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The development and manufacture of Ultra-Thin Cast Strip steel products with high residual element levels via the CASTRIP® process

Abstract

A range of Ultra-Thin Cast Strip (UCS) sheet steels with elevated residual levels was produced via the CASTRIP twin drum casting method at Nucor Steel, Indiana. This paper examines the influence of elevated levels of copper, chromium, nickel, and phosphorous on mechanical properties, surface quality, processing, and weldability of UCS sheet steel products produced by the CASTRIP process. Increased levels of copper and phosphorous were found to strengthen UCS sheet steel due to solid solution strengthening but chromium and nickel did not. At lower coiling temperatures and low hot reductions, where processing conditions promote microstructural strengthening, copper and chromium further enhanced strength via increased hardenability. The presence of elevated residual levels of copper is known to potentially lead to hot shortness, unless expensive counter measures are employed, such as nickel additions. Due to the unique solidification and thermal history conditions of the CASTRIP process, higher levels of copper can be tolerated without hot shortness or loss of surface quality. The CASTRIP process is capable of utilizing increased levels of scrap containing higher residual levels, such as post-consumer shredded material. These elevated levels of residual elements can be utilized as a strengthening agent in the finished sheet. Alternatively, this influence on strength can be mitigated when desired through the choice of processing parameters. Additionally, the elevated residual content did not influence either the surface quality or the weldability of the steel.

Keywords

element, residual, high, products, steel, strip, cast, ultra-thin, manufacture, development, castrip®, process, via, levels

Disciplines

Engineering | Science and Technology Studies

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The Development and Manufacture of Ultra-Thin Cast Strip Steel Products with High Residual Element Levels via the CASTRIP[®] Process.

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Key Words: Twin roll casting, UCS products, Residual elements, CASTRIP process, Tensile properties.

ABSTRACT

A range of Ultra-Thin Cast Strip (UCS) steel sheets with higher residual levels were successfully produced via the CASTRIP[®] twin drum casting method at Nucor Steel, Indiana. This paper will examine the influence of enriched levels of copper, chromium, nickel, and phosphorous on mechanical properties, surface quality, processing, and weldability of UCS sheet steel products produced by the CASTRIP process.

Increased levels of copper and phosphorous were found to strengthen UCS sheet steel due to solid solution strengthening but chromium and nickel did not. At lower coiling temperatures and low hot reductions, where processing conditions promote microstructural strengthening, copper and chromium further enhanced strength via increased hardenability. The presence of elevated residual levels of copper is known to potentially lead to hot shortness, unless expensive counter measures are employed, such as nickel additions. Due to the unique process conditions of the Castrip process, higher levels of copper can be tolerated without any countermeasures, without hot shortness or loss of surface quality. The Castrip process is capable of utilizing increased levels of scrap which contain higher residual levels, such as post consumer shredded material. These enriched levels of residual elements can either be used to help with strengthening or this influence on strength can be mitigated by other processing parameters. Additionally, the enriched residual content does not influence either the surface quality or the weldability of the steel.

INTRODUCTION

Since the start of commercial production at Nucor Steel's Indiana CASTRIP[®] facility (located at Crawfordsville, Indiana) efforts have been underway to expand the product range^{1,2,3,4,5}. Among these efforts is the drive to utilize more post consumer scrap and less prompt industrial scrap. As the usage of prompt industrial scrap decreases it can be anticipated that the amount of residual elements will increase. A residual element for this discussion is any element other than iron, carbon, silicon, or manganese that normally appears in scrap.

For current and future CASTRIP facilities that utilize electric arc furnaces (EAF), scrap is the principle source of iron. Scrap represents a wide variety of source materials from prime industrial scrap to post consumer shredded scrap. These various sources of scrap will vary widely in the levels of residual elements that they introduce. Depending on where a facility is located the readily available forms of scrap may have higher residual levels of a particular element; such as higher copper levels in shredded post consumer scrap.

Certain elements (specifically copper, nickel, chromium, molybdenum, tin, and phosphorous) are the typical residual elements that can have an influence on finished sheet steel mechanical properties and surface quality. While other elements may be present, they typically are only trace amounts in the finished sheet. Elements with low melting points and vapour pressures (such as zinc and mercury) are removed during the liquid metal processing. Other elements, such as lead, are typically not present in substantial levels in most forms of scrap. Many of the potential residual elements associated with post consumer scrap use, such as nickel and chromium, are known to influence hardenability⁶.

Given the relatively large austenite grain size that can be produced in UCS steel the effect of increased residual elements on the hardenability, and therefore the microstructure and mechanical properties of UCS steel, required investigation¹. The increase in hardenability in UCS steels provided by niobium and manganese, has been effectively exploited to produce a range of low carbon, high strength low alloy grades^{3,4,5}. In those studies it was seen that substantial changes in mechanical properties could be affected by influencing the hardenability and retaining a large austenite grain size by inhibiting austenite recrystallization⁵. As hardenability is an important aspect for the CASTRIP process, the potential influence of residual elements on hardenability should be considered in addition to solid solution strengthening and precipitation strengthening.

The Castrip process can be varied to provide the potential to tolerate elevated levels of certain residual elements better than is the case for slab based sheet steel production. Historically, high residual levels can influence the surface quality of sheet, for example:

- Copper and tin at sufficient residual content can create hot shortness related surface quality problems in slab-based sheet steel production^{7,8,9}. Hot shortness arises as a result of the accumulation of copper and tin at the scale/ substrate interface in the temperature range of about 1000-1150 °C. Hot shortness may be avoided in making steel strip by the CASTRIP process with the rapid cooling of the strip while proceeding through this temperature range.
- Phosphorous can cause embrittlement of the as cast steel, leading to the evolution of cracks. In addition, phosphorous is prone to segregate in cast slabs, which can lead to localised strength variations in the final strip.

