Reducing Crack Potential in CA40

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Background

Martensitic stainless steels such as CA40 are widely used in various applications due to their higher strength potential, responsiveness to heat treatment, and moderate corrosion resistance. Monett Metals Inc. produces a variety of wear components for use primarily in food-type extrusion applications. These parts are cast out of several different types of martensitic stainless steels. This product line accounts for approximately 45% of business, with the CA40 material attributing to nearly 35%. These products are supplied raw and in the annealed condition, and ultimately hardened after machining and polishing operations.

Introduction

Initial customer nonconformance reports were concerning a sizeable quantity of CA40 extrusion screws that exhibited visible cracks after polishing and machining operations. Most of these were contained with in-process customer weld repair to maintain production. These and similar castings had been in steady production at Monett for just over a decade. Throughout that time, only a handful of nonconformance reports had been received for similar issues. It is unclear whether this was an existing issue. Though not confirmed, it is speculated that customer disposition procedures and quality criteria have seemingly increased (as obviously seen throughout industry in general), and that this may not be a new development but rather now dealt with in a different manner; processes at Monett had seen no drastic changes in that time.

Though difficult to confirm on a near finished casting, most of the indications appeared to be in consistent locations. Those locations appeared to be riser bearing areas. A handful of castings were returned for review, only to confirm via magnetic particle inspection that cracks were present.

Immediate containment actions consisted of 100% magnetic particle inspection of all finished CA40 screw type castings prior to shipping. Amidst this containment phase, it was discovered that most CA40 screw type castings in process displayed related cracks. The issue was relatively prominent between various sizes, as well as geometry variations. Most cracks were identified on or near riser contact areas. Some parts displayed a higher severity of cracking issues than others. Those castings originally brought to attention displayed completely consistent and repetitive issues, and for the purpose of this report, shall be considered the subject casting.

Material Information

These castings are produced out of A743 CA40 material. However, the Carbon content is restricted to the top end of the range (see Table 1 below). Aluminum and Titanium are used as deoxidants and are added as the ladle is tapped at about 25% full; typical values are .03% for both elements. The melt is conducted under an argon shroud, which reduces interactions between the molten material and atmospheric gases. Lastly, the castings are annealed to 207- 250 Brinell.

C	Mn	P	S	Si	Cu	Ni	Mo	Cr	Al	Ti
.35-.40	1.00	.04	.04	1.50	-------	1.0 Max	0.5 Max	11.5-14.0	------	------

Table 1- Chemistry Specification

Casting Detail

The subject castings are approximately 9 inches in overall diameter and about 17 inches in overall length. The cast weight is 109 pounds, and they contain just under a 2-inch maximum section thickness at the flight/ body intersection.

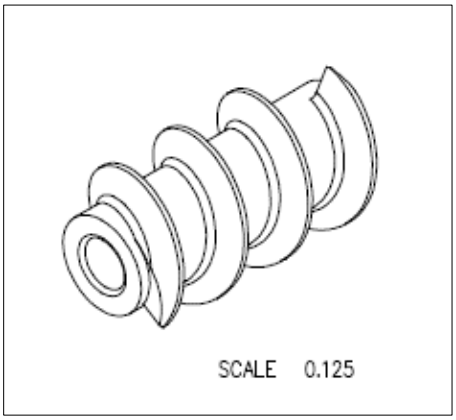


Figure 1- 3D Casting view

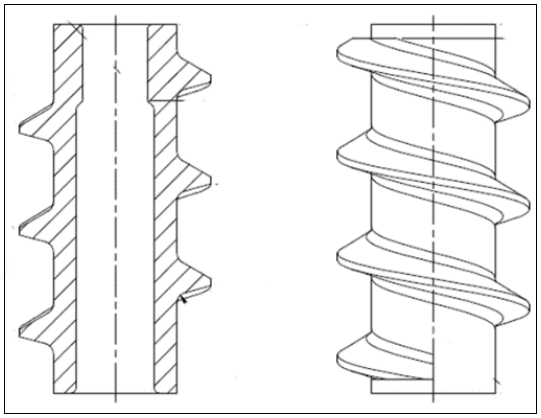


Figure 2- Casting cut section/ side view

Defect Information and Investigation

The cracks were found to be sporadic in both orientation and quantity, though there were usually multiple within a region. They were predominantly jagged in nature and identified in clusters. Cracks on near finished castings that had been polished were typically visible with the naked eye (bear in mind that castings in this state are in customer hands). Cracks on raw castings were usually only visible under magnetic particle inspection.

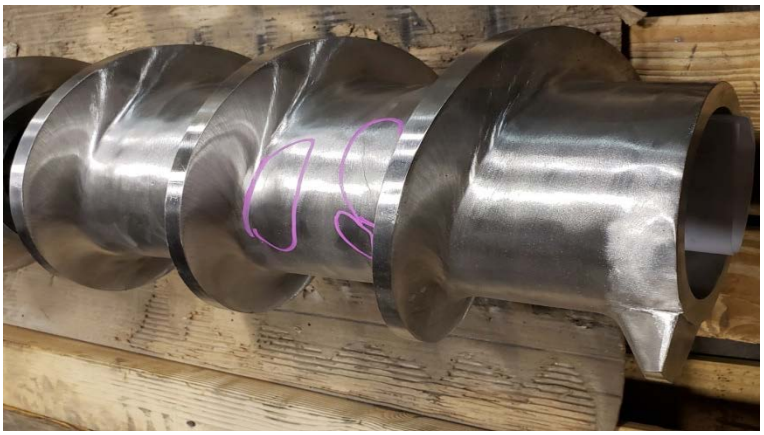


Figure 3- Visible cracks on near finished casting

Figure 4- Visible cracks on near finished casting

Figure 5 displays typical indications revealed under blacklight on a raw, in process casting. The jagged, nonlinear identity of the cracks can be noted as a modeled illustration to the cracks that were identified on most related CA40 castings. Occasionally, it was found that some cracks at the ends of the castings did break over into the inner diameter; however, due to the location, linear nature, and inconsistency, these were attributed at a greater degree to tearing issues related to possible constraints during solidification. It seemed that the bulk of the issues at hand correlated to riser locations.

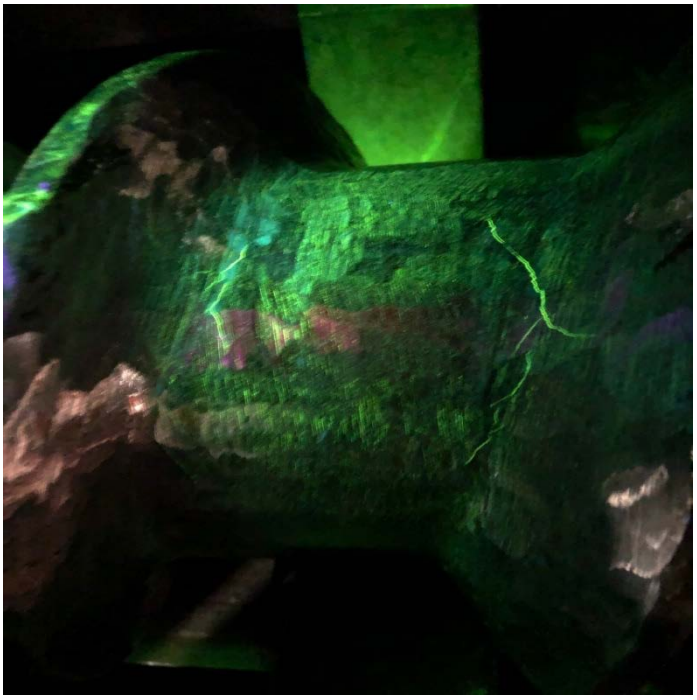


Figure 5- Cracks on raw casting identified under blacklight

Figure 6 below illustrates the subject casting as rigged with the corresponding defect rates at each riser contact area. The end risers are 3 inches in diameter and the center riser is 4 inches in diameter but tapers down to a 2-inch contact area on a square pad. A collection of data was compiled from extensive in-process magnetic particle inspection to determine severity and location correlation of the cracks. The center riser location proved to be the most consistent, as 100% displayed cracks in this region. Somewhat interestingly, it was observed that this is the shortest riser of the three. The riser to left side of the sprue, which has a slightly larger contact are than that of the right, exhibited roughly a 50% crack rate, and the riser to the right of the sprue displayed a mere 10% or less. It was unclear at this point whether the observed crack rates correlated to overall riser sizes. It was speculated that increasing height or diameter of some of the risers may reduce cracking potential if the cracks were somehow shrink induced. However, due to the magnitude and consistency across a plethora of different parts, it was found unreasonable to pursue such an action without further investigation.

