.71	0.90	0.29	0.010	0.0007
8b	0.13	0.25	0.68	0.91	0.28	0.013	0.0010
8c	0.13	0.26	0.72	0.91	0.28	0.007	0.0004
8d	0.18	0.30	0.81	0.99	0.29	0.007	0.0004
9	0.16	0.31	0.29	0.97	0.18	0.0044	0.0007

The measured casting speeds relating to beginning (IS) and end (HS) positions of the crack are presented in table IV and figure 2. When two speeds are given they concern the values observed in twin cast billets. As already pointed out, speed ramping was performed manually, which is one cause of variation in the observed start and stop speeds. Other causes are, e.g. uncontrolled casting temperature variation.

A first point to note is the considerable variation in initiation speed observed of about 40 %. While solidification path and RDG criterion suggested a low HCS value in variant 9 vs. a high HCS in 2, 5 and 8 the experimental results show a quite different outcome. Multivariable analysis is reported by table V.

Only Si, Fe, Mn and B were found to contribute significantly (P-value > 1%) to the statistical explanation of crack initiation speed. All other factors including casting temperature were found insignificant in this set of observations. Mn is the only element with a negative contribution. Fe and Si are found to work in the opposite direction: higher Fe and Si raise the crack initiation speed, i.e. lower the HCS. B, meaning grain refining, has a considerable effect, as well known in the industry.

Table IV: Casting speed at crack start and stop in mm/min

Var	IS	HS
0a	77 – 80	62 - 65
0b	64	
1a	67	61
1b	63	59
2a	95	
2b	92 - 95	74
2c	90	69
3	70	
4	71	67
5	99	72
6	80	
7	67	
8a	80	70
8b	83	-
8c	83	57
8d	71	53
9	83	64

Figure 2 presents these results in graphical form. Please note that they are sorted in increasing order of crack initiation speed, which is the inverse of HCS.

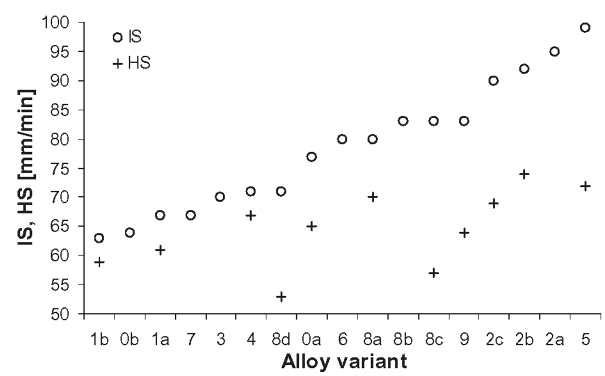

Figure 2: 3003 casting speeds when cracks form and vanish

Table V: Regression coefficients obtained
Overall standard error of 3.8 mm/min

	Coefficients	Coeff Error	P-value
Intercept	173	20.9	0.00%
Si	92.2	19.5	0.05%
Fe	124	21.5	0.01%
Mn	-156	25.6	0.01%
B	9430	2340	0.16%

5182 Castings

Experimental procedure

The sensitivity of 5182 to hot cracking was explored at Pechiney CRV automatic casting pit equipped with a 2 tons furnace and an

Alpur™ for inline liquid metal treatment, able to cast 3.5 m long products. Only one single billet was cast. Several casts were used to define the casting conditions: maximum casting speed set to 155 mm/min, pouring temperature set to 680-690 °C and water flow rate set to 11 m^3/h for two billets.

The Design Of Experiment was centred on the influences of the Cu and Mg contents (cf. Table VI). Grain refiner (Al5%Ti1%B) was or wasn't used. Moreover, casts were done with and without adding H_2. Two H_2 levels were reached directly in the Alpur™ by either using an Ar+Cl_2 gas treatment or by supplying Ar+5%H_2 gas [11]. The amounts of grain refiner or H_2 were in excess in order for their effects to be casting speed independent.

Table VI: 5182 actually achieved compositions in wt%

Fe	Si	Mn	Cu- ; Cu+	Mg- ; Mg+
0.26	0.11	0.37	0.062 ; 0.155	4.57 ; 5.07

The casting procedure was to use up and down speed ramps (cf. Figure 3). They were never changed during casting, whatever the US-sensor detected.