In this paper the experience gained to date with the manufacture of UCS sheet steel products with elevated residual element levels, particularly copper, tin, chromium, nickel and phosphorous will be summarized. Particular emphasis will be given to copper since it is the element that is most likely to undergo the most significant increase, as prime industrial scrap is replaced with other scrap sources. These observations were drawn from the experience with commercial scale production of elevated residual level UCS steels during the time period 2007 to 2010. While molybdenum and tin were potential elements of significance, actual levels encountered during this period were not substantially elevated; as such they will not be directly addressed in the following sections of this discussion. The ranges of the residual elements considered are as indicated in Table 1. The typical base composition of the steels in this study is 0.02-0.03 wt% carbon – 0.65-0.75 wt% manganese – 0.15-0.25 wt% silicon.

Table 1: The maximum and typical minimum residual levels in Castrip steel produced via CASTRIP at Nucor Steel Indiana.

Element	Copper	Nickel	Chromium	Phosphorous
Maximum	0.45	0.15	0.40	0.04
Minimum	0.05	0.02	0.03	0.01

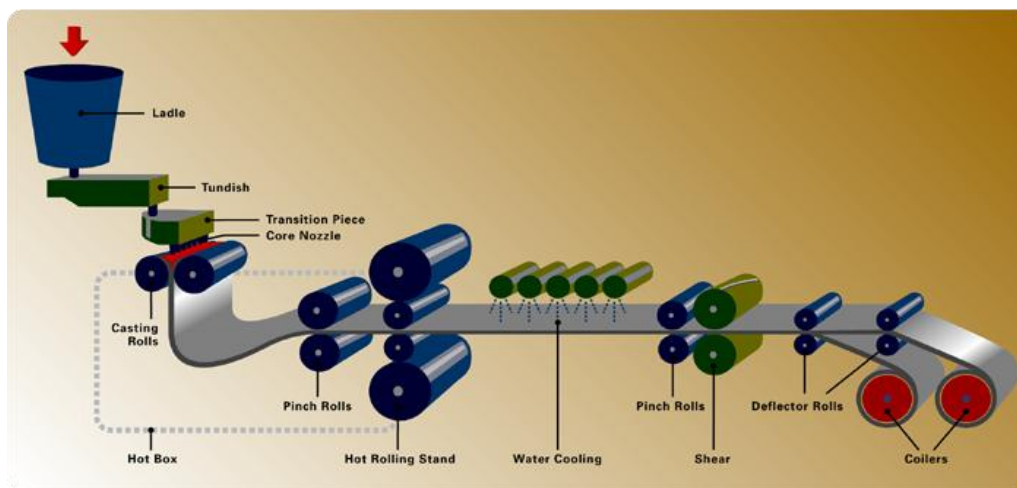


Figure 1: Main components of the CASTRIP process.

ULTRA-THIN CAST STRIP PRODUCTION VIA THE CASTRIP PROCESS

Hot Rolled Strip

The details of the CASTRIP process have been reviewed elsewhere^{10,11}. The following is a review of the relevant aspects of the process, as they are related to the final mechanical properties achieved in UCS products.

The CASTRIP process utilises two counter rotating rolls to form two individual shells that are formed into a continuous sheet at the roll nip. The main components of Nucor Steel's CASTRIP facility at Nucor Steel Indiana are schematically shown in Figure 1. The casting speed is typically in the range of 60-100 m/min and the as-cast strip thickness is typically 1.8 mm or less.

The steel type used for the grades in current production is a low-carbon (≤ 0.05 wt%)-manganese-silicon steel where the total oxygen content is held to 100 ppm minimum with the free oxygen at 30 ppm minimum. This alloy design is employed to ensure deoxidation products of MnO and SiO₂ are liquid during the casting process to avoid clogging and to enhance the heat transfer rate to the casting rolls¹². The rapid solidification rates possible with the strip casting process can, with control of certain parameters, promote a fine and uniform distribution of globular inclusions. An example of the inclusions that can be found in typical UCS is seen in Figure 2.

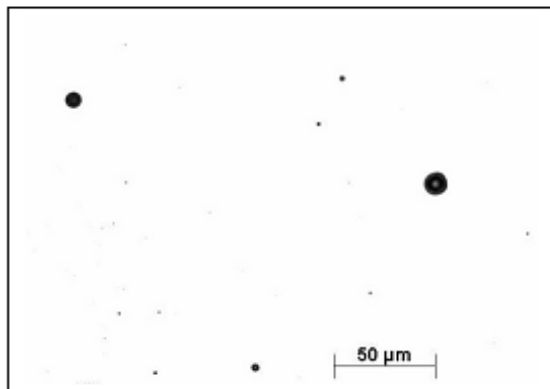


Figure 2: Typical worst case field showing globular inclusions found in UCS steel.

A benefit of the CASTRIP process is that it avoids the formation of type II MnS stringer inclusions, which are often present in Al killed steel produced from conventional slab casting. Due to the limited extent of hot reduction, globular inclusions are not significantly elongated during hot rolling, therefore enhancing the performance of UCS products during subsequent forming, shearing or punching operations. In the CASTRIP process, the resultant inclusion/ particle populations are tailored to achieve particle-stimulated intragranular nucleation of acicular ferrite. The size range of the globular inclusions in UCS products typically varies from about 10 μm down to very fine particles, less than 0.1 μm . The larger 0.5 - 10 μm size non-metallic inclusions play an important role in the development of the final microstructure since they are the particles that are effective in nucleating acicular ferrite^{13,14}. Some inclusions can be a complex mixture of phases, such as MnS, TiO and CuS, which has been reported as beneficial to the nucleation of acicular ferrite¹⁴.

Another microstructural feature of the CASTRIP process is the generation of a relatively large austenite grain size^{1,3}. This austenite grain size is significantly larger than the austenite grain size produced in hot rolled strip at the exit of a conventional finishing mill. This coarse austenite grain size, in conjunction with the population of tailored inclusion/particles, assists with the particle-stimulated intragranular nucleation of acicular ferrite. A representative schematic illustration of the formation of acicular ferrite microstructures is shown in Figure 3¹⁵.