An added uncertainty at this point was the depth of the cracks. Since only surface examinations had been conducted, it was unclear whether the cracks extended sub-surface. Radiography was conducted on two pieces that were confirmed to contain cracks, but results were deemed inconclusive, as no indications were identified. It appears the cracks may have been too fine to be detected in this manner. No other forms of non-destructive testing were pursued.

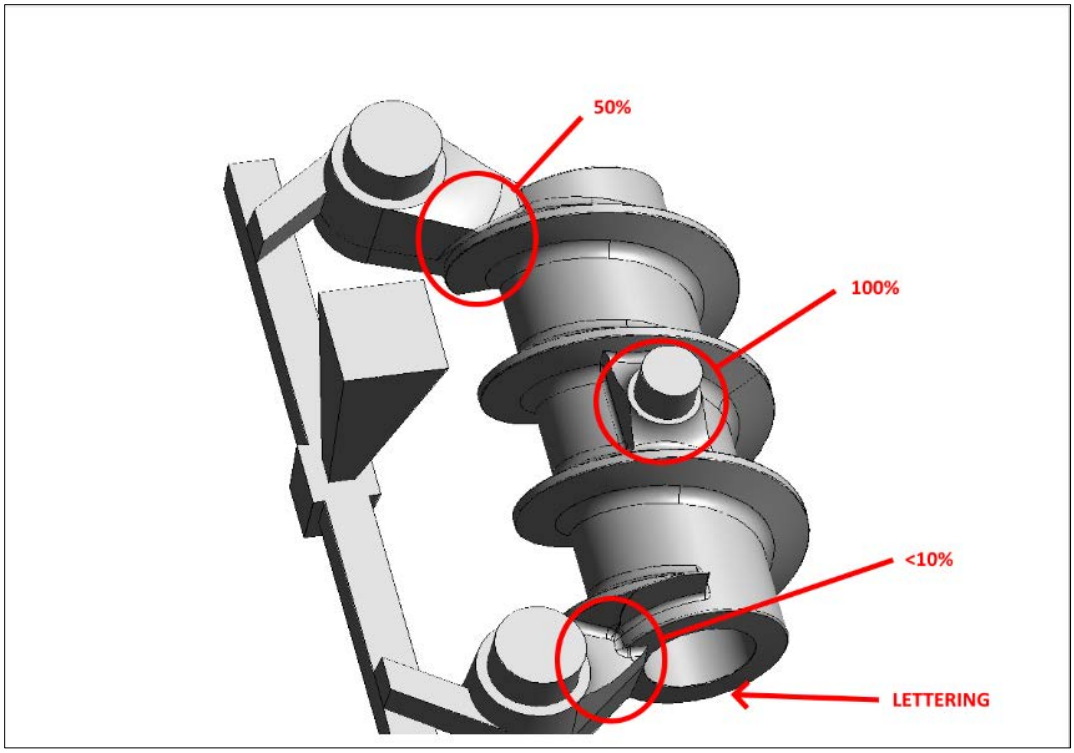


Figure 6- Approx. defect rates/ rigging model

A sample was chosen for mechanical excavation to determine representative depth. The original indication identified on a contact area appeared as axial running down the top flight with a smaller transverse indication at the radius of the flight and body intersection. Figure 8 details the excavation of the subject casting. The excavation revealed that there is a sub-surface continuation and networking of the cracks at various depths.

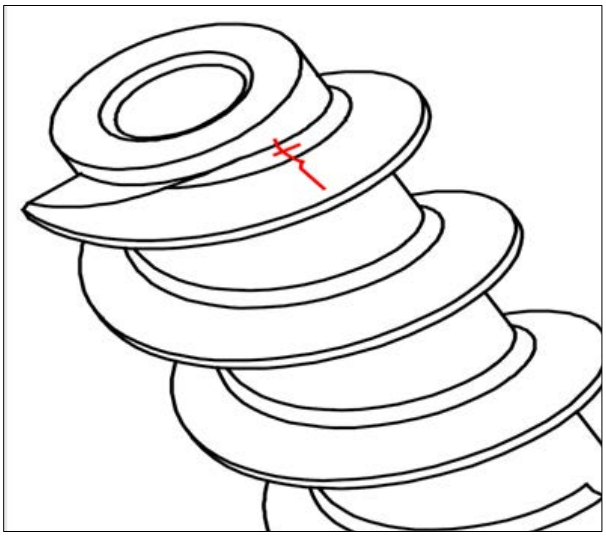
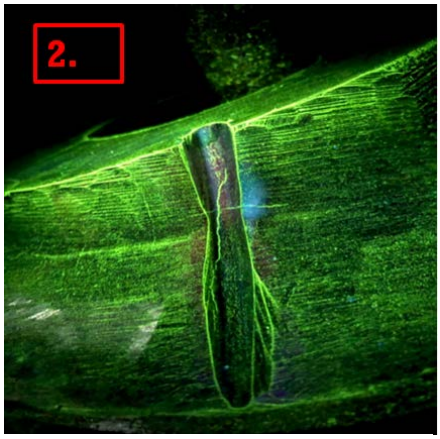
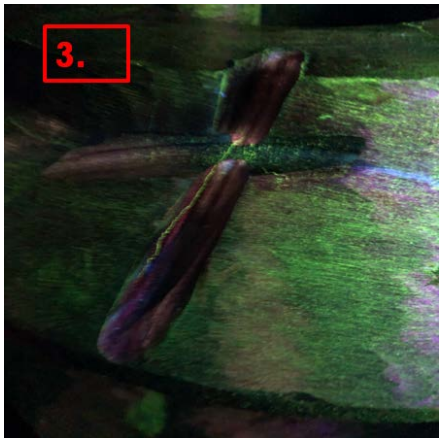


Figure 7- Top section illustration of original indication.

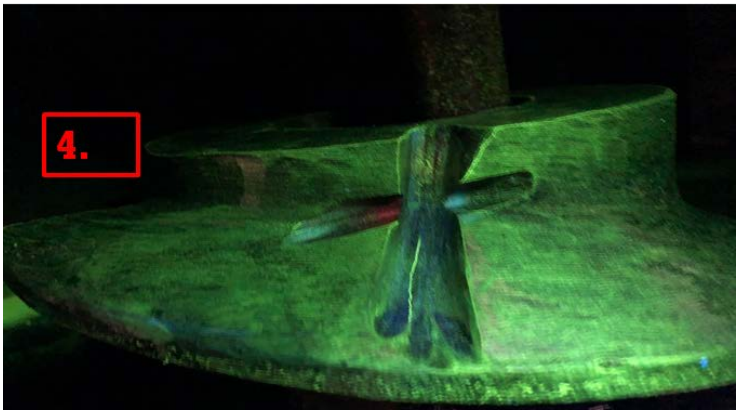
- Original Indication



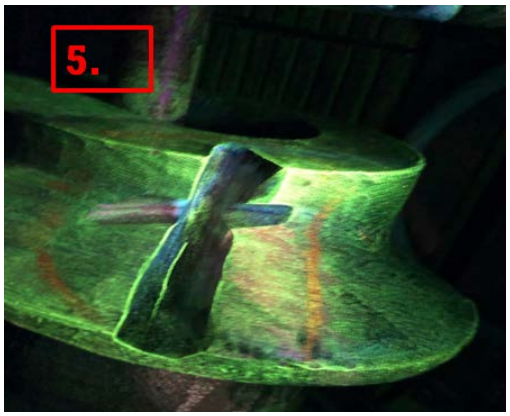
- Excavated to approximately 1/8” depth



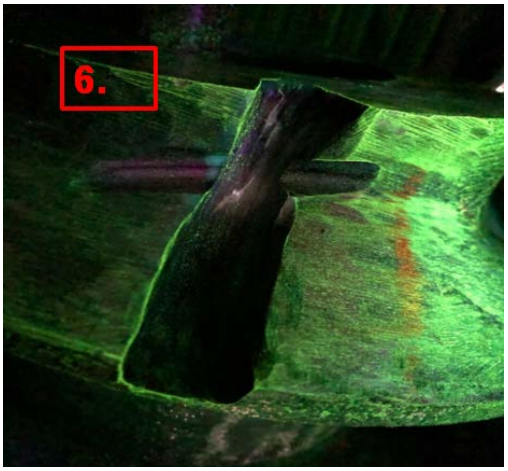
- Primary axial crack excavated to 3/16” and perpendicular to 1/8”



- Perpendicular crack seems to disappear, and primary axial crack seems to be moving down flight.