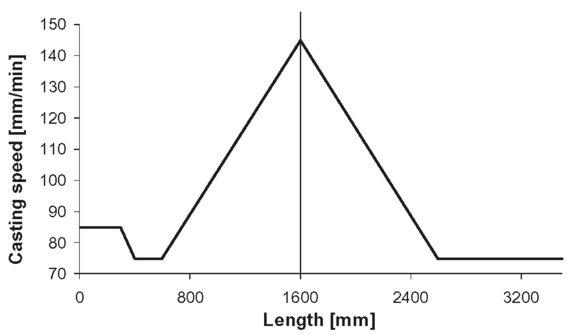

Figure 3: Prescribed speed pattern for 5182 casts

Casting characterisations

Casting parameters, like casting speed, pouring temperature and water flow rate, were recorded. The variable metal flow rate induced casting temperature variations.

The temperature field. The sump depth evolution was recorded around cast length 1600 mm, near the maximum drop speed position by touching the coherency front with a rod. The maximum sump depth was shifted by 250 mm from the maximum casting speed (cf. Figure 4). This lag is caused by thermal inertia of the sump in response to the constantly increasing casting speed.

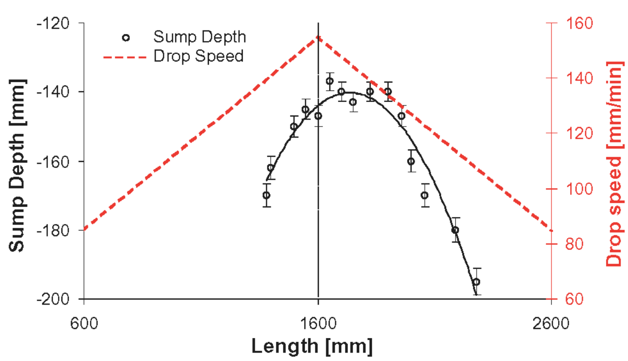

Figure 4: Sump depth measurement during drop speed variation

The H_2 level in the liquid metal was recorded using an Alscan™ system which was positioned in the trough behind the Alpur™. Each cast lasted about 30 min, which is enough to get at least two relevant measurements.

An ultrasonic system recorded hot cracking live. It was made of:

- The conventional ultrasonic head was positioned 200 mm below the mould in order to circumvent the deepest sump. The transducer has a diameter of 25 mm and an operating frequency of 2.25 MHz. A water box ensured a good contact between the transducer and the billet. The US waves traveled through 30 mm thick water before entering the billet. This extra water layer also cooled the transducer.

- The ultrasonic profile in the billet was recorded using a µtomo by RD/Tech.

Figure 5 displays recordings of two different casts. The measurements are presented as 2-D maps of US signals. The horizontal axis displays the travel time in the billet from left to right. The back echo is at a diameter distance to the entrance echo. The vertical axis is the casting time, related to the position in the billet. These US intensity maps are a picture of the defect distribution. The horizontal dotted lines position the maximum casting speed times.

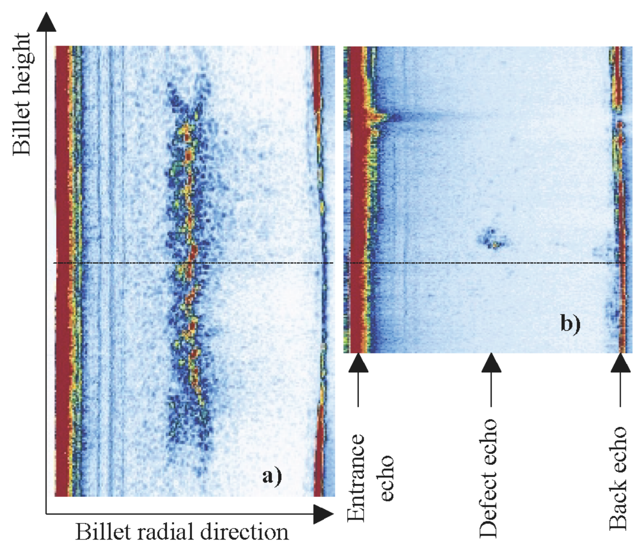

Figure 5: In line recording of the US signal for a) non grain refined cast and b) grain refined with a crack variant 720-2. The horizontal line marks the maxi drop speed

Traditional US inspection was performed on each cold billet. Billet bottoms were inspected, but no crack was found. The positions of crack start and stop were recorded in terms of positions from the bottom. Variant 720-2 had a crack starting at position 1615 mm and ending at 1750 mm. The starting is after the maximum casting speed, this is due to the thermal inertia (cf. Figure 5).

