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Overcoming Copper Limitations in Scrap Recycling via Twin-Roll Casting

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Abstract. Increasing scrap usage in steelmaking is vital for resource efficiency and CO_2 reduction, but elevated residual copper limits adoption due to hot shortness during hot forming. Conventional continuous casting promotes Cu segregation in interdendritic regions, and subsequent slab reheating accelerates oxidation-driven Cu enrichment at the steel-scale interface, where liquid Cu penetrates grain boundaries and weakens cohesion. Twin-roll casting (TRC) offers a promising alternative, as its high solidification rates suppress Cu segregation and its near-net strip production eliminates slab reheating and minimizes oxidation. In this work, the hot-shortness resistance of a 0.75 wt.% Cu construction steel processed by TRC is evaluated and directly compared with a conventionally cast and reheated counterpart. The comparison reveals that TRC effectively mitigates copper-related damage mechanisms. Cu remains primarily in the thin scale without penetrating the substrate, enabling hot rolling and downstream processing without cracking. In contrast, the conventional route forms a thick, brittle, Cu-rich scale that promotes grain-boundary penetration and severe hot shortness. Overall, TRC expands the allowable copper content in flat steel production and broadens alloy design opportunities for scrap-based steelmaking.

Introduction

The increasing use of scrap in steelmaking is widely recognized as a key pathway toward improved resource efficiency and reduced CO_2 emissions. However, the presence of residual elements imposes significant constraints on the applicability of scrap-based routes for flat steel production. Among these elements, copper is particularly critical, as it strongly promotes hot shortness during high-temperature forming operations and therefore limits allowable copper contents in industrial practice [1].

The susceptibility of copper-containing steels to hot shortness is governed by a combination of metallurgical and process-related factors. During solidification in conventional continuous casting, copper segregates into interdendritic regions due to its limited solubility in ferrite. Subsequent slab reheating prior to hot rolling accelerates oxidation of iron. During this process, iron oxidizes preferentially and at a significantly higher rate than copper, while the inward diffusion of copper remains limited, leading to progressive copper enrichment at the steel-oxide interface. When local copper concentrations increase and temperatures exceed the melting point of copper-rich phases, liquid copper can form and penetrate along grain boundaries. The presence of liquid copper substantially reduces grain boundary cohesion, and under mechanical loading during hot deformation these weakened boundaries are prone to rupture, giving rise to surface cracking and, in severe cases, liquid metal embrittlement. As a consequence, conventional slab casting routes impose strict upper limits on the permissible copper content in flat steel products, thereby limiting the use of copper-containing scrap [1].

A promising approach to enable the use of scrap containing elevated levels of copper and tin is to fundamentally modify the process conditions that give rise to hot shortness. In flat steel production, TRC directly addresses the key drivers of copper-induced embrittlement by simultaneously limiting oxidation, segregation, and high-temperature deformation. In contrast to conventional slab-based routes, TRC replaces slab casting and subsequent slab reheating by producing near-net-shape strip directly from the melt, thereby substantially reducing thermal exposure, oxidation, and overall process complexity while improving energy efficiency and material yield [2]. The fundamental differences between the conventional slab-based route and the twin-roll casting process, as well as their implications for copper behavior, are schematically illustrated in Fig. 1.