- Primary axial crack excavated to approx. ¼”. Location seems the same.



- Crack completely removed at ½” material depth.

Figure 8- Defect excavation

Current State Process

Figure 9 below details the process as in the current state. While the contributing factor is unclear, a noteworthy observation is that of the cut-off and grinding processes. Rigging and risering is removed via air arc gouging, and afterwards the castings undergo a swing grinding operation during which the bulk of the contact material is removed. After swing grinding, they are transferred onto the final hand finishing operations.

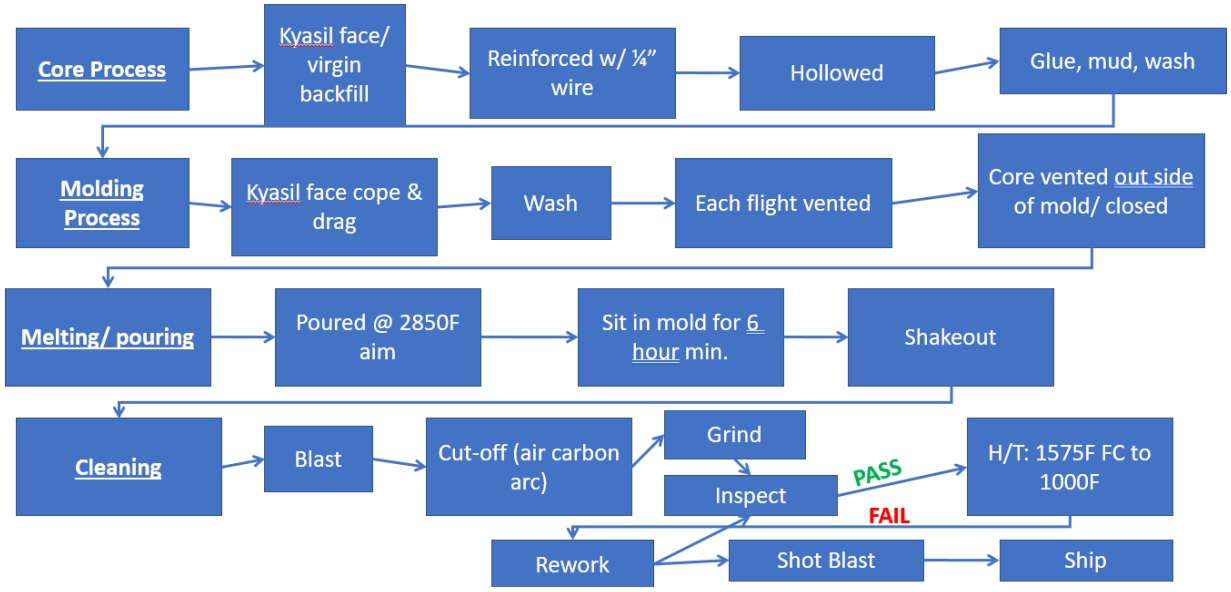


Figure 9- Current state process

Air arc gouging and swing grinding are seemingly aggressive processes concerning the potential for higher heat input at the cast surfaces. A handful of castings were inspected after cut-off and before grinding only to reveal that little to no cracking was present at this point. Following swing grinding, cracks were identified at suspect areas.

Technique during a manual operation such as cut-off can be a variable when considering heat input. A study was conducted to evaluate the effects of the air arc cut-off process between expert and entry level operators. [6] castings were produced under controlled molding and pouring processes: [3] of which were cut off by an "expert" operator (operator A), and [3] of which were cut-off by an "entry level" operator (operator B). No special instructions were given to either operator. The castings would undergo MT inspection directly after cut-off, and there again directly after swing grinding.

Process	Operator	Qty Cut-off	Qty Inspected	Qty Cracked
After Cut-off	A	3	3	0
	B	3	3	0
After Grinding	A	3	3	2
	B	3	3	3

Table 2- Cut-off trials

Results showed that the cut-off process was not a factor. No cracks were identified directly after cut-off; however, they were identified on most of the castings after grinding. It seemed as though the cracks at the casting surface were either induced by or revealed after swing grinding.

Destructive Testing

It was elected to pursue a more technical approach in order to observe material structure, and consequently determine metallurgical abnormalities that may attribute to cracking. [3] castings were chosen for sectioning and subsequent metallography. The castings remained fully rigged and risered and had no processing done. The sectioning was conducted via water jet process, so as not to induce any extreme temperatures into the material and consecutively maintain a completely as-cast structure. Figure 10 illustrates the sectioning. The center riser was chosen for study since this is the most consistent area that cracks are identified.

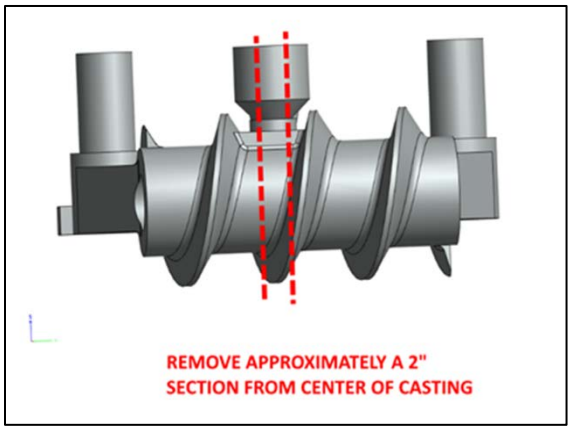


Figure 10- Sectioning of castings

Magnetic particle and dye penetrant testing were then conducted on the cut specimens. No indications were found, thus further suggesting that the cracking issue may be prompted by grinding operations.

After NDT, the specimens were surface ground and macroetched to reveal any discontinuities. Figure 11 below displays the cut sections, which are arbitrarily identified 1-3 from left to right. Two locations were reviewed on each sample. Location 1 was taken at the subject problem area, adjacent to the riser. Location 2 was used as a control and was taken opposite of the riser, adjacent to the center radius (ID). Both locations exhibited very similar features and data on all [3] samples both visually, and via metallographic and SEM/ EDS, so sample #2 was used for documentation purposes in this report. Visually evident discontinuities were identified at both locations and were sectioned for further analysis.

