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# Modelling the influence of thermal fields on residual stress evolution incorporating LTT effect in low and high alloy steels

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## Abstract

This study presents a numerical analysis of the influence of thermal fields on the development of residual stress in both low and high alloy steels, specifically addressing low-transformation-temperature (LTT) effects during electron beam welding. A coupled thermo-metallurgical-mechanical finite element model is created to simulate the interplay between transient heat transfer, phase changes, and stress development during cooling. The LTT phenomenon is integrated using a UEXPAN user defined subroutine by considering the transformation-induced plasticity and strain linked to martensitic transformation at lower temperatures. This combinational effect allows to depict the stress relaxation and distortion behavior. Comparative analyses of low and high alloy steels highlight the influence of localized thermal input and LTT characteristics on the determination of final stress states. The findings show the importance of accurately modeling both the position of the applied thermal field and the transformation kinetics when evaluating deformation and structural integrity in thermally processed components.

## Keywords

Laser beam welding, electron beam welding, low transformation temperature (LTT) effect, numerical simulation, residual stress, distortion

## 1 Introduction

In Beam welding, distortion and residual stress are inevitable problems that are primarily brought on by sudden change in temperature and uneven cooling. These effects can have a detrimental impact on the performance of welded components and frequently result in dimensional errors, particularly in applications where extreme precision is needed. It has become evident in recent years that metallurgical transformations have a significant impact on residual stress formation in addition to thermal effects. In particular, the martensitic transformation during cooling plays an important role in how stress develop in the weld [1,2]. Based on this understanding, low–

transformation–temperature (LTT) alloys have been introduced as a promising approach to reduce welding-induced stress.

The key idea behind LTT materials is that the martensitic transformation occurs at relatively low temperatures. This delayed transformation leads to a volume expansion that can counteract the shrinkage during cooling. As a result, tensile residual stress can be significantly reduced or even converted into compressive stress [3,4]. In addition, studies have shown that the effectiveness of this mechanism depends strongly on the chemical composition, as it directly influences the transformation temperature and the resulting strain potential [5]. Further work by Kannengiesser, Kromm, and Hübner has shown that LTT welding consumables can actively be used to tailor residual stress. Their results indicate that compressive stress can be introduced during cooling, with reductions in the range of several hundred MPa depending on weld geometry [6]. They also demonstrated that this approach could improve fatigue performance by reducing critical tensile stress in welded components [7].

To better understand these interactions, numerical simulations have been increasingly used. These models combine thermal, metallurgical, and mechanical effects and allow the prediction of residual stress with good spatial and temporal resolution [8]. It has also been observed that even small changes in chemical composition can influence melt pool behavior and transformation kinetics, which in turn affects the final stress state [9]. More recent developments focus on using this knowledge for process control. By adjusting the alloy composition locally, for example through controlled filler material deposition, it becomes possible to influence residual stress in a targeted way. This opens new possibilities for reducing distortion in complex welded structures [10–12].

## 2 Aim of the Investigation

The primary aim of this study is to mitigate welding-induced deformation by comprehending and regulating the formation of residual stress in fusion welding. The emphasis is on the utilization of chemical composition and phase transformations, especially in low-transformation-temperature (LTT) materials, to affect the stress state during cooling. A primary objective is to establish explicit correlations among chemical composition, temperature gradients, phase change behavior, and the resultant residual stress. Furthermore, the study aims to describe and predict these interactions by numerical simulations that integrate thermal, metallurgical, and mechanical influences. Based on this understanding, the final objective is to develop practical process strategies such as controlled adjustment of alloy composition during welding to enable targeted control of residual stress and minimize distortion in complex components.