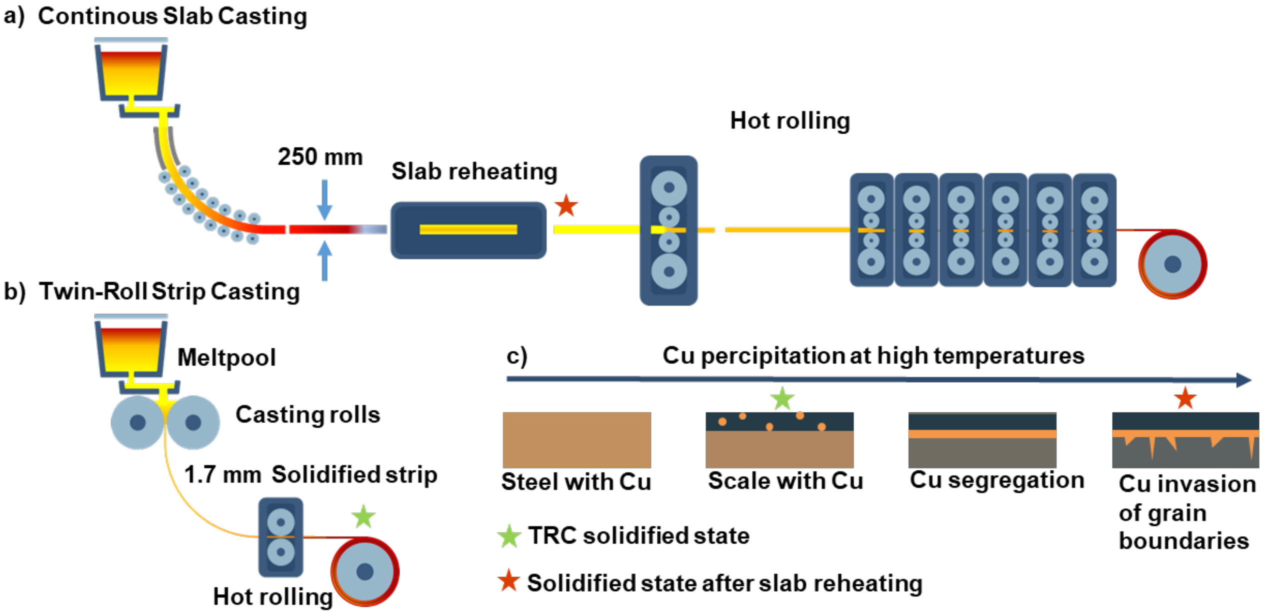

Fig. 1 Schematic comparison of a) conventional slab-based processing and b) twin-roll casting highlighting differences in c) copper behavior and hot-shortness-relevant mechanisms in flat steel production based on [7].

In the twin-roll casting process, molten steel solidifies between two counter-rotating, water-cooled copper rolls, forming a continuous strip with typical thicknesses of approximately 1 to 3 mm. Rapid heat extraction at the roll surfaces leads to the formation of thin solid shells that are joined in the roll gap, while ceramic side dams ensure a stable melt pool. As strip is produced directly from the melt, slab reheating is avoided, and further thickness reduction can be achieved by inline hot rolling using the residual casting heat.

By avoiding slab reheating and extensive high-temperature exposure, TRC substantially reduces oxidation and surface scale formation, thereby suppressing oxidation-driven copper enrichment at the steel-scale interface, which is a critical prerequisite for liquid copper formation and grain boundary weakening. In addition, the high solidification rates inherent to TRC, reaching up to approximately 1000 K/s, reduce copper segregation during solidification and contribute to maintaining grain boundary integrity. Similar effects have been reported for rapidly and sub-rapidly solidified copper-bearing steels, where increased cooling rates were shown to significantly improve resistance to hot shortness by suppressing copper segregation and grain boundary wetting [3].

Beyond these metallurgical effects, TRC also offers significant process and energy advantages. Compared to conventional hot strip production routes involving continuous casting, slab reheating, and multiple rolling stages, the energy demand can be reduced from approximately 3.5 GJ per ton of steel, or around 2.1 GJ per ton for thin slab casting, to values as low as 0.5 GJ per ton due to the elimination of reheating and extensive hot deformation [4].

The metallurgical and process-related advantages of twin-roll casting are not only of academic relevance but have also been demonstrated under industrial conditions. Ultra-thin strip casting technologies based on the twin-roll principle have reached a high level of technological maturity, enabling stable near-net-shape production of flat steel products at industrial scale [5]. In particular, industrial experience gained with the CASTRIP® process has shown that strip casting routes tolerate higher levels of residual elements than conventional slab-based processing, including steels with elevated copper and tin contents [6]. Earlier investigations on near-net-shape cast strip produced from scrap have similarly demonstrated improved processability and property profiles for Cu- and Sn-containing steels compared to conventional routes [7].

In addition to copper-containing construction steels, twin-roll casting has been successfully applied to compositionally demanding alloys such as high-silicon electrical steels. Previous studies have demonstrated that the high cooling rates inherent to TRC strongly influence microstructure evolution, texture development, and downstream processability, thereby expanding accessible alloy design windows beyond conventional limits [8,9].

While current industrial practice demonstrates the feasibility of processing copper-containing steels via strip casting, the copper levels applied remain deliberately conservative, primarily to ensure process robustness and product consistency. Building on these industrial achievements, further exploration is required to assess the true limits of copper tolerance achievable through twin-roll casting and to develop a deeper understanding of the governing metallurgical mechanisms.