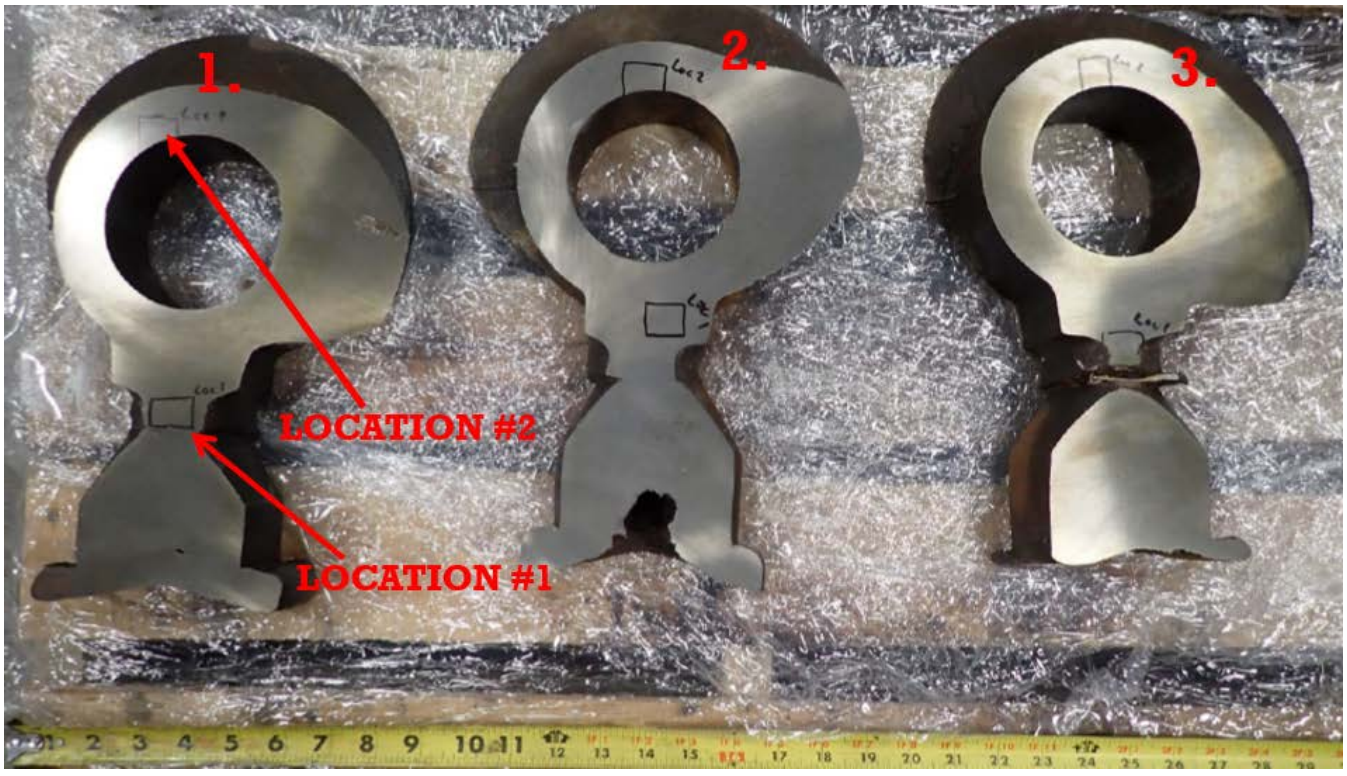


Figure 11- Cut sections, visual examination, macroetch results

Location #1 (Figure 12 below) exhibits a darker etching microstructural component adjacent to the riser, which is quite typical in most steel castings. Location #2 (Figure 13 below) did exhibit very fine porosity, but likely much better than that of a level 1 RT.

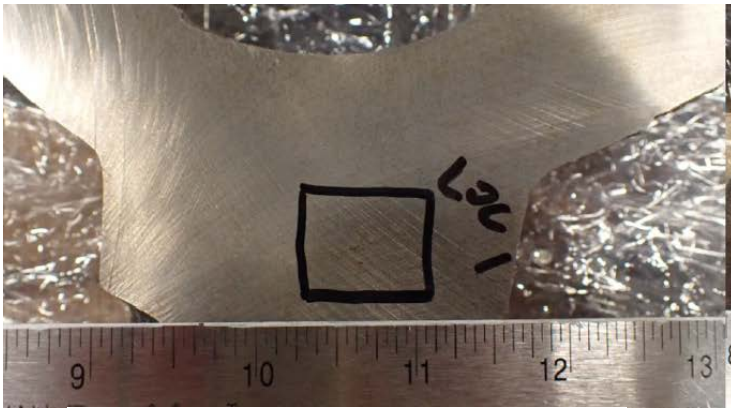


Figure 12- Location #1: adjacent to riser

Figure 13- Location #2: opposite of riser

Location 1- Adjacent to Riser

An interdendritic networked phase was observed at location #1. This location also contained manganese sulfide and titanium carbide inclusions, as well as some very minor under riser shrink. The sporadic titanium carbide inclusions were not of concern since titanium is deliberately added to control nitrogen. As well, the manganese sulfide inclusions were found infrequent. Energy dispersive spectroscopy (EDS) was conducted at both locations noted in figure 15 below. Location 1 (EDS 1) was taken right at the networked boundary and was found to have extremely elevated carbon and chromium. Location 2 (EDS 2) was found to have elevated carbon and manganese at the inclusion. Tables 3 and 4 detail results of EDS.

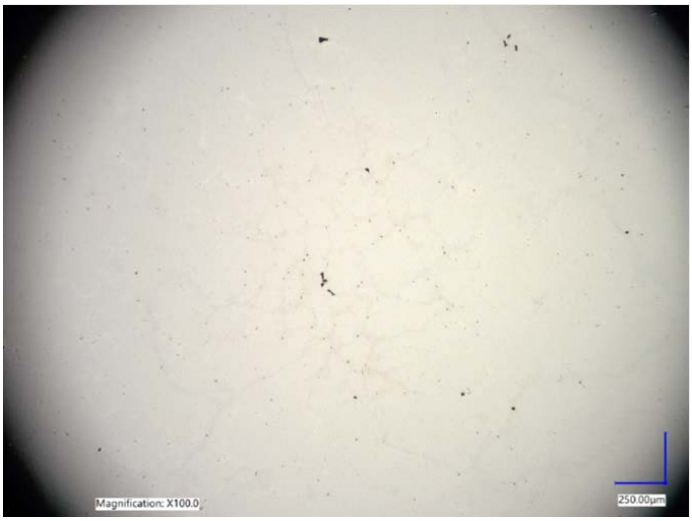


Figure 14- Location 1, magnification: X100

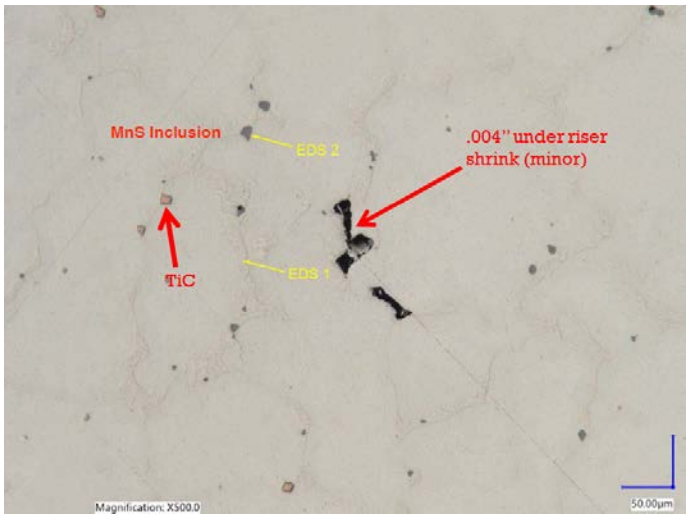


Figure 15- Location 1, magnification: X500

EDS 1	
Element	**Wt.%**
Carbon	10.50
Oxygen	0.35
Aluminium	0.00
Silicon	0.18
Sulfur	0.40
Titanium	0.06
Chromium	48.22
Manganese	0.01
Iron	39.11
Zirconium	0.00
Niobium	1.16

Table 3- EDS 1 results

EDS 2	
Element	**Wt. %**
Carbon	5.15
Oxygen	0.00
Aluminium	0.03
Silicon	0.06
Sulfur	34.09
Titanium	0.00
Chromium	5.95
Manganese	51.87
Iron	2.02
Zirconium	0.25
Niobium	0.57

Table 4- EDS 2 results

The location 1 sample was then etched with Vilella's Reagent, and a darker network was observed. Figure 17 shows locations of EDS 3 and 4, both of which contained elevated carbon, manganese, zirconium, and oxygen.