## 3 Materials and Experimental Details

The materials used in this study were low-alloy carbon–manganese steel S235JR and austenitic stainless steel EN 1.4301. Both were made into plates measuring 100 × 50 × 5 mm. These steels were chosen to represent two very different metallurgical structures: the low-alloy steel had a ferritic–pearlitic structure, while the high-alloy steel had a fully austenitic structure. This enables a comparative investigation of the low–transformation–temperature (LTT) effect under contrasting phase stability and thermal conditions. To ensure consistent weld geometry and controlled filler material deposition, all samples were prepared with a central groove measuring 1 × 1 mm in both width and depth. Two filler wire types supplied by ESAB (Sweden) were used: a high-alloy wire G19 9 (EN ISO 14343-A G 19 9 L Si / AWS A5.9: ER308LSi) and a low-alloy wire G3Si1 (EN ISO 14341-A G 38 3 C13Si1 / AWS A5.18: ER70S-6), both with a diameter of 1 mm. The LTT effect was introduced using an in-situ alloying approach by varying the combination of base and filler materials. For the low-alloy steel S235, the LTT condition was achieved by alloying with the high-alloy filler wire G19 9, while the reference weld was produced using G3Si1. In contrast, for the austenitic stainless steel EN 1.4301, the reference weld was produced using the high-alloy filler wire G19 9, whereas the LTT condition was obtained by dilution with the low-alloy filler wire G3Si1. This approach allowed controlled modification of the weld metal composition and transformation behavior in both material systems. The chemical compositions of the base materials and filler wires were determined using optical emission spectroscopy, **Table 1**.

**Table 1:** Chemical compositions for base material and filler wire in wt%

| | | Fe | C | Si | Mn | Cr | Ni | Mo |
|---|---|---|---|---|---|---|---|---|
| Base Material | S235JR | 98.2 | 0.08 | 0.056 | 1.01 | 0.413 | 0.041 | 0.014 |
| | EN1.4301 | 70.7 | 0.02 | 0.42 | 1.68 | 18.2 | 8.24 | 0.036 |
| Filler wire | G 19 9 | 67.4 | 0.026 | 0.75 | 1.84 | 19.84 | 10.14 | 0.026 |
| | G3Si1 | 97.3 | 0.07 | 0.86 | 1.44 | 0.045 | 0.019 | 0.008 |

The welding experiments were carried out using both an electron and laser beam welding system equipped with a clamping fixture and a filler wire feeding unit **Figure 1**. Welding parameters were optimized through preliminary trials and finalized in accordance with ISO EN 13919-1:1996, ensuring that all welds met quality group B requirements.

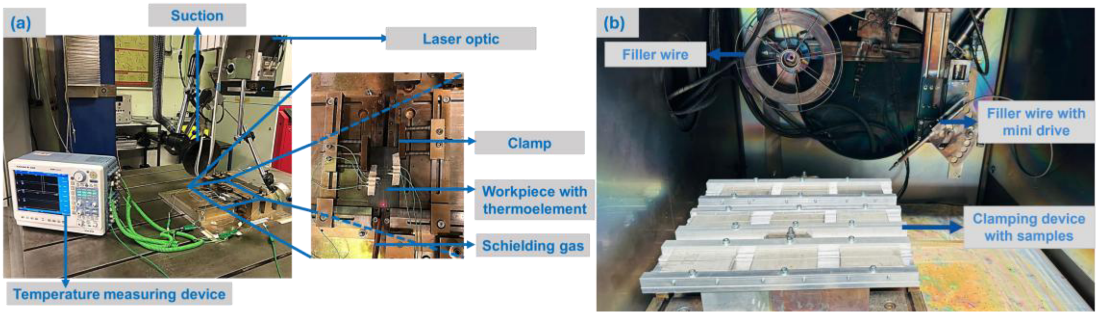

**Figure 1:** (a) Laser beam welding setup, (b) electron beam welding setup with filler wire set up at the Welding and Joining Institute (ISF)

Residual stress is measured using a near-surface method. A drill with a diameter of 0.8 mm was used, and measurements were taken at a depth of 0.5 mm, where the highest tensile residual stress is typically expected in beam welded joints. The longitudinal residual stress component, parallel to the welding direction, was recorded at intervals of 3 mm in the transverse direction up to a distance of 9 mm from the weld centerline. Angular distortion was evaluated using a laser line-scan technique by comparing the geometry of the specimens before and after welding.