The aim of the present study is to improve the understanding of how twin-roll casting affects copper-related hot-shortness behavior in comparison to conventional processing. Particular emphasis is placed on oxide scale formation and copper enrichment at the surface as key indicators of hot-shortness susceptibility. To this end, a hot-shortness-sensitive construction steel containing 0.75 wt.% Cu was produced by twin-roll casting and characterized in the as-cast condition as well as after selected downstream processing steps.

To approximate conventional slab-based processing, the same alloy was subjected to a reheating treatment representative of industrial slab reheating conditions. The behavior of the twin-roll-cast material is directly compared with this reheated condition in order to isolate the influence of solidification rate and thermal exposure on copper-related damage mechanisms. The following sections describe the materials, processing routes, and experimental methods employed in this study.

Materials and Methods

Strip casting, reheating simulation and further processing To demonstrate the robustness of twin-roll casting with respect to elevated copper contents, a hot-shortness-sensitive construction steel alloy containing 0.75 wt.% Cu was investigated. The strip casting experiments were conducted on the laboratory-scale twin-roll caster at the Institute of Metal Forming (IBF), RWTH Aachen University. For this purpose, approximately 150 kg of the alloy were melted in an induction furnace and transferred via a refractory channel system and a tundish into the casting gap between two counter-rotating, water-cooled copper rolls with a width of 150 mm. To suppress oxidation of the melt surface and to control the heat transfer conditions between the casting rolls and the solidifying strip shells, the melt pool was shrouded with argon gas. Solidification occurred directly at the roll surfaces due to rapid heat extraction, leading to the formation of thin solid shells that were joined in the roll gap to produce a continuous steel strip. A more detailed description of the twin-roll casting facility and process conditions is provided by Daamen et al. [10]. The as-cast strip had a nominal thickness of approximately 1.7 mm. Samples were taken from the strip for subsequent characterization and further processing.

To approximate the thermal exposure associated with conventional slab-based flat steel production, a reheating simulation was performed on samples extracted from the twin-roll-cast strip. The material was held at 1100 °C for 3 h under conditions representative of industrial slab reheating in a pusher furnace. This treatment was intended to reproduce oxidation behavior and copper redistribution comparable to those occurring during conventional slab reheating prior to hot rolling, while maintaining identical alloy composition.

In order to investigate the influence of downstream processing on microstructure and mechanical properties, selected samples of the twin-roll-cast strip were further processed via two different routes. For the hot rolling (HR) route, specimens were heated for 5 min in a furnace under an argon atmosphere and subsequently rolled in a single pass from the as-cast thickness of 1.7 mm to a final thickness of 1.2 mm. This processing step was intended to approximate an inline hot rolling pass following strip casting.

For the cold rolling route, the as-cast strip was cold rolled from an initial thickness of 1.7 mm to a final thickness of 0.5 mm in three rolling passes. The cold-rolled material was subsequently subjected to recrystallization annealing at 710 °C for 5 h under an argon atmosphere in order to obtain a fully recrystallized microstructure. The experimental process chain used to compare twin-roll casting, rolling states and reheating conditions is illustrated in Fig. 2.

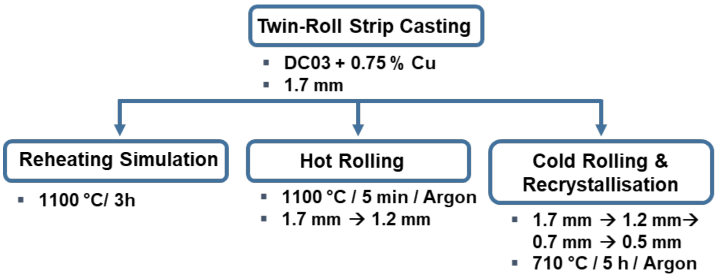

Fig. 2 Experimental process chain of the twin-roll-cast material.

Microstructural characterization, chemical analysis and mechanical testing Microstructural investigations were carried out on metallographically prepared cross-sections using light optical microscopy (LOM). The analyses were performed using a VHX-7000 digital microscope (Keyence). In addition, scanning electron microscope (SEM) images were acquired using a ThermoFisher Helios 5 Hydra UX. Particular emphasis was placed on the characterization of oxide scale formation, copper distribution at the steel-scale interface, and potential copper penetration along grain boundaries. Microstructural features resulting from the different processing routes were documented and compared.