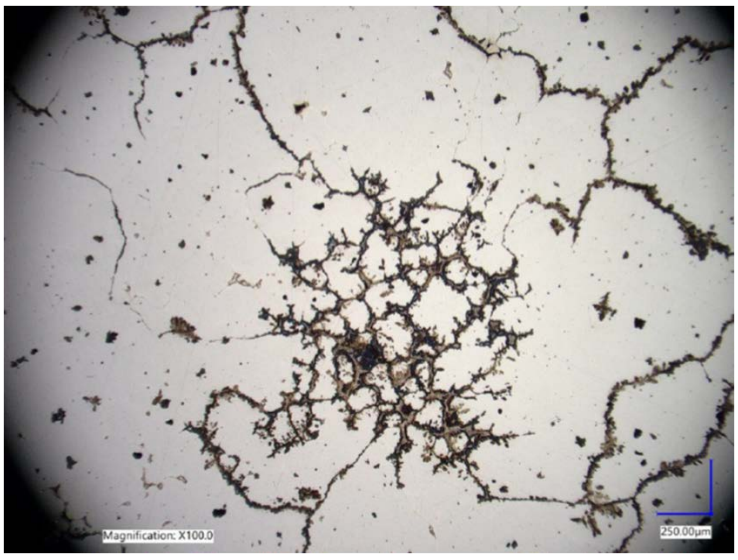


Figure 16- After etching, magnification: X100

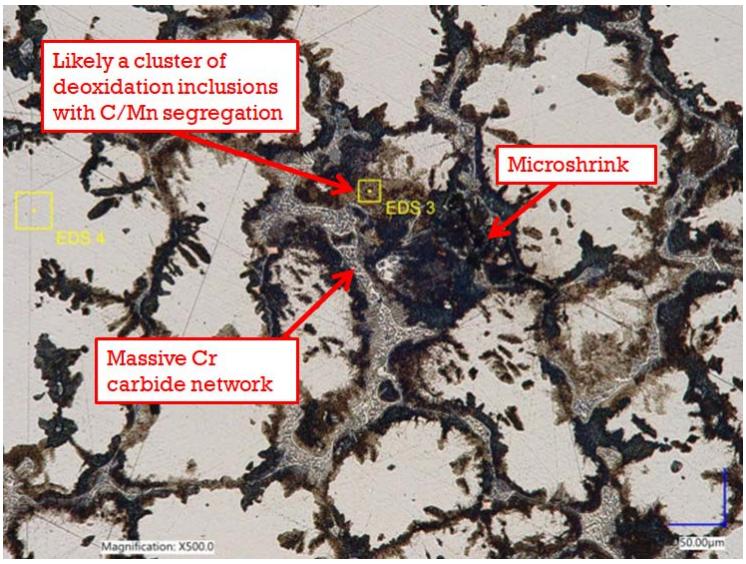


Figure 17- After etching, magnification: X500

Color coded EDS mapping shown in Figure 18 below displays the highly elevated chromium content in the interdentritic network (blue), which is likely resultant of riser segregation. The remainder of the element matrix appears to be well distributed. All three casting samples exhibited very similar segregation in this region.

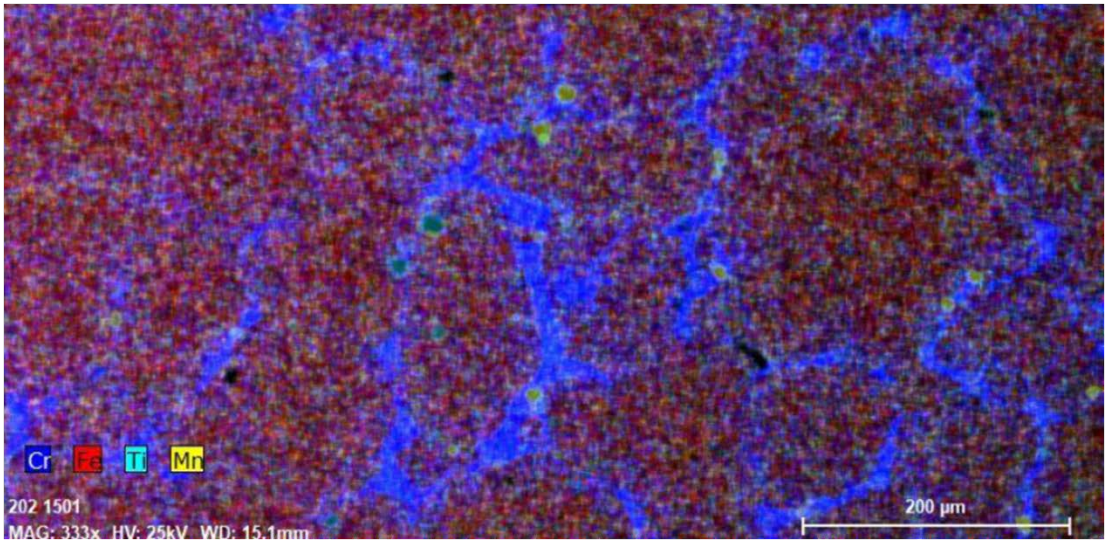


Figure 18- Location 1, EDS mapping

Location 2- Away from Riser

Location 2 was then reviewed in the same manner as that of location 1. Some sporadic micro shrink was observed. While the bulk of it was viewed directly adjacent to the casting ID, some did span approximately .040" in from the casting ID but was still found to be very minor.

Several peculiar discontinuities within this region were reviewed in additional analysis. It seemed that the bulk of these inclusions were oxidation related to some extent or another. EDS 1 revealed elevated titanium, aluminum, and zirconium (aluminum and titanium are deoxidation additions). EDS 2 revealed elevated titanium, nitrogen, and oxygen and is probably another deoxidation cluster. The crack-like feature at EDS 3 is somewhat unclear without further analysis: it may be minor cracking between inclusions and microshrink, however, more likely may be carbide precipitation at grain boundaries; this area resulted in elevated aluminum, oxygen, and manganese.

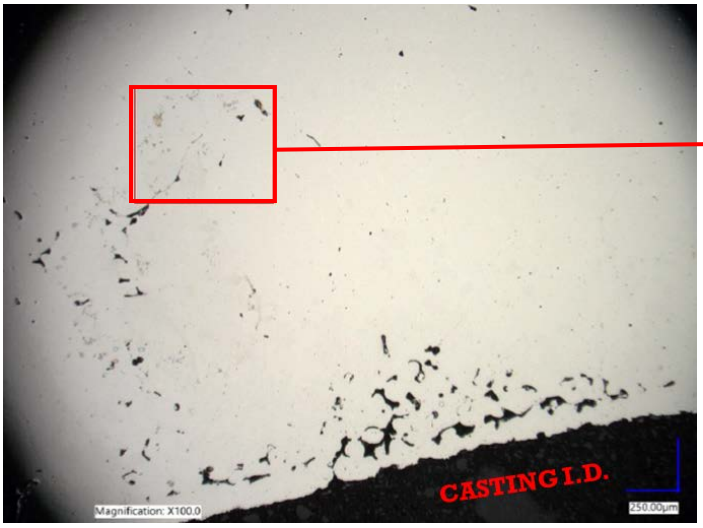


Figure 19- Location 2, magnification: X100

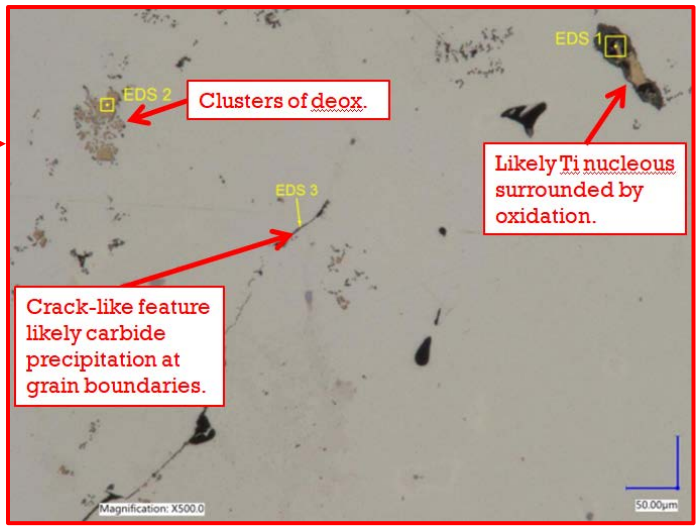


Figure 20- Enlarged view of red boxed area shown in Figure 19. magnification: X500

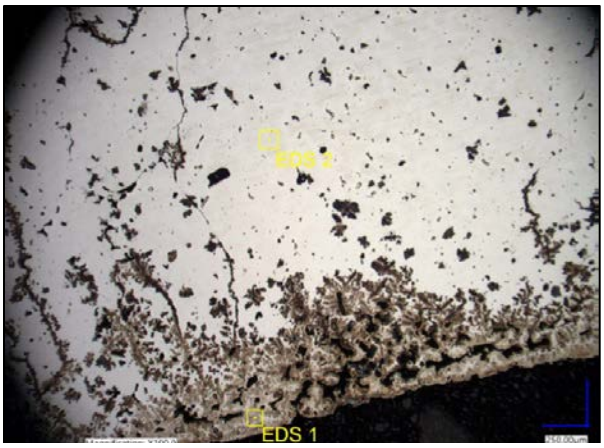


Figure 21- Location 2 after etching. magnification: X100

EDS results at location 2 revealed elevated carbon, phosphorus, and oxygen. This, in conjunction with the observed micro shrink previously mentioned is likely due to diffusion of the mold and probably does not correlate to the interdendritic phase observed in location 1 (subject area), adjacent to the riser. Figure 20 below details results after etching, as well as locations of EDS 1 and 2.