Optical verification was performed to validate the US measurements, as well as to record crack width and shape. Both line and spider cracks were observed, all spanning over 25 to

30 mm (cf. Figure 6[7]). They are very fine and not widely opened, but the aperture was sufficient for the dye to penetrate. Metallographic observations proved that cracks are intragranular. The microstructure of unrefined alloys shows a combination of equiaxed and globular grains in the billet center.

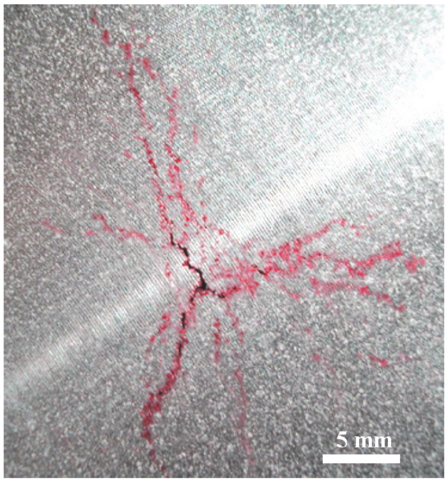

Figure 6: Optical observation of crack

SEM observations proved defects to be hot tearing (cf. Figure 7). The fracture surface revealed dendrite shapes covered by precipitates of various structures. Quantitative analysis of precipitates revealed compounds made of (Al-MnFeMg), (Al-MnFeMgSi) and (Al-MnFeMgCu).

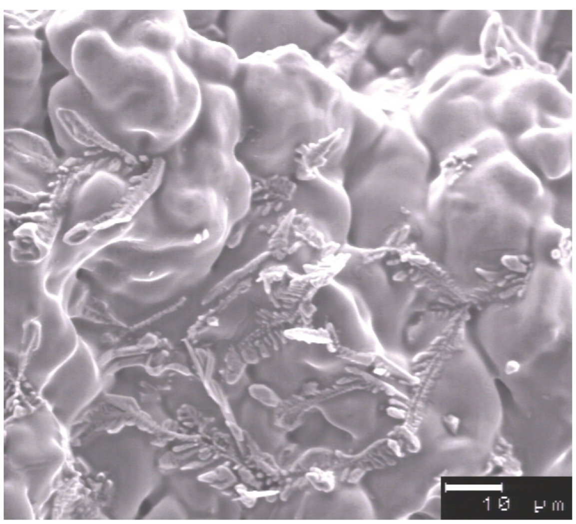

Figure 7: SEM fractography – SDAS scale

Results

The crack positions were translated into speeds, which are the speeds at the local cast lengths. Table VII presents the measured Initiation Speed (IS) and Healing Speed (HS) in the different casting conditions. Within the range of hydrogen levels, no clear effect on cracking can be seen. Grain refining is found to increase the crack initiation speed strongly, but does not suppress tearing.

Table VII: 5182 hot tearing results with DOE parameters

Var	Cu wt%	Mg wt%	GR	H_2 cc/100g	IS mm/min	HS mm/min
717-1	0.06	4.60	-	0.247	122	115
717-3	0.06	4.60	-	0.213	113	110
721-1	0.06	4.49	-	0.2	119	110
721-2	0.06	4.49	+	0.2		
721-3	0.06	4.49	-	0.3	117	112
721-4	0.06	4.49	-	0.3	113	107
718-1	0.065	5.11	+	0.212		
718-2	0.065	5.11	-	0.180	118	120
718-3	0.065	5.11	-	0.190	121	119
718-4	0.065	5.11	-	0.230	124	124
719-1	0.152	4.66	-	0.218	105	105
719-2	0.152	4.66	+	0.2	131	77
719-3	0.152	4.66	-	0.263	124	118
719-4	0.152	4.66	-	0.265	114	107
720-1	0.16	5.02	-	0.214	122	118
720-2	0.16	5.02	+	0.197	154	145
720-3	0.16	5.02	-	0.298	129	118

In most cases IS > HS. Grain refined variant 719-2 shows a strange behaviour, low IS and the lowest HS measured. This result has been ignored. Table VIII gathers mean critical speeds for the four main compositions. Mg has a clear tendency to prevent hot tearing. Even if it is less clear, the same holds true for Cu. Results are compatible with HCS first calculations.