To verify the chemical composition of the cast material and to account for potential deviations or impurities introduced during processing, chemical analyses were performed using spark emission spectroscopy. The analyses were carried out on ground samples that were cleaned with ethanol prior to measurement, using a BELEC Variolab spectrometer.

Mechanical properties were evaluated by uniaxial tensile testing at room temperature. A50 tensile specimens were tested on a Z100 universal testing machine (ZwickRoell) at a constant quasistatic strain rate of 1×10^{-3} s^{-1}. Yield strength, ultimate tensile strength, and total elongation were determined in order to assess the influence of processing route and microstructure on mechanical performance.

The susceptibility of the investigated alloy to hot shortness was assessed based on metallographic observations of surface condition, oxide scale formation, and copper distribution after processing. In addition, the behavior of the material during hot rolling was evaluated qualitatively with respect to surface integrity and the occurrence of cracking. The twin-roll-cast material was directly compared with the reheated condition representing conventional slab-based processing.

For industrial benchmarking, two commercially produced CASTRIP strip materials with copper contents of 0.35 wt.% and 0.40 wt.% were acquired and characterized. These materials were selected to represent industrial strip-cast steels with elevated residual copper levels. Chemical composition and mechanical testing were performed under the same conditions as applied to the twin-roll-cast material investigated in this study.

Results and Discussion

Castability, chemical composition and surface condition after twin-roll casting The chemical composition of the cast strip, determined by spark emission spectroscopy, is summarized in Table 1. The alloy is based on a DC03 deep-drawing steel with low carbon and manganese contents and deliberately excludes alloying elements such as Ni and Si that are known to mitigate copper-induced hot shortness. With a measured copper content of 0.75 wt.%, the investigated material represents a composition that exceeds typical limits for conventionally processed flat steels.

Table 1 Measured chemical composition of the twin-roll-cast strip alloy used in this study with comparison of the two Castrip alloys, determined by spark emission spectroscopy (wt.%).

	IBF Twin-roll-cast strip	CASTRIP Twin-roll-cast strip t=1.88 mm	CASTRIP Twin-roll-cast strip t=0.7 mm
Fe	Equ.	Equ.	Equ.
C	0.092	0.014	0.002
Si	0.02	0.13	0.15
Mn	0.42	0.47	0.44
P	0.01	0.007	0.011
S	-	0.002	0.002
Cr	0.03	0.10	0.14
Ni	0.02	0.11	0.12
Mo	-	0.02	0.03
Cu	**0.75**	**0.35**	**0.40**
Al	0.002	0.002	0.002
Sn	0.001	0.013	0.015

Despite this composition, strip material could be successfully produced by twin-roll casting. The casting trial yielded a continuous strip segment of sufficient length for subsequent characterization and processing, demonstrating that elevated copper contents do not adversely affect solidification and strip formation during twin-roll casting. The strip casting step itself does not promote copper-related damage. Instead, the solidification conditions established during casting define the initial copper distribution, which governs its behavior during subsequent high-temperature exposure and deformation.