To further investigate phase transformation behavior, dilatometry experiments were conducted. For this purpose, samples with controlled chemical compositions were first prepared by melting predefined amounts of base and filler material in an electric arc furnace. Optical emission spectroscopy was used to confirm the chemical makeup, specifically to verify the intended chromium and nickel concentrations. Subsequently, the material underwent machining to produce hollow cylindrical specimens. These specimens measured 10 mm in length, had an outer diameter of 4 mm, and possessed a wall thickness of 1 mm, as specified by ASTM A1033-18.

Dilatometry experiments were conducted utilizing a quenching and deformation dilatometer. Temperature data were acquired via a K-type thermocouple, and dimensional alterations were assessed using a linear variable displacement transducer. The specimens underwent heating to an austenitization temperature of roughly 930 °C, maintained for a duration of 5 minutes, subsequent to which they were quenched at a rate of 100 °C/s within a helium environment. The resulting dilation curves were used to analyze phase transformation behavior.

Since the primary transformation occurs during the cooling stage, the phase fractions were determined from the cooling segments of the dilation curves. The martensitic transformation was evaluated using both a graphical approach based on the lever rule and an empirical method based on lattice parameters. Due to the high cooling rate, the transformation from austenite to martensite occurred directly without intermediate phases. The martensite fraction was found to depend mainly on the martensite start temperature and the associated volume expansion, with the transformation temperature determined from the dilatometry data as well as empirical relationships based on chemical composition.

The numerical simulations were carried out to describe the coupled thermo-metallurgical-mechanical behavior during welding and to predict the resulting residual stress, **Figure 2**. A multi-physics modeling approach was adopted, in which heat transfer, phase transformation, and mechanical response were solved in a sequentially coupled manner. Initially, the thermal field was determined through the simulation of the welding heat source and its consequent heat input into the material. This involved accounting for temperature-dependent material characteristics and relevant boundary conditions, such as heat dissipation via conduction, convection, and radiation for laser beam welding and just radiation in case of electron beam welding. The dynamic heat source was specified in accordance with the welding process parameters, thereby facilitating the computation of transient temperature profiles and cooling rates.

