

# Steel Ladle Lining Design and Performance Improvements at U. S. Steel – Fairfield Tubular Steelmaking Operations



In 2020, U. S. Steel – Fairfield Tubular Steelmaking Operations achieved a significant milestone by transitioning from a blast furnace-QBOP to an electric arc furnace steelmaking process. Central to this transformation was the complete redesign of steel ladles, which are pivotal for ensuring a safe, stable and cost-effective operation. This article delves into the innovative features of the newly designed steel ladles, the advanced refractory lining configurations and the cutting-edge operational practices that have collectively propelled performance to new heights, setting a benchmark in the industry.

## Authors

**Mike O'Neal** (top left), Refractory Manager, U. S. Steel – Fairfield Tubular Operations, Fairfield, Ala., USA  
mkoneal@uss.com

**Frank Sides**, Area Manager – Operations, U. S. Steel – Fairfield Tubular Operations, Fairfield, Ala., USA  
fmsides@uss.com

**Anthony Faulds**, Plant Manager, U. S. Steel – Fairfield Tubular Operations, Fairfield, Ala., USA  
awfaulds@uss.com

**Rakesh K. Dhaka** (top right), Research Consultant – Refractories, U. S. Steel Research & Technology Center, Munhall, Pa., USA  
rkdhaka@uss.com

**David J. Radakovic** (bottom), Senior Research Engineer, U. S. Steel Research & Technology Center, Munhall, Pa., USA  
dradakovic@uss.com

## Introduction

The facility currently operates a 170-ton heat size AC electric arc furnace (EAF) integrated with a ladle metallurgy furnace (LMF), a vacuum tank degasser (VTD) and a 4-strand rounds caster. The typical process data for the facility are presented in Table 1.

Following the installation of the new EAF and VTD, the steelmaking process continued to utilize the existing LMF and rounds caster. Consequently, the overall dimensions of the steel ladles were required to remain unchanged. However, the existing ladles were found to be in

poor condition, exhibiting significant shell deformation. Given that the ladle shells were expected to experience higher temperatures post-VTD processing, it was determined that the fabrication of new ladle shells was necessary.

While maintaining the original outer dimensions (height and diameter), several design modifications were implemented to enhance the refractory performance, particularly in the ladle top section. A review of historical ladle top designs, combined with past operational experience and finite element analysis (FEA) modeling, led to the development of an

Table 1

### Typical Process Data (2024)

Tapping temperature (average)	[°F]	3,027°F
Tap carbon	[%]	0.08
Slag basicity (CaO/SiO <sub>2</sub> ) (aim)	–	2.0 typical
Tap-to-tap time (average)	minutes	72
No. of ladles	–	9
Residence time (average)	minutes/heat	231
Ladle metallurgy furnace arc time (average)	minutes	28

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innovative ladle top design. This new design has significantly improved ladle performance, with minimal maintenance required over a 4-year operational period.

The optimization of the ladle refractory lining was achieved by balancing factors such as ladle volume, freeboard requirements, campaign life and heat loss through the shell. To further enhance operational safety, thermal scanning cameras were installed at both the LMF and VTD. Additionally, in 2024, a laser scanning tool was implemented to profile each ladle prior to tapping a heat. This tool has enabled the extension of ladle campaign life beyond the typical duration, provided the lining remains in good condition and has also facilitated the premature removal of ladles from service if any areas of the lining are compromised.

Operationally, the number of ladles in service has been optimized, effectively reducing ladle cycling time and improving overall operational efficiency.

## Discussion

### Ladle Shell Top Redesign

For consistent and reliable performance of refractory linings, the top section — commonly referred to as the “lip ring” — plays a critical role. This section must generate sufficient compression to secure the remainder of the lining. Typically, a castable material is used in this area. Due to the expansion of the refractory lining, the cleaning practices involving a Gradall machine and the effects of thermal cycling, the lip ring castable is subjected to significant thermal and mechanical stresses. To ensure the retention of this castable throughout the ladle lining campaign, various design approaches have been explored and implemented over time. Several of these designs, utilized across various U. S. Steel facilities, are illustrated in Fig. 1.