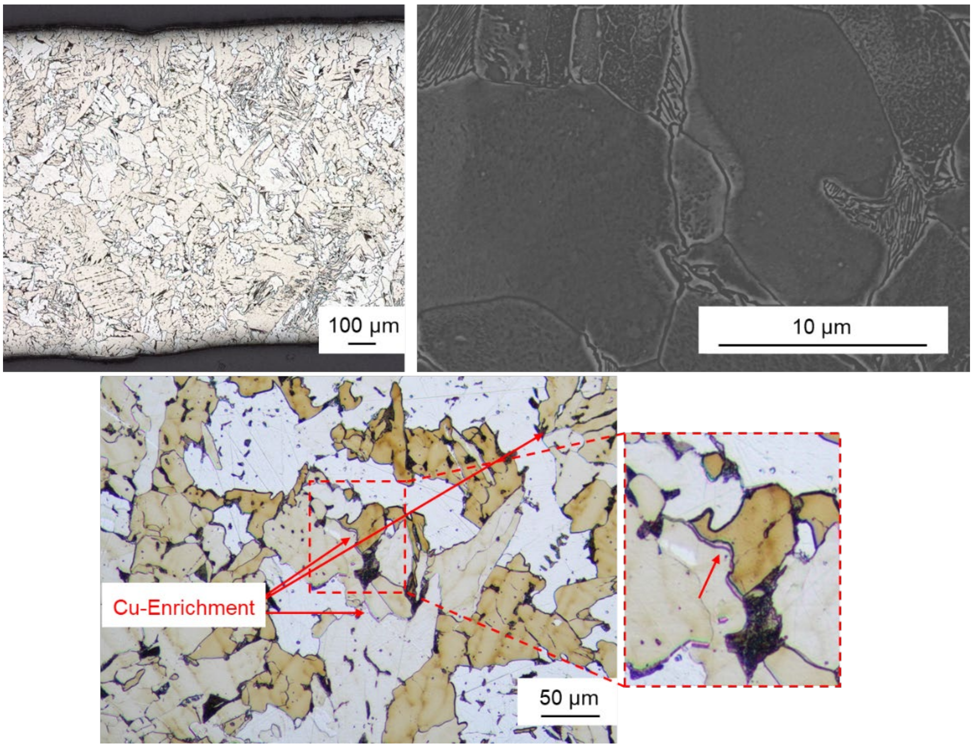

Fig. 3 Ferritic-pearlitic microstructure of the as-cast twin-roll-cast strip and localized copper-rich features along grain boundaries

Microstructural examination of the as-cast strip revealed a ferritic-pearlitic microstructure characteristic of low-carbon steels processed under high cooling rates. In addition to the matrix microstructure, isolated copper-rich features were locally observed along grain boundaries as can be seen in Fig. 3. These copper enrichments remain limited in extent and are not associated with surface cracking or other indications of hot-shortness-related damage in the as-cast condition.

Metallographic examination further revealed the formation of a very thin oxide scale on the strip surface. Copper was predominantly incorporated within this scale layer, as illustrated in Fig. 4, while no penetration of copper into the steel substrate was observed. This behavior indicates that the limited thermal exposure and reduced oxidation inherent to the TRC process effectively suppress the conditions required for copper enrichment at the steel-scale interface and subsequent grain boundary wetting. In contrast to conventional slab-based routes, the absence of prolonged high-temperature exposure prevents the formation of liquid copper films during processing.

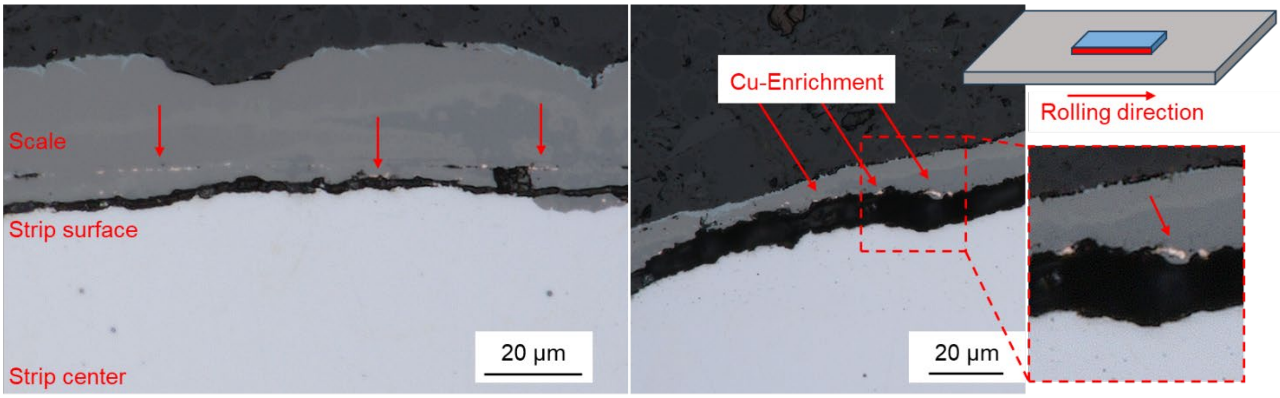

Fig. 4 Oxide scale on the as-cast twin-roll-cast strip with copper-rich inclusions within the scale.

Effect of reheating simulation on copper redistribution and hot-shortness susceptibility To evaluate the behavior of the investigated alloy under conditions representative of conventional slab-based processing, a reheating simulation was applied to the twin-roll-cast strip. The objective of this experiment was to isolate the effect of prolonged high-temperature exposure in an oxidizing atmosphere, corresponding to the slab-reheating step. Reheating at 1100 °C for 3 h resulted in a pronounced change in surface condition and copper distribution compared to the as-cast state.