Table VIII: Mean composition effects on critical casting speeds Non grain refined castings only.

Variant	Cu	Mg	IS	HS
717 - 721	0.060	4.60	117	111
718	0.065	5.11	121	121
719	0.152	4.66	114	110
720	0.160	5.02	126	118

Figure 8 presents the results in graphical form sorted by increasing order of crack initiation speed.

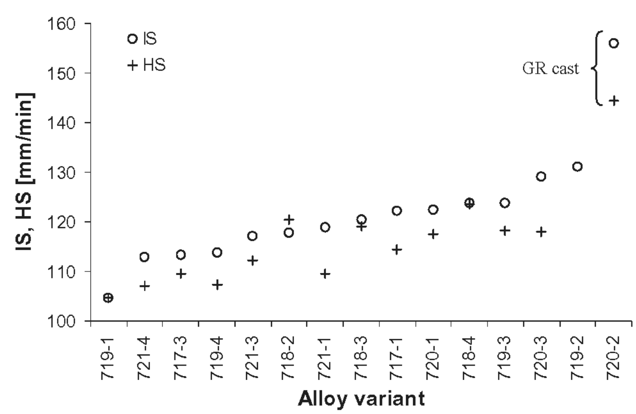

Figure 8: 5182 casting speeds when cracks form and vanish

[7] Crack picture made available by P. D. Grasso, EPFL. Red dye technique to reveal crack.

Discussion

Comparison between alloys

The HCS criterion predicts that 3003 alloys as more prone to crack than 5182. This is supported by the previous experimental results. 10" billets in 3003 have critical cracking speeds [53-99 mm/min] far lower than those for 5182 [105-150 mm/min]. One reason is the water flow rate, twice smaller for 3003 than for 5182 cast. Another reason is that the feeding deficiency does not only depend on mush thickness (solidification interval) but also on the permeability evolution, which is linked to the solidification path (cf. Figure 9).

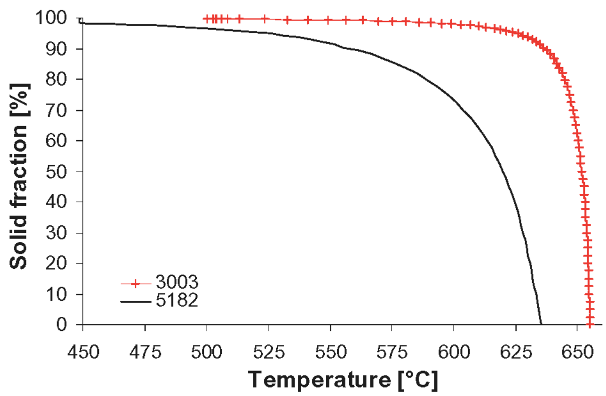

Figure 9: Compared solidification path of cast alloys

The Fs curve is an image of the interdendritic space evolution within the mush. The 3003 Fs curve is strongly asymptotic near Fs=1 due to solute effects. The 5182 alloy has a lower solidus temperature but is less tangential towards Fs=1 due to the presence of a larger residual eutectic liquid fraction, which makes mush feeding easier.

Comparing 3003 and 5182, elements like Fe, Cu and Mg have opposite influences on hot tearing. Only Si causes a decrease in crack speeds in both alloy systems.

Comments on result interpretation

Each cast provided locations in the final billet of start and end of cracks. The common procedure is to associate this position with the cast length where the defect occurs, which is then related to the local casting speed. The present results have been analyzed in this way, but this is inaccurate for two reasons.