Despite several observed factors related to overall material cleanliness, there was no chromium carbide precipitation present at location 2, as compared location 1. Overall, this area exhibited a well homogenized elemental distribution. Figures 18 and 22 below display a direct side-by-side comparison of color-coded EDS mapping to illustrate the drastic difference in the locations.

Location 1- Adjacent to Riser

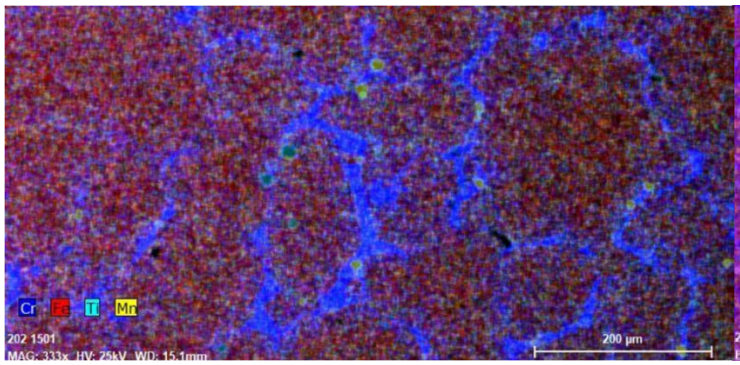


Figure 18 (repeated)- Location 1, EDS mapping

Location2- Opposite of Riser

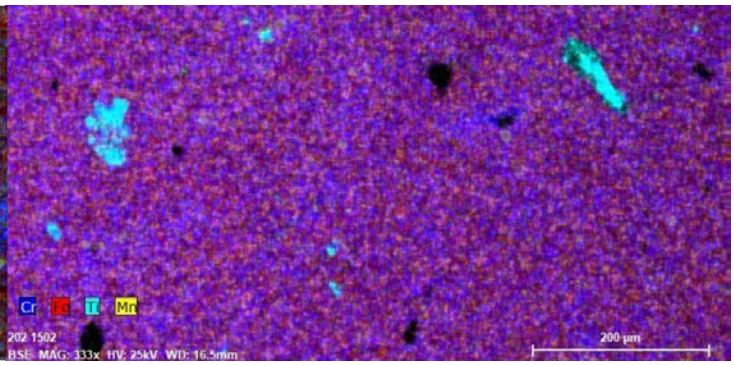


Figure 22- Location 2, EDS mapping

Summary/ Conclusions

Location 1 at the area near the riser contact displayed excessive chromium carbide precipitation. Surrounding this network is a region rich in carbon, manganese, zirconium, and oxygen. These carbide phases are brittle, and the density of these phases could lead to process cracking during casting finishing operations such as swing grinding. Location 2 away from the riser exhibits some diffusion of the mold (cored area) and sporadic inclusions, however, *no similar elemental segregation or carbide precipitation is present*. The overall material cleanliness (sporadic inclusions, micro shrink, etc..) that were brought to light during the analysis could be dealt with in different manners but are not of concern for the purpose of this investigation, as most of this area is machined away, and furthermore, there have been no associated concerns regarding these characteristics. It is speculated that adequate heat treatment could solutionize some of these phases.

Heat Treatment

Location 1 (adjacent to the riser) specimens from each of the [3] sectioned castings were then annealed at various cycles to investigate the change in microstructure and attempt to solutionize the large carbide networks. Since the castings are supplied in an annealed state, the heat treatment conducted was similar to that of the current process, with the austenitizing temperature modified slightly for each specimen. The current cycle is held for two hours at 1575°F and then furnace cooled to 900°F and typical Brinell values average between 200 and 220. A production lot of castings typically cools 675° in 10-12 hours, depending on the load size. The furnace is not on a programmed cooling rate, but rather shut off and allowed to cool naturally. The heat treat trials were conducted in small laboratory electric furnaces, and the specimens were small, at approximately 1 ½" X 1" X 1 ½", so upon cool-down, they were wrapped in ceramic refractory insulation to simulate a cooling rate more representative to that of a load of castings in a production furnace. The

specimens were also preheated to 1450°F and held for a period prior to ramping up to the final austenitize temperature so as to ensure through heating, since due to the small section size, there was concern that the furnace would heat entirely too quickly.

The cycles conducted were as follows:

- Sample #1: preheat to 1450F for ½ hour, ramp up to 1650F and soak for 1 hour. Wrap in wool and shut oven off for slow cool.
- Sample #2: preheat to 1450F for ½ hour, ramp up to 1700F and soak for 1 hour. Wrap in wool and shut oven off for slow cool.
- Sample #3: preheat to 1450F for ½ hour, ramp up to 1850 and soak for 1 hour. Wrap in wool and shut oven off for slow cool.

	Core Rockwell Hardness		
Reading	Sample 1 (HRB)	Sample 2 (HRC)	Sample 3 (HRB)
1	97	32	97
2	97	36	99
3	98	42	98
4	92	38	97
5	98	35	100
Average	**96**	**37**	**98**
Brinell Eq.	**212**	**302**	**223**

Table 5- Core hardness of heat-treated specimens

Rockwell hardness was performed in the core of each specimen following heat treatment. Samples 1 and 3 exhibit values typical to that seen on current production castings. Sample 2 displays the highest hardness. It is presumed that with the inability to accurately control the cooling rates, sample 2 may have exhibited the greatest variation when considering the higher value. The cooling rates of the samples were much less than that of actual castings.

The heat-treated specimens were then etched using Villela's reagent and re-evaluated. Figures 23 and 24 below display results from sample 3, which are representative of results from samples 1 and 2; all three samples displayed very similar features. The microstructure in sample 1 consists of martensite and bainite with some inclusions, chemical segregation, and a lingering tenacious carbide network. Sample 2 contained the best structure of the three samples, which consisted predominately of martensite with interdendritic inclusions, chemical segregation, and an aggressive carbide network, however, less than that of samples 1 and 3. The microstructure in sample 3 consisted predominately of martensite with chemical segregation and yet another remaining large carbide network.

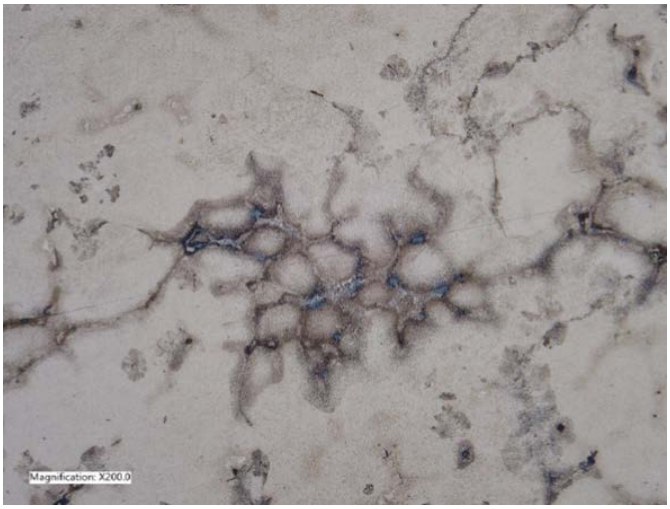


Figure 23- Sample 3, etched. magnification: X200

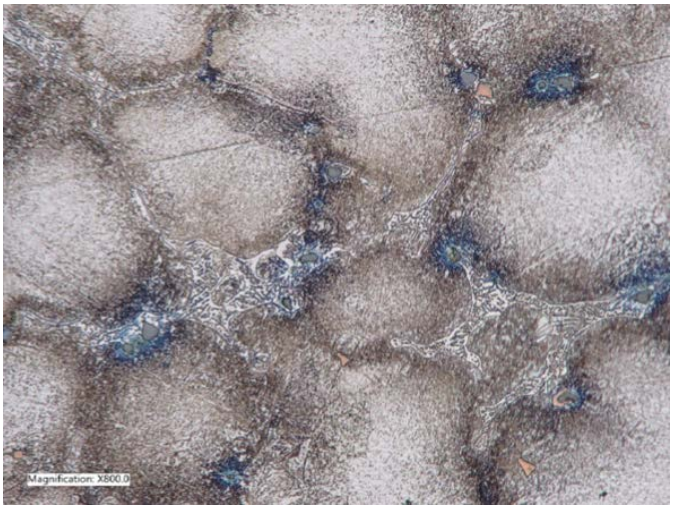


Figure 24- Sample 3, etched. magnification: X800

It can be concluded that following the aforementioned heat treatment, no significant solutionizing of the interdendritic carbides and chemical segregation were visually evident in samples 1 and 3. Sample 2 did exhibit some evidence of solutionizing in comparison to the previously analyzed in the as-cast state, however only to a very minor extent; the carbide network and chemical segregation remained seemingly aggressive.