The tapered section, currently the preferred design, is widely used; however, its effectiveness diminishes over time. Existing tapered designs fail to provide adequate taper compression for the working lining due to suboptimal taper angles and insufficient taper lengths. Furthermore,

Figure 1

Showing various design of a steel ladle top section utilized in various U. S. Steel facilities.<sup>1,2</sup>

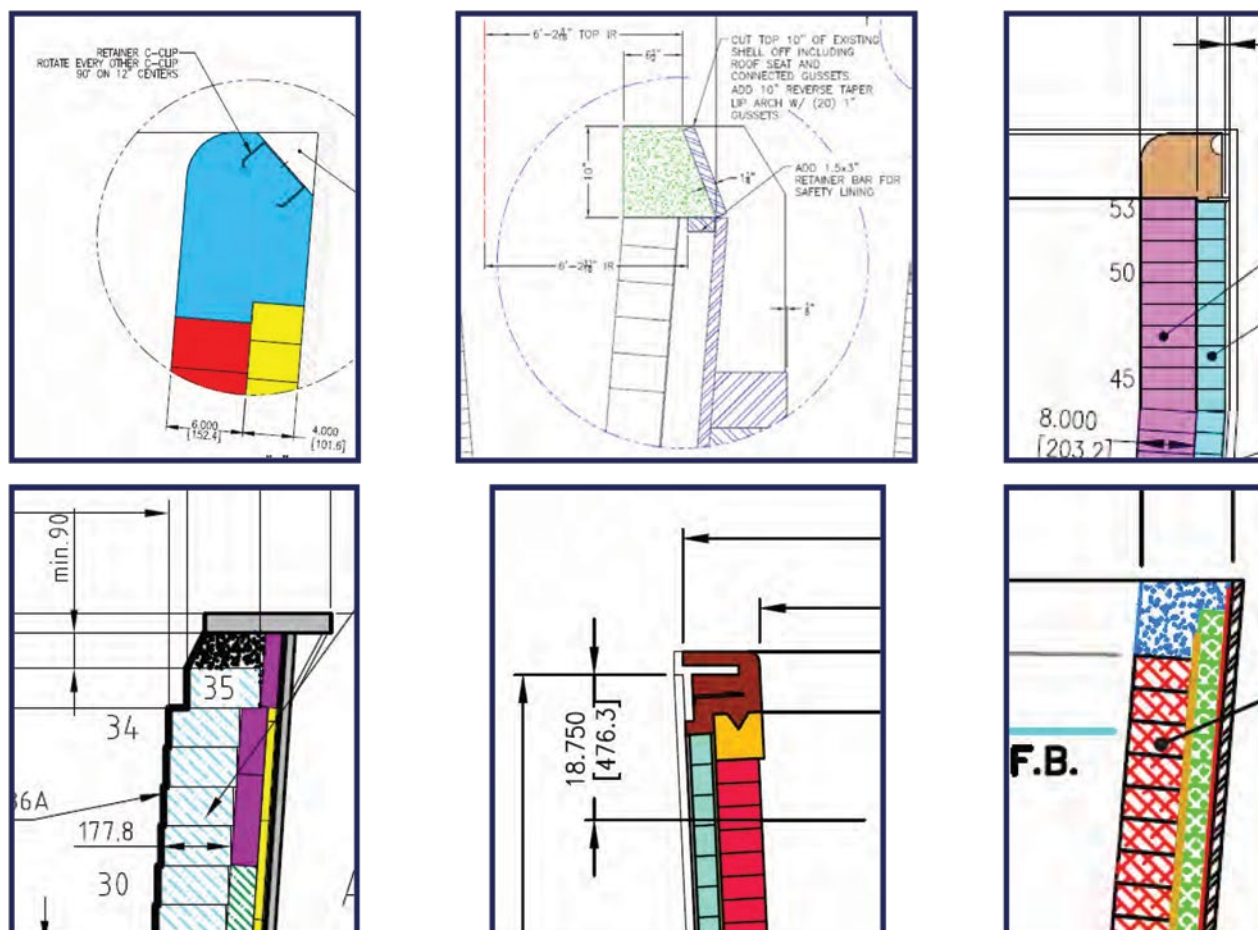
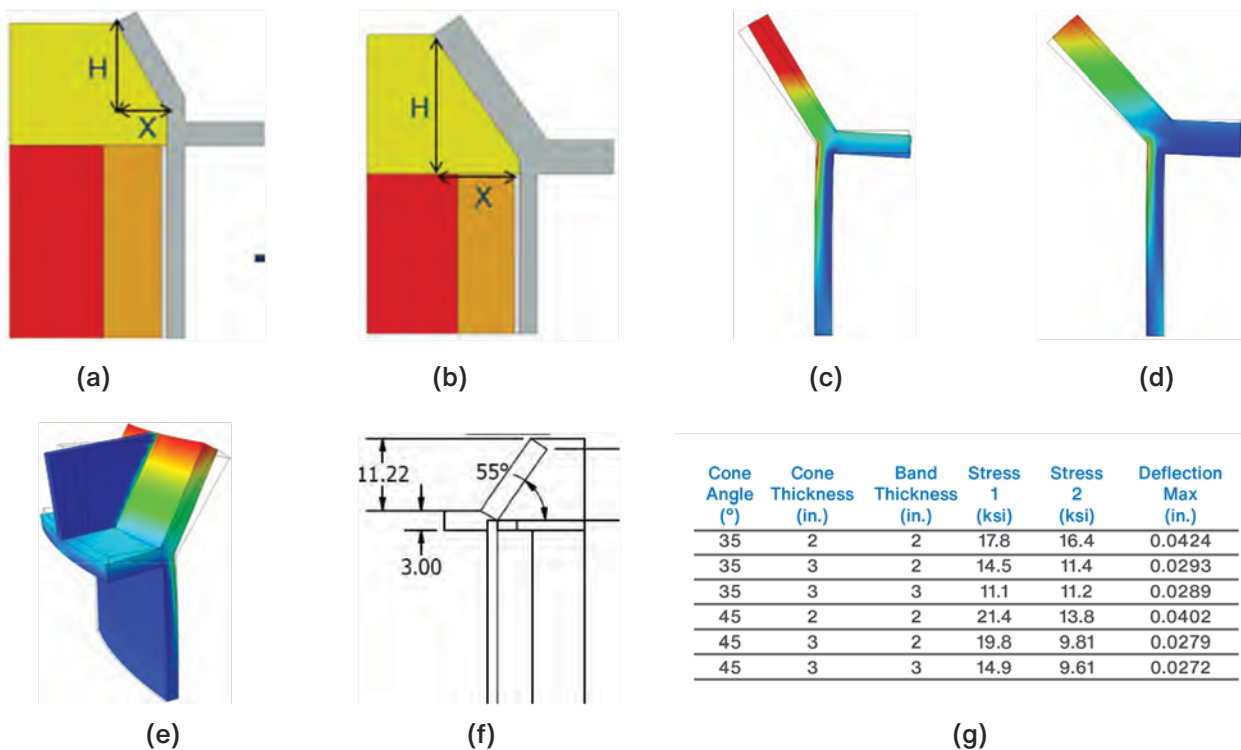