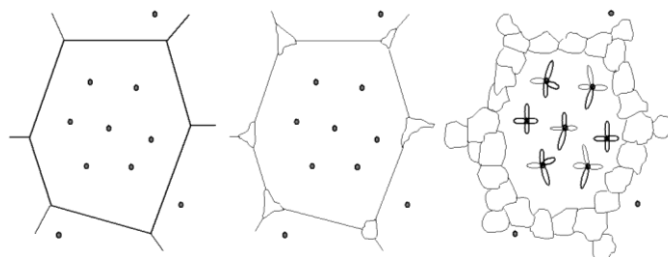


Figure 3: Schematic representation of the formation of acicular ferrite microstructures.

The in-line hot rolling mill is generally utilized for reductions of 10 to 50%. On the run-out-table (ROT) there is a water cooling section utilizing air mist cooling. Control of the cooling rates through the austenite transformation assists in achieving the desired microstructure and resultant properties of the UCS products.

Hot reductions greater than 20% will induce recrystallization of austenite in plain low-carbon steels. This in turn reduces the austenite grain size and its hardenability so that the volume fraction of acicular ferrite is reduced on transformation and a

reduction in strength is observed. Prior countermeasures such as alloying or an increase in the cooling rate during spray cooling on the ROT have been investigated for the production of thinner and stronger UCS steels with the desired microstructure and mechanical properties^{2,5}.

A final feature of the CASTRIP process is that with the rapid solidification it is anticipated that there will not be significant segregation of any element. In this discussion this should be important in avoiding conditions that can promote unwanted effects, particularly for surface condition of the produced strip.

Residual Elements in UCS

There are three main aspects to be evaluated related to the presence of residual elements. While each will be discussed in detail in the following sections, a brief overview of these key aspects is provided below.

- i) Effects on mechanical properties via increased hardenability and solid solution hardening. In the case of UCS, it is anticipated that some residual elements will promote austenite stability, which may lead to an increase in the amount of acicular ferrite present in lieu of polygonal ferrite in the final microstructure. Some of these elements, such as molybdenum, chromium and nickel, are deliberately added to steels where high levels of hardenability are desired. In regard to solid solution strengthening, phosphorous is known to be particularly potent. It is not anticipated that at the compositions indicated in Table 1 that precipitation will have an effect on the mechanical properties of the UCS steel discussed here.
- ii) The propensity for cracking or other similar defects. The principle mechanism of concern is hot shortness. Hot shortness is basically the result of liquid metal embrittlement leading to surface cracking in the presence of high copper and tin contents. This is caused by an accumulation of copper in the oxide layer that forms on the slab prior to hot rolling. When a critical level of copper concentration is achieved in the oxide, melting and penetration into the slab along the austenite grain boundaries can occur. Depending on other conditions (such as furnace atmosphere), this cracking can become quite pronounced. Two other common mechanisms that can generate defects that affect surface quality are low hot ductility and local segregation issues. It is not anticipated that either of these mechanisms will be significant in UCS due to the rapid cooling associated with solidification and the brief time from casting to rolling the strip.
- iii) The influence of residual elements on the weldability of UCS sheet steels. Spot welding and electric resistance welding (ERW) during tube manufacture (i.e. ERW seam welds) are the main welding methods used for thin strip products. The two main concerns to address in relation to welding are; first if the weld is brittle and fractures readily and second a lack of fusion in the weld zone. Additionally, there is the consideration that for ready adoption of UCS the welding parameters (such as input current and line speed) will not be altered from the case for steel with a lower residual element content.

INFLUENCE OF RESIDUALS ON MECHANICAL PROPERTIES OF UCS

The principle residual elements from scrap that can be anticipated to have an influence on the mechanical properties of steel are copper, nickel, chromium, molybdenum, and phosphorous. To date, all of these elements have been studied in UCS steel from production heats, except molybdenum. It should be noted that these elements can also be deliberate additions for some alloys such as those described in SAE J404 and ASTM A606. As previously discussed, the principle means by which these elements can influence mechanical properties are: solid solution hardening, hardenability and precipitate effects.

Solid solution strengthening can be predicted based on composition. Based on the work of Irvine and Pickering¹⁶ the potential strengthening effect on yield strength for the concentration ranges of the residual elements listed in Table 1, can be estimated and values are shown in Table 2. As shown by the values in Table 2, it is predicted that copper and phosphorous can provide significant solid solution hardening, nickel should have no affect and chromium should have a negative influence on yield strength.

Table 2: Estimated effect on yield strength from residual elements at the concentrations given in Table 1, based on the work of Irvine and Pickering¹⁶

Element	Copper	Nickel	Chromium	Phosphorous
Increase in YS	35 MPa	0 MPa	-12 MPa	26 MPa

In the CASTRIP process, mechanical properties are controlled by the processing conditions; low hot rolling reductions and low coiling temperatures promotes acicular ferrite and stronger grades, while high hot reduction and high coiling temperatures promote ferrite/pearlite microstructures and lower strength products. Manganese is also used to manipulate the strength of the steel⁴; therefore the production data used in the following sections were restricted to 0.65-0.75 wt% manganese, unless stated otherwise.

Due to the strong influence of hot rolling and coiling temperature on mechanical properties, care was taken to compare the higher residual coils with regular production data produced using similar processing conditions. In the case of hot reduction (HR), levels over 20%, in carbon-manganese-silicon UCS steels, induces static recrystallization of the austenite, which significantly reduces the austenite grain size and hence, hardenability. As a consequence, any effect from residual elements on hardenability will be

mitigated at higher hot rolling reductions. In the case of coiling temperature (CT), results presented here have been separated into “high CT” (>650 °C) and “low CT” (<560 °C). Low coiling temperatures are equivalent to high cooling rates through the austenite to ferrite transformation, which promotes low temperature transformation products. Consequently, the effect of these residual elements on hardenability will be more apparent for low coiling temperatures.