Metallographic analysis after reheating revealed the formation of an approximately 1.43 mm thick, brittle oxide scale accompanied by pronounced copper enrichment beneath the scale layer. In addition, copper penetration along grain boundaries into the steel matrix was observed (Fig. 5). This redistribution of copper establishes critical conditions for hot shortness, as grain boundary cohesion is locally reduced once copper-rich regions form during prolonged high-temperature exposure.

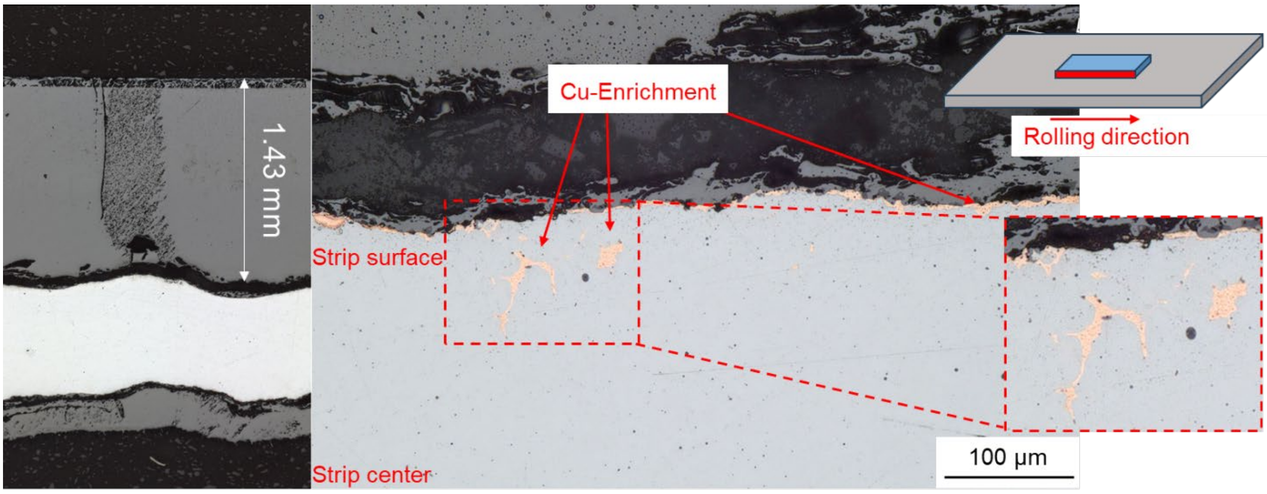

Fig. 5 Oxide scale and copper redistribution after reheating simulation, showing a thick scale layer (left) and copper enrichment beneath the scale and along grain boundaries (right).

In contrast to the comparatively homogeneous copper distribution in the as-cast TRC condition, the reheating treatment promotes pronounced subsurface enrichment driven by diffusion and oxidation kinetics. The results demonstrate that copper-related degradation is not primarily governed by the solidification stage but can be activated by extended thermal exposure under oxidizing conditions. Since conventional slab casting typically involves slower cooling and increased segregation tendencies, local copper accumulation during reheating is expected to be at least comparable, if not more pronounced.

These findings highlight the decisive role of slab reheating in conventional processing routes and help explain why elevated copper contents remain challenging in slab-based flat steel production.

Influence of downstream processing on microstructure and mechanical properties To assess the processability of the twin-roll-cast material and the range of achievable microstructures, different downstream processing routes were applied, including hot rolling with a low thickness reduction and cold rolling followed by recrystallization annealing.

Hot rolling of the as-cast strip resulted in a fine-grained ferritic-pearlitic microstructure with predominantly equiaxed grains, as shown in Fig. 6 a). This microstructure is characteristic of thermomechanical processing involving moderate deformation and subsequent phase transformation under controlled cooling conditions. The absence of surface damage during hot rolling confirms that copper-related degradation mechanisms remain suppressed in the twin-roll-cast condition.

In contrast, cold rolling followed by recrystallization annealing produced a homogeneous, pancake-like grain structure, as illustrated in Fig. 6 b). This microstructural state reflects complete recrystallization after substantial cold deformation and represents a distinctly different grain morphology compared to the hot-rolled condition.