Figure 2

(a) Commonly used taper top design, (b) modified taper top with circumferential support located at the base of the tapered section, (c) finite element analysis (FEA) of a case with 2-inch thickness of the tapered section, (d) FEA analysis of a case with 3-inch thickness, (e) gussets added on the tapered section are not effective, (f) design selected for implementation in U. S. Steel – Fairfield Tubular Steelmaking Operations (FTSO) ladles and (g) stresses and deflection generated in top section of various angles and thicknesses when 1,000 kpsi vertical stress is applied. It is important to note that the new design had taper section length and angle such that its horizontal projection (x) was covering at least 20% of the working lining thickness. Increased thickness and circumferential support were crucial to reduce deformation.



the taper section deforms over time, losing its ability to maintain the necessary compression.

To address these deficiencies in conventional tapered top designs, FEA modeling was conducted for various design configurations. The results revealed that the commonly employed tapered design deforms under excessive hoop and bending stresses. To mitigate this issue, the addition of circumferential support at both the top and the base of the taper was recommended. Fig. 2 illustrates the standard tapered design alongside the variants analyzed through FEA modeling. The design exhibiting the lower hoop stress and deflection under a vertical stress of 1,000 kpsi was a tapered section with a 3-inch thickness, set at a 35° angle from the vertical axis, coupled with a 3-inch circumferential band around the base of the taper. This design (U.S. Patent #11,602,787)<sup>3</sup> was subsequently implemented in the steel ladles at U. S. Steel – Fairfield Tubular Steelmaking Operations (FTSO).

### Ladle Refractory Lining

The ladle capacity for the QBOP production process was initially 210 tons with a 22-inch freeboard. However, when the same ladle size was used for a 170-ton heat size with approximately a 40-inch freeboard, an opportunity arose to redesign the refractory lining. As shown in Fig. 3, various configurations with different thicknesses for the safety, working and insulating boards were analyzed. After considering factors such as the maximum temperature limit of the insulation board, overall volume requirements, shell temperature and campaign costs, the optimal lining design was determined: a 7-inch barrel thickness, 8-inch slagline, 5-inch safety lining and 0.5-inch insulation board. It was also decided to use two slaglines per campaign. This configuration was implemented during the first two years of operation.