Evaluation of Elevated Residual Levels of Copper

Copper is the element that is typically the most elevated from the scrap selections for the Nucor Steel Indiana production facility. For clarity purposes, the yield strength results from routine production testing were grouped into low (0.05 to 0.15 wt% copper) and elevated (>0.29 to 0.45 wt% copper) copper levels, for two coiling temperature ranges. The outcome of this analysis is presented in Figure 4 as a function of the extent of hot reduction. This figure clearly demonstrates the strong influence of coiling temperature and hot rolling reduction on yield strength, consistent with previous studies¹. At higher coiling temperatures, the cooling rate is sufficient for polygonal ferrite to dominate the microstructure; even from coarse grained austenite that is typical for low hot rolling conditions (i.e. the effect of hot rolling on properties is limited). At low hot reduction and low coiling temperatures, hardenability is high, microstructural strengthening is active and the yield strength results were much higher compared to higher hot rolling reduction levels, where austenite recrystallization diminished hardenability and microstructural strengthening.

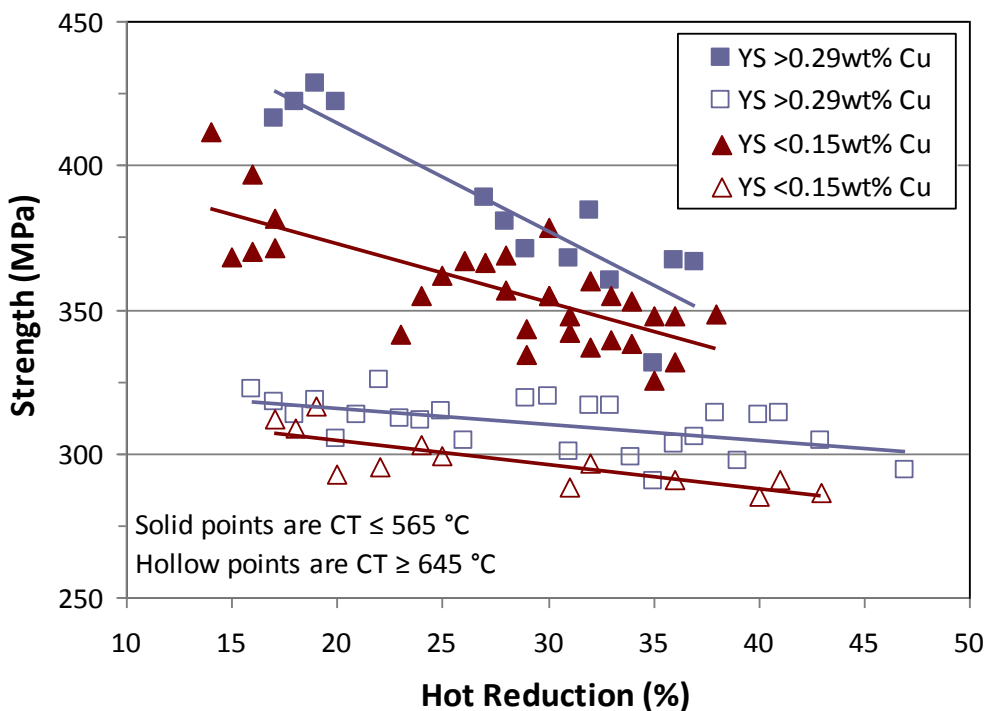


Figure 4: Effect of enriched copper content on the yield strength of UCS sheet steel products for coiling temperatures ≤ 565 °C or ≥ 645 °C.

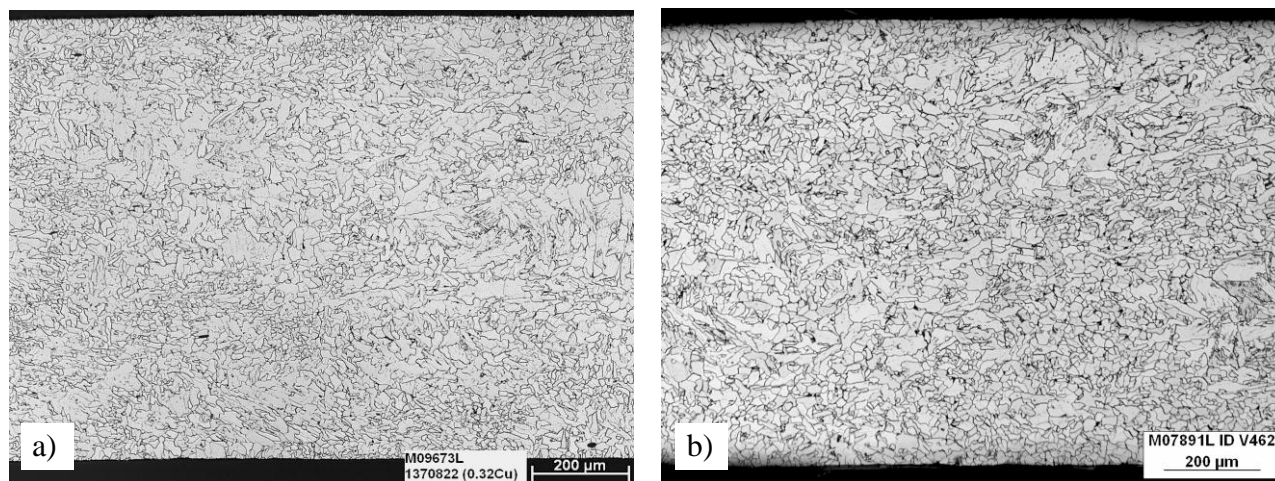


Figure 5: Optical images of a) enriched residual copper (0.32 wt%) UCS grade (HR 44%, CT 616°C) compared to b) lower copper UCS product (HR 42%, CT 640°C).