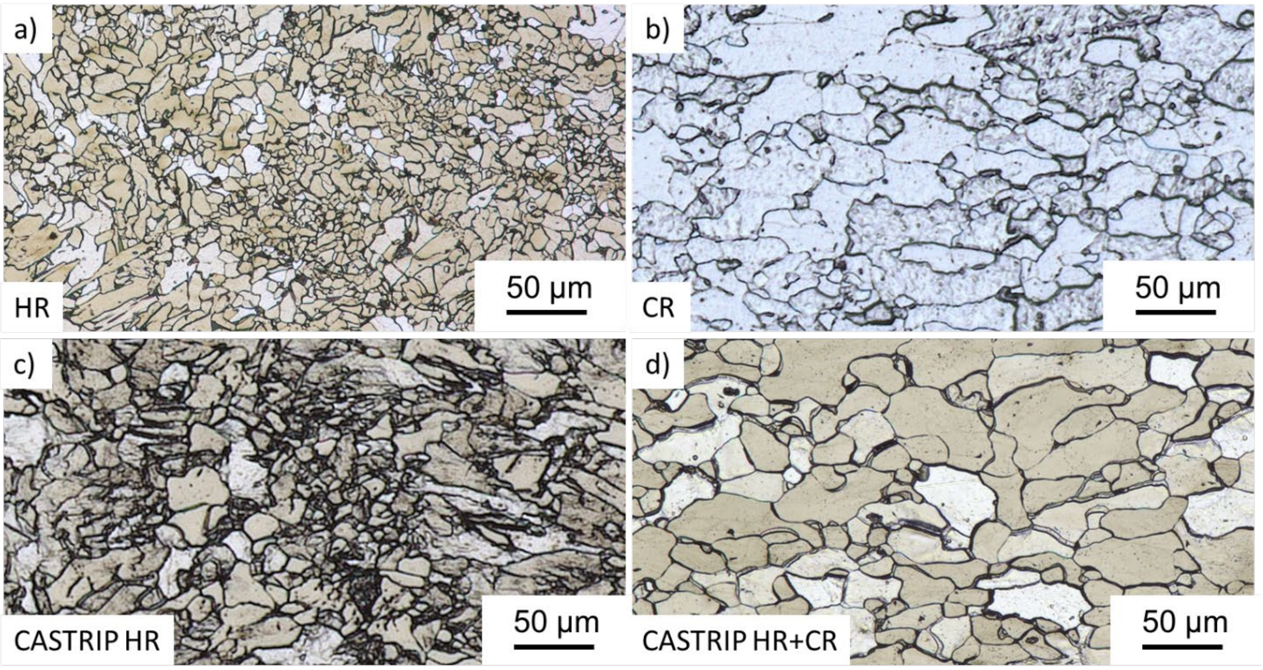

Fig. 6 Comparison of microstructures after different downstream processing routes: twin-roll-cast material investigated in this study after a) hot rolling with low reduction and after b) cold rolling followed by recrystallization annealing and industrial CASTRIP reference material after c) low inline hot rolling and after d) high rolling reduction (t = 0.7 mm).

For industrial benchmarking, these microstructures are compared with those of two industrial CASTRIP reference materials, shown in Fig. 6 c) and d). While both materials are produced via strip casting, they differ in alloy design. The alloy investigated in this study is based on a DC03-type low-carbon steel with a deliberately increased copper content of 0.75 wt.% and without additions of Ni and Si. In contrast, the CASTRIP reference materials are ultra-low-carbon steels containing 0.35-0.40 wt.% Cu in combination with small additions of Mn, Si, Ni and Cr.

The CASTRIP material processed with a low degree of inline hot rolling exhibits a pronounced Widmanstätten-type ferritic microstructure. In contrast, the hot-rolled twin-roll-cast material shows a predominantly equiaxed ferritic-pearlitic grain structure without pronounced acicular features. Conversely, the CASTRIP material subjected to a higher degree of inline rolling reduction shows a homogeneous, pancake-like grain structure comparable to that obtained after cold rolling and recrystallization annealing in the present study. Despite these differences in alloy composition and copper content, the close qualitative agreement highlights that similar microstructural states can be achieved in laboratory-scale and industrial strip casting routes.

Mechanical properties and benchmarking The different microstructures obtained through these processing routes are reflected in the mechanical properties. A quantitative comparison of yield strength, ultimate tensile strength and elongation at fracture is summarized in Table 2. The hot-rolled twin-roll-cast material exhibits a comparatively high yield strength combined with moderate elongation, consistent with its fine-grained ferritic-pearlitic microstructure and the associated grain-boundary strengthening formed under conditions of limited hot deformation. In contrast, the cold-rolled and recrystallized condition shows lower yield strength but increased ductility, reflecting the homogeneous pancake-like grain structure obtained after complete recrystallization and the reduced dislocation density after annealing. These trends follow established structure-property relationships for low-carbon steels.