For the ladle bottom, a 2.5° slope was incorporated into the safety lining to optimize yield. By utilizing this slope in the safety lining, the benefit of the slope is maintained throughout the entire ladle campaign, independent of the features of the working lining bottom. This is

more effective than incorporating a slope or high-yield features into the working lining bottom, as these typically do not last the full duration of the campaign and are not cost-effective.

To further optimize the lining design, several modifications were made over the past 2 years, including increasing the slagline and barrel brick thickness by 1 inch, incorporating a starter set in the precast working bottom, and discontinuing the practice of changing the slagline mid-campaign.

### Safety and Operational Improvements

- **Ladle Thermal Vision** – The implementation of thermal vision cameras to monitor the shell temperature of steel ladles is a critical advancement for both safety and performance in steelmaking operations. Recognizing the importance of this technology, FTSO adopted it at start-up, establishing it as a standard practice. These thermal

cameras are currently in use at both the LMF and VTD, where they monitor the shell temperature and provide alerts if any hot spots are detected. The ability to proactively identify temperature anomalies enhances the safety of the operation by preventing potential failures.

- **Ladle Laser Scanning** – In 2024, a laser scanning system was installed to profile the thickness of the ladle refractory lining. This addition has proven invaluable in extending ladle campaigns when the lining remains in good condition and alerting operations if the lining has been compromised. The integration of laser scanning technology has provided critical insights, enabling operations to confidently extend the campaign. Additionally, the laser scanning tool has been essential in preventing catastrophic failures. For instance, as shown in Fig. 4, a ladle with only 66 heats was found to have a lining thickness of just 1.5 to 2.5 inches in one

Figure 3

(a) The heat transfer calculations done for various lining configurations, (b) the initial lining design with 7-inch barrel and 8-inch slagline that was considered for the start-up, (c) a ladle coming off a preheater and (d) current lining design consisting of 8-inch barrel and 9-inch slagline.

Shell Temperature (F) and Heat Loss (Btu/hr/ft <sup>2</sup> ) for Various Cases							
	Case 1	Case 1A	Case 2	Case 2A	Case 3	Case 3A	
Safety lining thickness, in.	4	4	4.5	4.5	5	5	
Insulation board, in.	0.75	0.50	0.75	0.50	0.75	0.50	
Working lining thickness, in.	9.00	590(2032)	616(2225)	580(1954)	604(2135)	570(1883)	593(2051)
	8.00	604(2134)	630(2344)	593(2049)	618(2245)	582(1971)	606(2153)
	7.00	618(2247)	646(2476)	606(2154)	633(2366)	595(2068)	621(2265)
	6.00	634(2374)	663(2624)	621(2271)	649(2502)	609(2176)	636(2390)
	5.00	651(2517)	682(2793)	637(2401)	667(2655)	624(2296)	652(2530)
	4.00	669(2680)	702(2986)	655(2550)	686(2829)	641(2432)	670(2688)
	3.00	690(2870)	725(3212)	674(2720)	707(3032)	659(2586)	690(2871)

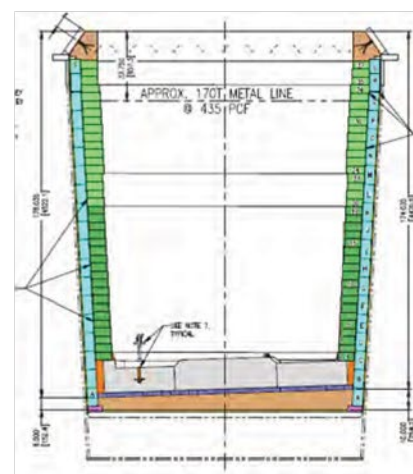
(a)



(b)



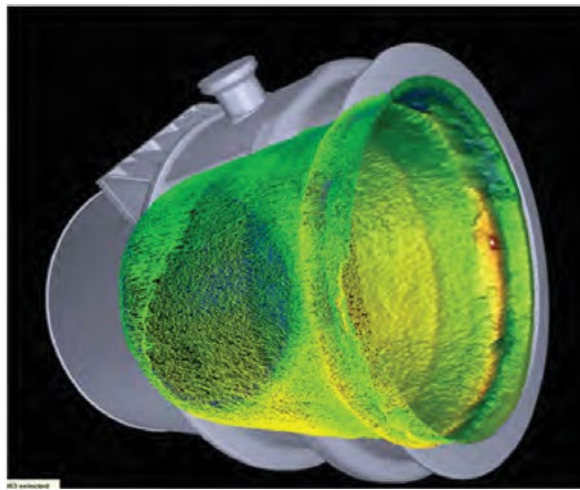
(c)