In Figure 4, for the high coiling temperature results, the effect of the increased copper (low to high range) was about 20 MPa which is consistent with the anticipated increase due to solid solution strengthening. For low coiling temperature conditions, the enriched copper content appears to provide both solid solution hardening and increased hardenability, as evidenced by the greater increase in yield strength at low hot reductions. When the hot rolling was $\leq 20\%$, yield strength increased by approximately 40-50 MPa, while at higher hot reductions, the increase was about 20-30 MPa, which is in agreement with the expected solid solution strengthening.

The microstructure for a 0.32 wt% copper specimen is compared to 0.07 wt% copper production material in Figure 5, where both coils were coiled above 615 °C and hot reduction was $> 40\%$. In these images there was no significant difference in the microstructure present after hot rolling. This is consistent with the information presented in Figure 4, where there was only a moderate increase in strength that can be accounted for by solid solution strengthening.

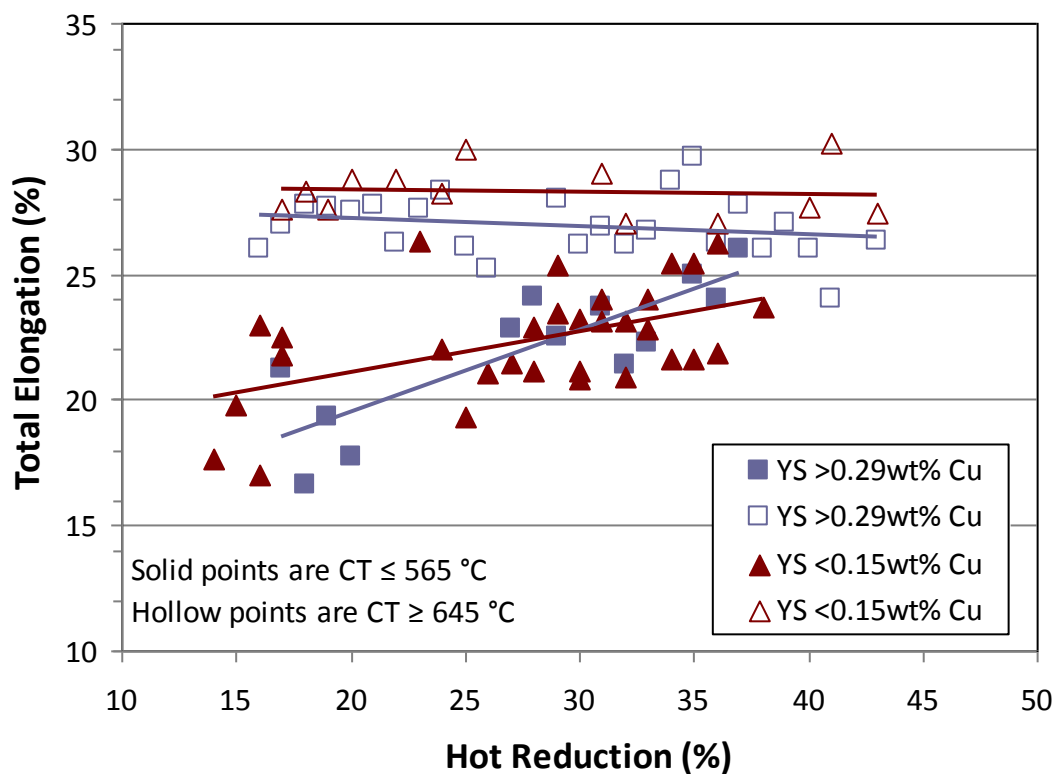


Figure 6: Effect of elevated copper content on the total elongation of UCS sheet steel products for coiling temperatures ≤ 565 °C or ≥ 645 °C.

The effect of elevated copper content on the total elongation of UCS sheet steel products, for the same conditions as those given in Figure 4 above, is shown in Figure 6. At higher coiling temperatures, where the residual copper content was increased, the total elongation of the polygonal ferrite was decreased by 1-3 percent, reflecting and consistent with, the increased yield strength. Due to the scatter in the data for the low coiling temperature results, it is difficult to ascertain if elevated copper levels decreased total elongation values, although there appears to be a trend of lower elongation for lower hot reductions, again reflecting the higher strength levels recorded. Overall, the strengthening provided from the elevated residual copper only marginally reduced the ductility. Moreover, the total elongation values were still well above the respective grade requirements. However, adjusting the alloy design and/or the processing conditions to offset the strengthening gained from the elevated residual content, would return the strength levels and total elongation values to the levels for the low residual material.

Evaluation of Elevated Residual Chromium Levels

The next element considered from this family of residual elements was chromium. The tensile properties are summarized in Figure 7 as a function of the residual chromium content (0.05 to 0.40 wt%) and again for high and low coiling temperature conditions

For the higher coiling temperature material there was not any apparent effect of increasing chromium content on the yield strength of the UCS product. This is consistent with the higher coiling temperature material generally transforming to polygonal ferrite, where hardenability is inactive. It is also consistent with the predicted effect (negative) from solid solution strengthening. In the case of lower coiling temperature, there does appear to be about a 40 MPa increase in yield strength at the enriched chromium level

of 0.18 wt%. Taking into account the predicted solid solution effect (negative) it is reasonable to attribute this strength increase to enhanced hardenability of the steel.