Considerations

- Riser design change to allow faster cooling rate at risered areas- While this would potentially decrease the amount of segregation and subsequent cr-carbide precipitation, it would likely sacrifice soundness by opening potential for solidification issues due to inadequate feeding. Furthermore, due to the sizeable catalogue of parts with related issues, it would not be a practical approach.
- Increase riser height to allow oxides to float up out of casting and keep segregation in riser- This would be a practical approach if dealing with a single component, however, similar to the point made above, due to not only the index of parts affected, but also the existing various riser configurations that exhibit similar issues already, this approach begins with a fair amount of uncertainty and speculation.
- Reduce carbon and chromium content- This may be beneficial in reducing the severity of the inherent chemical segregation and carbide networks. Obviously, carbon is restricted to an already tightened range (.35%-.40%), so reduction here would be minimal. Nominal chromium values in current production average around 12%, so lowering that content close to the lower specification limit (11.5%) would account for a moderate reduction.
- Increase austenitizing time and temperature to allow further diffusion of undesirable phases- It was understood that solutionizing of such phases is primarily of a time/ temperature relationship. Making a generous increase to both factors *may* allow for further dissolving of the material.

Corrective Actions and Sampling

It was elected to implement and trial the following corrective actions:

- Chemistry modification to restrict C and Cr to the low end of the specification limit:
  - C: .36%-.37%
  - Cr: 11.55%-11.60%
- Heat treatment modification to solutionize carbide phases prior to processing:
  - 1900°F [6] hours, air cool
  - 1325°F [3] hours, air cool

Though these carbide networks are seemingly inherent in this steel at most riser locations, the ultimate goal of modifying the chemistry is to reduce the severity of the development as much as possible and provide a more accommodating structure. In terms of the heat treatment, austenitizing at 1900°F for [6] hours is significantly more than had previously been investigated, and a separate tempering cycle was added to aid in hardness and processing by refining to tempered martensite. Since it has been confirmed that the chemical segregation and cr-carbide precipitation are resultant of the solidification and therefore present in the as-cast state, it seems that the ideal heat treatment would be conducted prior to any processing, with all rigging and risering attached. However, to investigate all avenues of approach, several different sequences are carried out.

A heat of the subject castings was produced using the revised chemistry and heat treatment; all other parameters remained the same. Table 6 below details the processing conditions. The castings would undergo magnetic particle testing at various stages.

Job ID	Qty	Procedure
W1	3	Control samples, normal practice. After shakeout, cut off and MT for cracks. Then grind and MT for cracks.
W2	3	Cut off, then heat treat with revised heat treat, grind. Then MT for cracks.
W3	3	Heat treat with revised process, cut off, grind. MT for cracks.
W4	2	Heat treat with revised process, water jet section, and conduct metallography.

Table 6- Corrective action sampling plan

Table 7 details results of inspection. Aside from the carbon and chromium chemistry modification, the control samples (W1) were processed in the same manner as current production, and as expected, did exhibit cracks after grinding, although somewhat less severe. Following heat treat, [2] of these [3] samples exhibited cracks that had seemingly worsened. The second set of samples (W2) which were cut off and inspected before further processing did not display any cracks on [2], but did display a minor indication on the third. Following grinding and heat treat, all were found to have cracked conditions severe enough for repair. The third set of samples (W3) were fully heat treated before any further activities and *no cracks were identified.*

Job ID	Qty	Procedure	After Cut-off	After Grinding	After Heat Treat	After H/T, and cut-off	After H/T, cut-off, and grind
W1	3	Control samples, normal practice. After shakeout, cut off and MT for cracks. Then grind and MT for cracks.	No cracks identified	All [3] castings were cracked, however, cracks were less severe than normal.	[1] casting w/ small cracks, acceptable [2] castings severe cracks, needed repair	X	X
W2	3	Cut off, then heat treat with revised heat treat, grind. Then MT for cracks.	[1] w/ small thin crack approx. 1.5" long. [2] with no cracks	X	All [3] cracked-repair	X	X
W3	3	Heat treat with revised process, cut off, grind. MT for cracks.	X	X	X	No cracks found	No cracks found
W4	2	Heat treat with revised process, water jet section, and conduct metallography.	X	X	X	X	X

Table 7- Corrective action results after inspection

Following results of the corrective action trials, a second heat of [10] castings was produced with the same revised heat treat and chemistry processes for verification purposes. They followed the same cleaning operations as that of the W3 samples where heat treat was conducted while still fully rigged, prior to any further processing. Upon magnetic particle inspection, *no cracks were identified* on any of the [10] pieces.

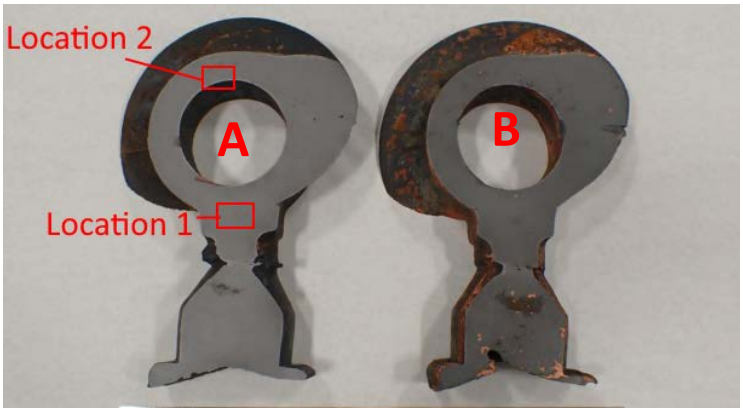
Hardness was then checked on the [10] samples and found to range from approximately 230-250 brinell, which is slightly higher than results typically obtained from that of the current state process (approx. 200-220). This was concerning to some degree considering the trivial fact that it differs from what the customer is accustomed to receiving, as well as potential added difficulty in machining operations.

The hardness concern was communicated, and ultimately approved as an acceptable range. The [10] samples were then submitted for final customer processing. Upon completion, feedback was positive: the parts were found acceptable with no cracks.

Corrective Action Analysis

Two more samples (W4) were then prepared for metallography in the same manner as the original as-cast samples: by means of water jet sectioning through the center riser, taking into account that these pieces were produced with the revised chemistry and heat treatment; no other processing was done. The scope of the analysis is to observe the extent of dissolving of the carbide networks and chemical segregation, and to accurately characterize any discontinuities.

A series of hardness measurements were taken at approximately ½” below the cast surfaces. Brinell values ranged from 238 to 249. Though tensile properties are not required in this instance, these values would equate to somewhere around 115,000 psi which would exceed the 100,000 psi requirement in A743 if supplement S12 was specified.



The two cut specimens were surface ground and macroetched. Neither sample displayed any macro segregation, or discontinuities in location 2 opposite of the riser. Both samples did exhibit some shrinkage at location 1 (risered area) towards the base of the riser as expected. Both locations on both specimens display a structure that consists of uniform fine equiaxed grains. Some slight carbon depletion was identified at location 2 adjacent to the cored area on both samples.

Figure 25- Cut sections

Figure 26 displays location 1 adjacent to the riser on the first sample and is representative of that of the second sample. Both samples were very similar in features. No discontinuities are present.