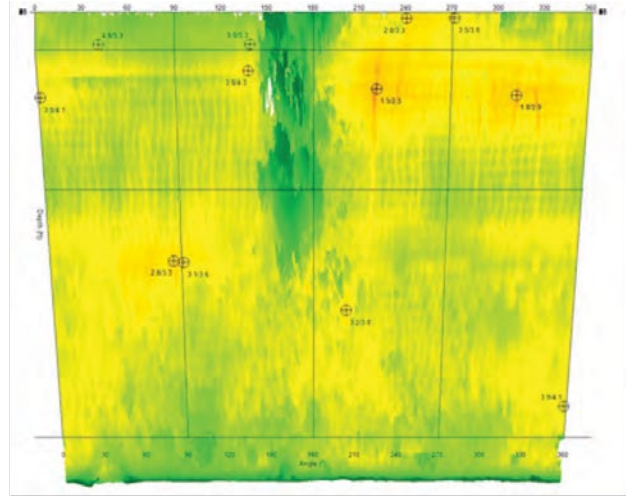
(d)

Figure 4

A 3D view<sup>4</sup> (a) and a plan view (b) of the ladle lining and associated lining thickness. The laser scanning system was able to alert operation of a thin spot in slagline area.



(a)



(b)

Table 2

## Steel Ladle Campaign Data

	Initial barrel/ slagline thickness, in.	Average ladle metallurgy furnace arc time/heat, min.	Average steel contact time, heat/min.	Average steel time/ campaign, min.	Maximum steel contact time/ campaign, in.	First slagline life, heats	Average ladle campaign, heats	Maximum ladle campaign, heats
2021	7.0/8.0	43	266	17,669	18,842	37	66	70
2022	7.0/9.0	32	261	16,730	19,114	38	64	73
2023	8.0/9.0	32	2,321	16,562	17,491	36	72	80
2024	8.0/9.0	28	231	16,795	18,660	—	73	82
2025*	8.0/9.0	29	241	16,491	17,900	—	68	77

\*2025 data is only up to January

area. Further investigation revealed that the brick in this region had been compromised, likely due to the KT-Grant machine. After removing the ladle from service, a thorough examination confirmed that the lining was significantly thinner in this specific spot.

- Ladle Cycling – Optimizing the number of ladles in service has been key to improving overall performance. While five ladles are always kept hot, only four ladles are actively rotated unless a ladle delay is anticipated (such as from a nozzle or stir plug punch). In those instances, the fifth ladle is brought into service to prevent delays in furnace

tapping and avoid production slowdowns. Once the issue is resolved, the ladle is removed from service and parked under a preheater. The authors' analysis has demonstrated that operating with four ladles in rotation, rather than five, significantly enhances shop efficiency. This optimized rotation better aligns with production pacing, reducing unnecessary idle time for the ladles. Furthermore, the use of four ladles has minimized the time spent on the tap or rotator car, leading to improved throughput and enabling the achievement of up to 82 heats per ladle. This adjustment has proven to be a critical factor in boosting overall ladle performance

## Performance

The performance of the steel ladles since start-up is summarized in Table 2, showing a consistent year-over-year increase in ladle campaign life. In early 2023, the barrel thickness was increased by one inch to 8 inches, and the practice of changing the slagline mid-campaign was eliminated. These changes led to reductions in both overall costs and ladle turnaround time, while maintaining or even enhancing campaign life. By 2024, the ladle lining achieved a notable maximum of 82 heats, with a total of 18,660 minutes of contact time. Additional process optimizations further contributed to improved performance, including reduced steel contact time per heat and less power-on time at the LMF, both of which have extended the life of the ladle lining.

*This article is available online at AIST.org for 30 days following publication.*

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## Conclusions

The transition of FTSO from a QBOP to EAF process presented an opportunity to redesign the steel ladle shell and the refractory lining. Utilizing the FEA modeling and operational experience resulted in implementation of an innovative ladle top design (U.S. Patent #11,602,787) that has performed very well. Operational process optimization, utilization of thermal scanning and laser profiling tools coupled with refractory lining configuration changes over the last 4 years resulted in remarkable performance of the ladle lining.

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