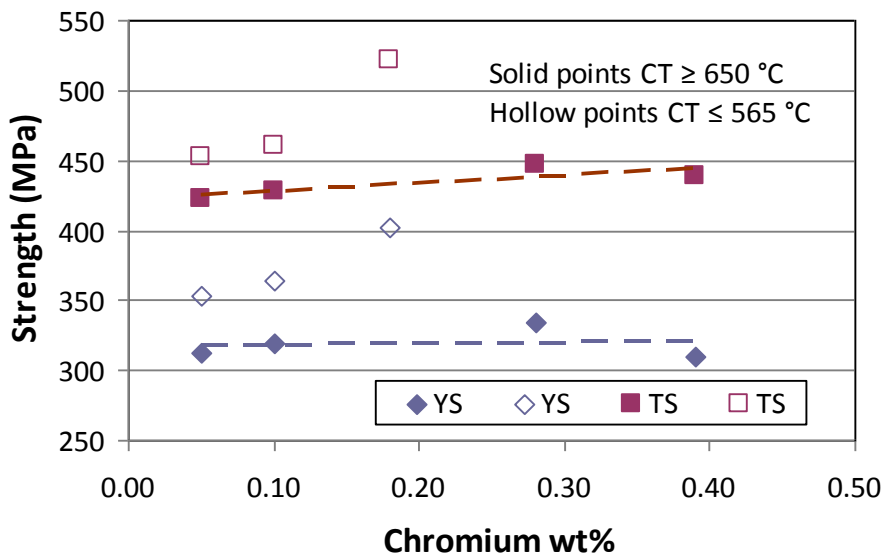


Figure 7: Effect of residual chromium content on tensile properties of UCS sheet steel.

Evaluation of Effect of Elevated Residual Phosphorus Levels

In the case of phosphorous, results from heats with a higher residual phosphorous content, 0.04 wt%, are contrasted with regular production, where the typical phosphorous content was 0.015 wt%. In this case, the manganese content was 0.85 wt%. The results of phosphorous content on mechanical properties as a function of hot rolling reduction are shown in Figure 8. The increase in the yield strength was about 25 to 50 MPa, which is consistent with the estimate from solid solution strengthening. Additionally from Figure 8, a significant increase in yield strength was observed across a wide range of hot reductions, where the increase in yield strength was slightly higher at low hot reductions.

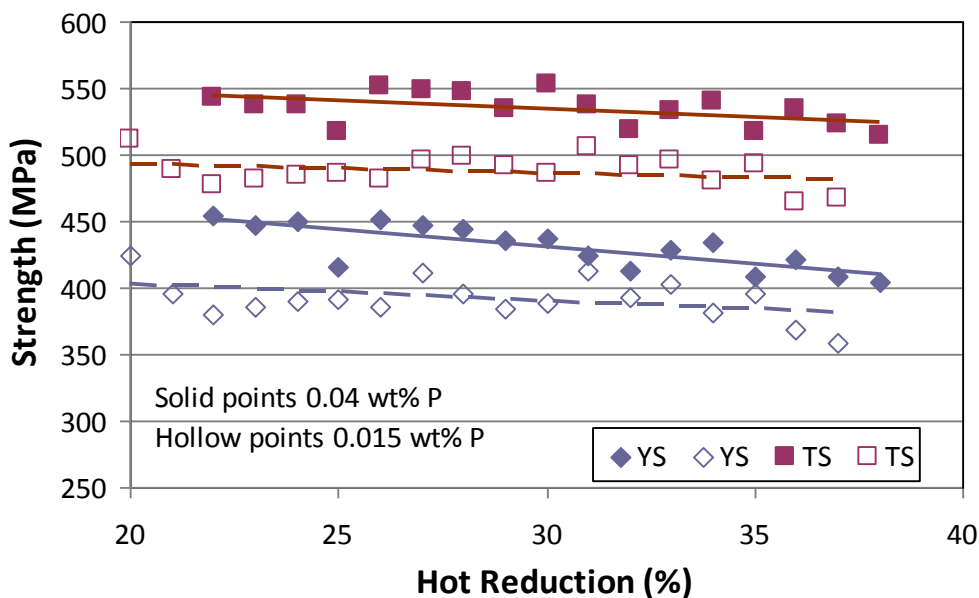


Figure 8: Role of Phosphorous in 0.85 wt% Mn UCS.

Evaluation of the Effect of Elevated Residual Nickel Levels

The final element investigated for its influence on tensile properties was nickel. Limited production data was available for higher nickel contents, restricting the analysis of the influence of nickel. In Figure 9, the results from a 0.15 wt% nickel heat is compared to production data (typically 0.05 wt% nickel) at high coiling temperatures. There was very little influence from this small nickel

increase for the given conditions, as would be expected based on nickel's limited impact on solid solution hardening. Further work is required to determine if small increases in nickel will enhance hardenability of UCS when coiled at low temperatures and low hot reductions, as nickel is traditionally used as a hardenability agent.