Fact 1. When the casting speed changes, it changes instantaneously in the whole solid billet, but the mush shape and the thermal strains react with a delay due to thermal inertia. The billet is in a kind of perpetual transient state. This is proven by the various measurements made during the casts. At one point, the defect measured is a consequence of a former casting condition. This leads to an **overestimation** of crack position. This lag depends on the alloy, the size of the billet (format) and the slope of the speed ramp.

Fact 2. On the other hand, the assumption that the measured position of the defect is the cast length where it occurs is wrong. Hot tearing occurs at the bottom of the mush in the billet center, i.e. the lowest point of the mush and the farthest from the mould: Lcrack < Lcast. This leads to an **underestimation** of crack position. This effect depends on the sump depth, which is a function of the alloy and the product S.D^2 (S=Casting Speed, D=Diameter).

These two facts have opposite effects that roughly cancel out. The traditional approach to read crack speed as the local speed at crack location is good at first glance. But the consequence is that usually IS > HS, which was interpreted as the physical necessity to provide more energy to tear the matter than to propagate the defect. However, the gap IS-HS is not constant among casts. IS and HS have been measured with respect to a given dynamic situation. A numerical analysis is needed to differentiate the various contributions of facts 1 and 2 as effects of the transient conditions (casting speed, pouring temperature).

Live US inspection

In grain refined casts, a crack was only detected once near maximum drop speed (cf. fig. 5.b). It is very small and the US-signal was not analyzed correctly.

For unrefined casts, the US signal along the billet height is divided in two areas: the body and the head/tail (cf. fig. 5.a). The body is located along the billet center and is a very strong echo, i.e. a crack. Also the head/tail signals are smoothly increasing/decreasing. They are symmetrical. The US signals in the billet center and at the back appear and disappear simultaneously (cf. Figure 10). There is no no-man's land where one vanishes before the other appears. The signals in head/tail areas are more diffuse and spread than in the body, analyzed as porosity. They are of two shapes:

- **">-<"**. The extremity signals have a fork shape, suggesting that the crack initiates from an off-center position, on an annulus (cf. fig. 5.a). Later optical observations showed mostly spider cracks.
- **"---"**. The extremity signals are straight suggesting that the defect initiates in the center. Later optical observations showed mostly line cracks.

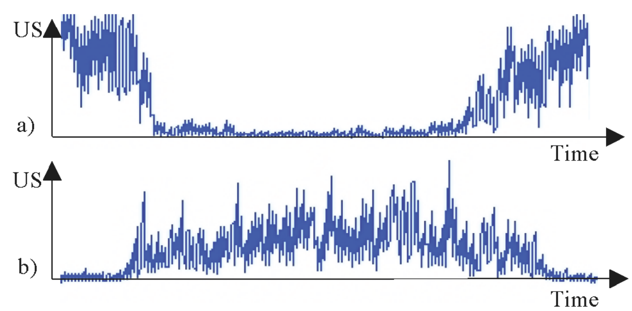

Figure 10: Comparison of a) back and b) central echo intensities. The crack initiation is on the left and crack end is on the right.

Conclusion

Part 1 of the 5th framework VIRCAST project is dedicated to the industrial problem of hot tearing, by understanding the physical phenomenon and on building a model validated against measurements on 3003 and 5182 alloys. These industrial alloys have been cast at Corus and Pechiney facilities. A rigorous casting procedure with help of in line US characterization was applied.

Composition, grain refinement and hydrogen level have been changed.

The casting procedure is based on a speed ramp technique. A crack initiates during the speed increase and heals during the speed decrease. Those two critical speeds IS and HS are the cast results. They were found to be very sensitive to grain refining and not to H_2 content. 3003 is more crack prone than 5182, with specific casting parameters. Element sensitivity is very alloy dependent.

This technique is accurate but not intrinsic. IS and HS are measured with respect to a given speed ramp and cannot be extrapolated in casting conditions. More intrinsic critical speeds will be obtained by numerical analysis to differentiate the casting parameter influences. This is the next research step of VIRCAST project on hot tearing.

Use of US inspection during casting is powerful to get a live feedback for casting procedure optimization. Also, this non-destructive tool was used to get an image of the defect distribution inside the billet. Diffuse porosity is present at crack start and stop. Crack concentrates in the billet center on a porosity bed. Initiation and healing are symmetrical phenomena.

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