Figure 27 displays location 2 opposite of the riser on the first sample and again, is representative of that of the second sample. Some minor shrinkage porosity is present, similar to that observed on the original as-cast samples, likely resultant of mold diffusion. The overall cleanliness also appears improved.

Figure 26- Location 1 Adjacent to riser. Unetched

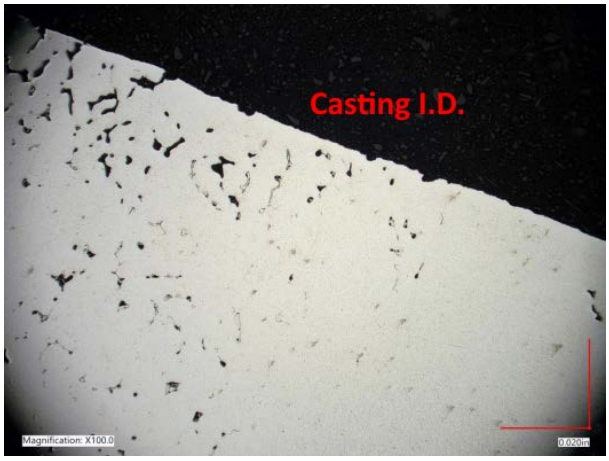


Figure 27- Location 2, opposite of riser. Unetched

Figures 28-31 on the following page display location 1, adjacent to the riser(s) from both samples after etching. Results from both samples contained very similar features. Some chemical segregation is still present, but very much less than that of the original samples. A light, networked boundary is still visually evident, but again, much less than that previously reviewed. EDS results found chromium content at this area to be around 12.5%- 13.8% which is only slightly elevated in comparison to not only the bulk analysis, but other areas within the casting (recall that original chromium content at this area averaged around 50%). Likewise, carbon content was found to be slightly elevated at approximately 4.5% (recall that originally, carbon content at this area averaged around 10.5%). The overall microstructure consists of tempered martensite, with some carbides remaining in the grain boundaries.

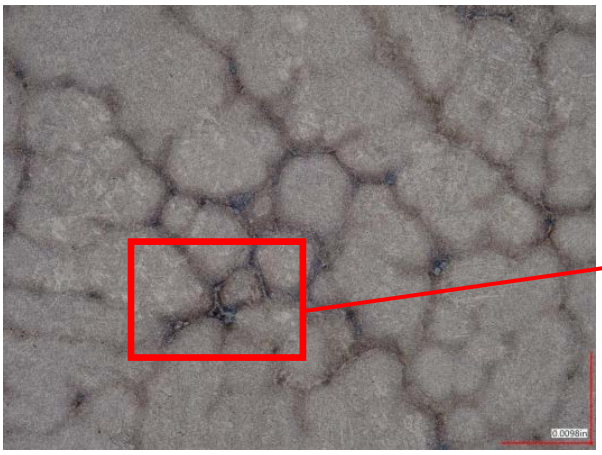


Figure 28- Location 1, Sample A, adjacent to riser. Vilella's Reagent. Magnification: X100

Figure 29- Location 1, Sample A, adjacent to riser. Vilella's Reagent. Magnification: X800

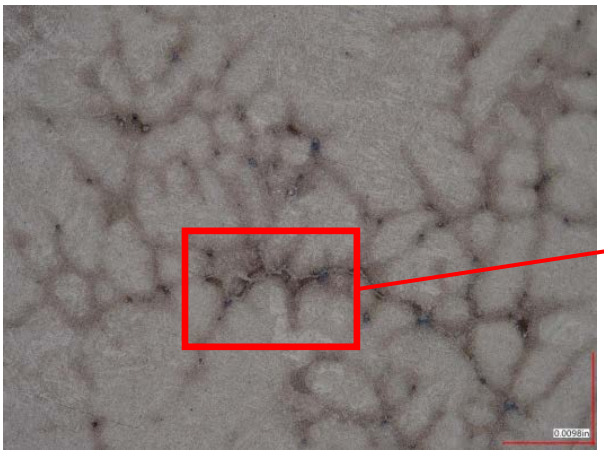


Figure 30- Location 1, Sample B, adjacent to riser. Vilella's Reagent. Magnification: X100

Figure 31- Location 1, Sample B, adjacent to riser. Vilella's Reagent. Magnification: X800

Conventional EDS mapping was again conducted on the samples and showed that the analyzed elements were reasonably uniformly distributed. Only a slight amount of chromium segregation was present at this point, as well as a few sporadic manganese sulfide inclusions. Figures 32 and 33 exhibit color coded mapping of sample B, location 1 adjacent to the riser, with features very similar to that of sample A, and overall, display a fairly homogenized matrix. No contaminant elements such as phosphorus, zirconium, nickel, molybdenum, oxygen, or niobium were detected.

Similarly, EDS mapping of the metallographic section from location 2, opposite of the riser (color coded map for this location not pictured), showed a uniform elemental distribution as well. Only a minute amount of chromium segregation was evident, as well as some sporadic manganese sulfide inclusions.

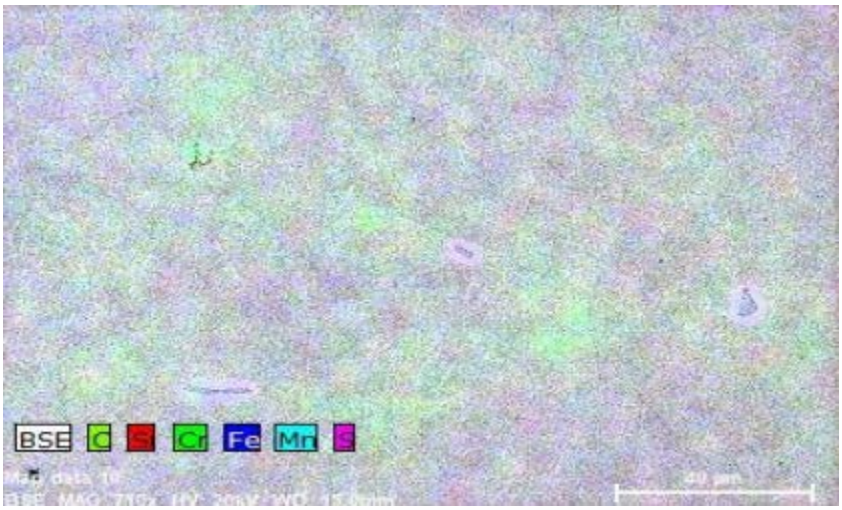


Figure 32- Location 1, sample B, EDS mapping, all elements

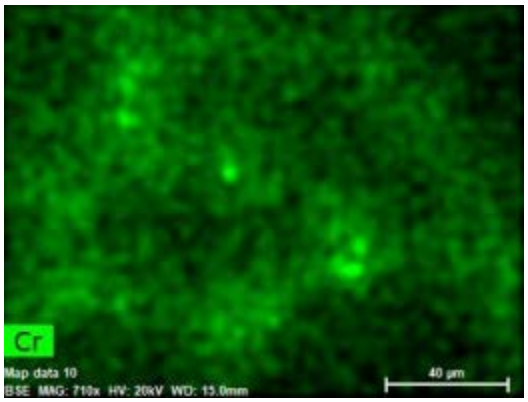


Figure 33- Location 1, sample B, EDS Cr map

Concluding Thoughts

The chemistry modification in conjunction with the aggressive solution annealing process produced a material that was substantially improved over that of the original. The severe chromium carbide precipitation has been primarily dissolved, and the overall material condition is much improved. Some evidence of chromium segregation does remain, however, only in a small amount. If found necessary, further diffusion may be possible by increasing the time/ temperature relationship during the heat treat process.

The heat treat process is likely adequate for most of the material when considering section thickness and through soaking. However, it is possible that some configurations could require additional soak time, or even increased temperature if found to have a larger than typical section thickness at any given contact area.

Since the heat treatment is now conducted prior to processing, an optional post-weld temper cycle has been implemented, should there be a need due to any production welding that may have taken place.

Following full scale implementation of the corrective actions, magnetic particle inspection was continued on production for an extended period. During this time a variety of components were inspected, with no cracks found. Ultimately, the elimination of the added in-process inspection and subsequent extensive repair made a significant reduction in overall cycle times.

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