Table 2 Overview of processing routes and mechanical properties of the investigated twin-roll-cast alloy compared with industrial CASTRIP reference materials and standardized low-carbon steels [11,12].

Material	Composition	Process route	Cu (wt.%)	YS (MPa)	UTS (MPa)	A50 (%)
This work-HR (t = 1.2 mm)	DC03-type low-C steel, no Ni/Si	TRC; reheating; hot rolling	0.75	365	420	21
This work-CR+RX (t = 0.7 mm)	DC03-type low-C steel, no Ni/Si	TRC; cold rolling; RX (710 °C, 5 h)	0.75	275	341	22
CASTRIP (t = 1.88 mm)	Ultra-low-C strip steel	Industrial TRC; inline HR	0.35	235	403	18
CASTRIP (t = 0.7 mm)	Ultra-low-C strip steel	Industrial TRC; high HR reduction; CR	0.4	340	325	35
ASTM A1039 CS Type B	Commercial low-C sheet steel	Slab / thin slab; HR & CR	≤ 0.20	170-240	300-380	25-35
DC03 (EN 10130)	Low-C deep-drawing steel	Slab; CR; RX	< 0.10	140-200	270-330	34-42

For industrial benchmarking, the mechanical properties of two CASTRIP reference materials were determined under identical testing conditions as applied to the material investigated in this study. The CASTRIP material processed with a low degree of inline hot rolling exhibits a strength-ductility balance comparable to that of the hot-rolled twin-roll-cast material, whereas the CASTRIP material subjected to a higher rolling reduction shows mechanical behavior similar to that of the cold-rolled and recrystallized condition. This correspondence is consistent with the qualitative microstructural similarities discussed in Section 3.3.

Quantitative differences in strength levels between the investigated alloy and the CASTRIP reference materials can be attributed primarily to differences in chemical composition. The twin-roll-cast material produced at IBF exhibits consistently higher yield strength, which is associated with its higher carbon content and deliberately increased copper level of 0.75 wt.% compared to the ultra-low-carbon CASTRIP steels containing 0.35-0.40 wt.% Cu. Despite these differences, comparable elongation values are achieved, indicating that elevated copper contents do not inherently compromise ductility when copper-related damage mechanisms are suppressed by the strip casting route.

In comparison, conventionally produced low-carbon sheet steels such as DC03 and standardized grades according to ASTM A1039 CS Type B exhibit similar mechanical property windows only at significantly lower copper contents [11,12], as summarized in Table 2. This reflects the limitations imposed by slab-based processing routes, in which prolonged reheating and extensive hot deformation restrict the allowable copper content. The present results therefore demonstrate that twin-roll casting enables mechanical property levels comparable to industrial and standardized low-carbon steels while accommodating substantially higher residual copper contents.

Summary

This study demonstrates that twin-roll casting fundamentally shifts the processing window for copper-containing steels. A construction steel alloy with 0.75 wt.% Cu, exceeding typical limits for conventionally processed flat steels, was successfully produced as strip and further processed without hot-shortness-related damage.

Microstructural analysis reveals that copper-related degradation mechanisms are not activated during strip casting itself but are governed by thermal exposure and oxidation during subsequent processing. While the twin-roll-cast material exhibits only localized copper enrichments and a thin oxide scale, reheating under conditions representative of conventional slab-based processing leads to extensive oxidation, pronounced copper enrichment beneath the scale, and grain-boundary penetration.

By applying different downstream processing routes, the twin-roll-cast strip can be transformed into distinct microstructural states with corresponding mechanical property profiles. The resulting strength-ductility combinations are comparable to those of industrial strip-cast reference materials and conventionally produced low-carbon sheet steels, despite the substantially higher copper content. These findings demonstrate that elevated copper levels do not inherently limit mechanical performance when copper-related damage mechanisms are effectively suppressed.

Overall, the results identify twin-roll casting as a key enabling technology for increased scrap utilization and circular flat steel production. By tolerating higher residual copper levels, the process appears well suited to act as a sink for copper-bearing scrap streams and thus offers a viable pathway to accommodate the increasing availability of recycled steel in future flat steel production.

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