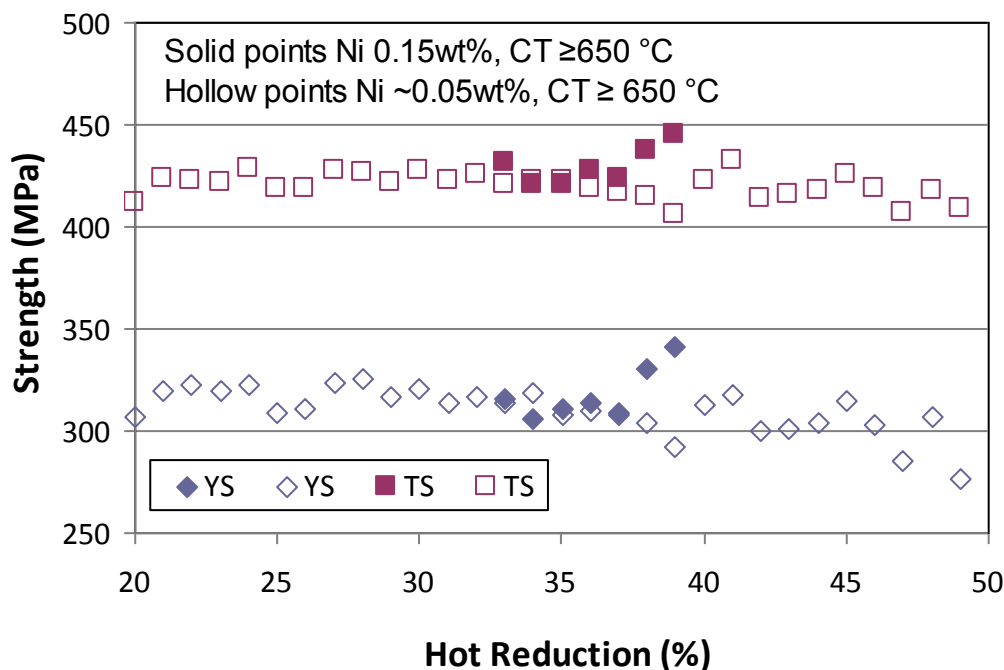


Figure 9: Comparison of a slightly enriched nickel content on tensile properties of UCS products.

HOT SHORTNESS AND SURFACE CONDITION

Copper levels over about 0.15 wt% are generally avoided in conventional and thin slab casting sheet steel production methods due to concerns over hot shortness. In cases where copper levels are higher than 0.15 wt% (such as in steels with improved atmospheric weathering resistance), expensive alloy additions such as nickel, are commonly added to mitigate the risk of hot shortness. Tin is also of concern when considering the evolution of hot shortness in sheet production in slab based production. A typical consideration of the overall risk from the combined influence of copper and tin utilizes a factor determined as follows:

$$F = Cu + (6 * Sn)^9$$

As stated in the introduction, the tin content in production UCS steel at the CASTRIP facility in Nucor Steel Indiana is sufficiently low that it will not be considered in this discussion.

The CASTRIP process has several features that effectively eliminate the potential for copper hot shortness. The key features are the controlled atmosphere in the hot box, the brief interval between casting and rolling, and very rapid solidification, which maintains copper in solution. These features will prevent the build up of copper in the surface oxide layer that is required for hot shortness to occur. Due to the above mentioned advantages, steel scrap that is higher in copper can be employed for UCS steel production without the potential for hot shortness.

A substantial number of heats with residual copper levels in the range of 0.2 to 0.4 wt% have been successfully produced for commercial consumption without recourse to any countermeasures such as a Ni addition. None of this product has exhibited hot shortness and even the highest Cu level cast to date, 0.6 wt% was free from the defect⁴. This experience verifies the expectation that the CASTRIP process can successfully process high residual levels of copper without incurring hot shortness while also avoiding special practices or alloy additions. This also allows for the utilization of lower cost scrap thereby improving the cost of strip production via the CASTRIP process.

Figure 10 demonstrates the observed surface conditions from production heats spanning 2007 to 2010. The surface quality rating is a value generated from a standard in process inspection utilized on all production material at the CASTRIP facility at Nucor Steel Indiana. The method involves gathering multiple samples per production heat; they are treated with a dye and then the surface is manually inspected for any indications of dye retention (such as in a roll mark or scratch). The results presented in Figure 10 are the average results of the four years of production material sorted by composition as indicated. It can be seen in this Figure that there was no appreciable change in the surface quality rating with highly elevated copper contents. For reference, it is anticipated that

similar testing on sheet from slab based production will generate an average value of 5 to 10; it would be anticipated to be significantly for a copper plus tin content greater than 0.15 in slab based production.

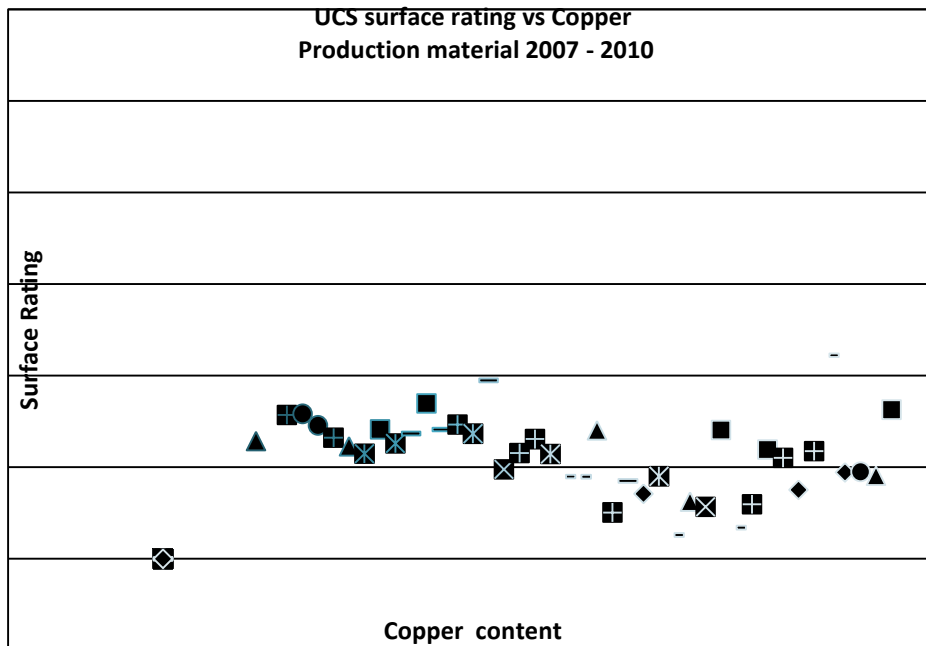


Figure 10: Surface inspection ratings relative to copper content from production of UCS steel during 2007 to 2010.

As an additional demonstration of the absence of hot shortness at elevated Cu levels, several simple dome tests were conducted using 100 mm former and assessed for cracking with the dye penetrate technique. Examples of the domes produced are shown in Figure 11. It can be seen in both images that there was not any crazing / cracking on these specimens. These specific domes have been imaged after the application of dye in a similar test to the method indicated above and its subsequent removal.



Figure 11: Images from dome testing, after dye penetration testing, of enriched copper UCS steel.

WELDABILITY

To assess the weldability of material with enriched residuals a series of spot welding and ERW test were conducted at the Edison Welding Institute¹⁷. The welds were assessed for; soundness of the weld, indications of embrittlement and a general lack of fusion. Full details of the welding tests will not be described here, but the conclusion of the study was that elevated residuals had no effect on welding performance. In both the case of spot welds and ERW no difference was seen in the test results from UCS with elevated residual content (copper in excess of 0.30 wt%) and a lower residual content (copper contents of 0.13 – 0.17 wt%).

Figure 12 includes the metallographic examination of some selected spot welds generated for this study¹⁷. It can be seen that in these images there is full fusion of the weld without expulsion and no subsequent evolution of cracking in the heat affected zone of

the weld. In all cases tested the current ranges used were what would be anticipated for industrial use (such as in automotive spot welding) for both elevated and lower residual element content material. In addition all the spot welds had weld sizes and tensile strengths that exceeded AWS D8.1, C1.1, and D17.2¹⁷ standards.

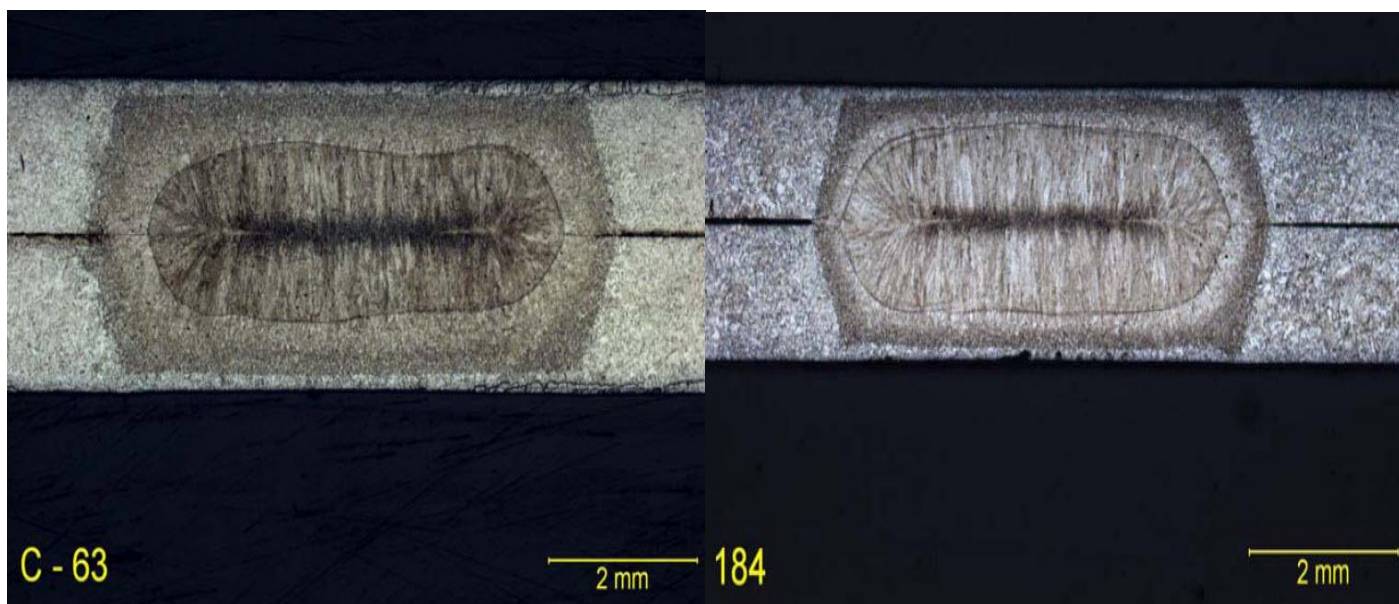


Figure 12: Optical images of selected spot welds from EWI study.

Figure 13 is representative of the welds produced in the electric resistance welding (ERW) tube that was produced for this study¹⁷. In this case the image presented is from a section of tubing where the weld flare was not scarfed from the inner wall of the tube. What can be seen is the remnant of material flow from the forging aspect of the ERW process on the inner tube wall side of the image, it is not expulsion of material from the weld zone proper. For all material tested the welds were found to be sound in both crush and flare testing of the welded tube for industrially relevant line speeds and current ranges. In this case there are not any standardized test methods to contrast the results to, however it was reported during the tube manufacturing that the UCS material (elevated residuals or otherwise) behaved similarly to sheet steel from other sources.



Figure 13: Optical image of a selected high frequency (ERW) weld.

SUMMARY

In this paper the potential effect of enriched residual elements in UCS has been addressed. For each of the material characteristics considered it has been shown that the presence of residual enrichment does not impede the performance of UCS sheet.

For mechanical properties, increases in yield strength generally corresponded to solid solution effects, but at low coiling temperatures and low hot reductions, where hardenability effects are active, additional strengthening from enhanced hardenability was realised. The strengthening influence from higher residuals can assist in producing higher strength grades and allow the reduction of deliberate alloy additions, such as manganese, while still achieving the desired properties. For the production of softer grades, higher residuals were shown to have a limited effect at high coiling temperatures and this effect can be easily mitigated via alloy reductions or processing condition adjustments.

Due to the unique casting and solidification conditions of the CASTRIP process, residual levels of copper considered too high for safe production of conventional sheet steels, without the use of expensive countermeasures, can be utilized without any hot shortness or surface quality issues. This attribute of the CASTRIP process broadens the range of scrap selection, allowing increased use of prompt industrial scrap.

Finally, weldability studies demonstrated that elevated residuals, particularly enriched copper, did not deteriorate weld performance. High quality welds were obtained, with sound fusion zones, no cracking or expulsion and no indications of embrittlement.

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