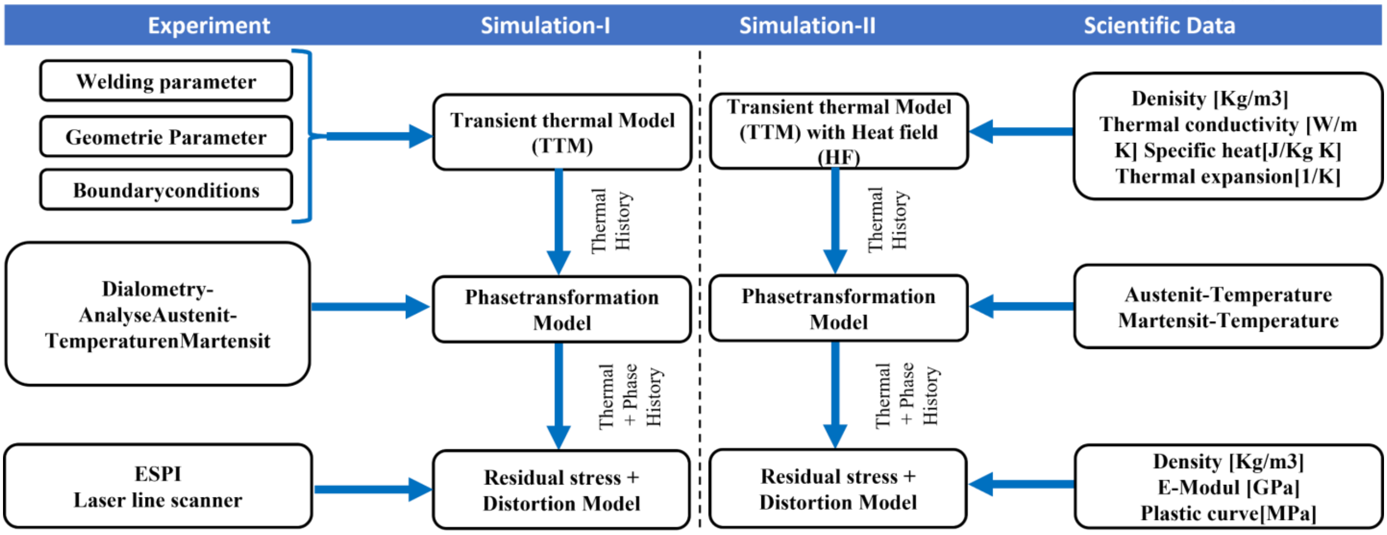

**Figure 2:** Simulation methodology

Based on the computed temperature field, the metallurgical model was applied to describe phase transformations during the cooling cycle. In particular, the martensitic transformation was modeled as a function of temperature and chemical composition, allowing the determination of transformation start temperature and phase fractions. The transformation-induced strain associated with the formation of martensite was included in the model to capture its influence on stress development. The mechanical analysis was then performed, using the calculated temperature history and phase fractions as input. Thermal strains, transformation-induced strains, and elastic-plastic material behavior were considered to determine the evolution of residual stress. The interaction between these effects enabled a realistic prediction of distribution of stress in the weld region. In addition, the simulation model was extended to include the effect of an external heat field applied during or after welding. This allowed the investigation of how modified thermal conditions influence cooling behavior, phase transformation timing, and residual stress formation. The model was validated by comparing the simulation results with experimental measurements of temperature, phase fraction, and residual stress. Simulation methods provide a comprehensive way to analyze and predict how process parameters and material properties affect the development of residual stress during welding.

## 4 Results and Discussion

In Phase 1, the study focused on the influence of chemical composition on residual stress formation and on confirming the LTT effect, using low-alloy steel as the base material and electron beam welding as the process. The results clearly show that residual stress formation is not governed solely by thermal effects but is strongly influenced by the interaction between chemical composition and phase transformation behavior. In conventional materials, cooling primarily results in tensile residual stress due to thermal contraction under constraint. With the introduction of LTT materials, a clear reduction in residual stress was observed. The delayed martensitic transformation at lower temperatures caused volume expansion during the final stages of cooling, which counteracted thermal shrinkage. As a result, the weld area, especially near the center, showed a shift from tensile to compressive residual stress. Furthermore, a strong influence of chemical composition was identified, confirming that alloy design plays a key role in controlling residual stress development and validating the effectiveness of the LTT approach, **Figure 3**.

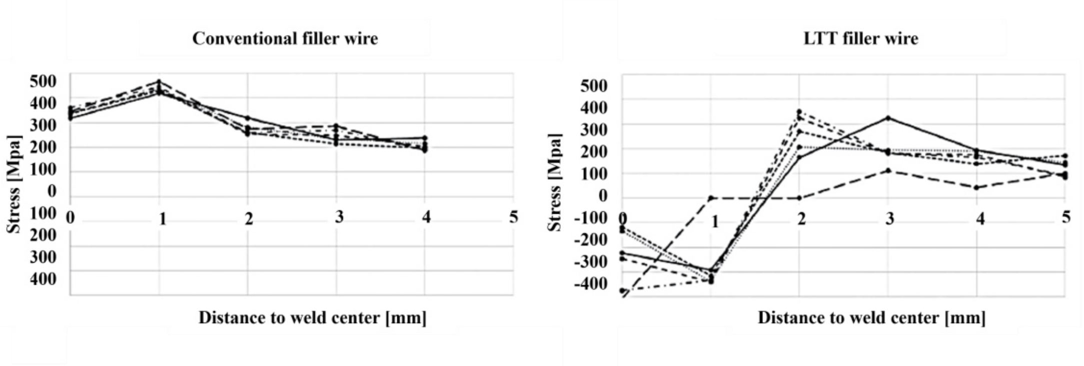

**Figure 3:** Comparison of residual stress measurements for conventional and LTT wires

In Phase 2, the focus was on temperature gradients and phase transformation behavior using numerical simulations, supported by in-situ experimental validation.

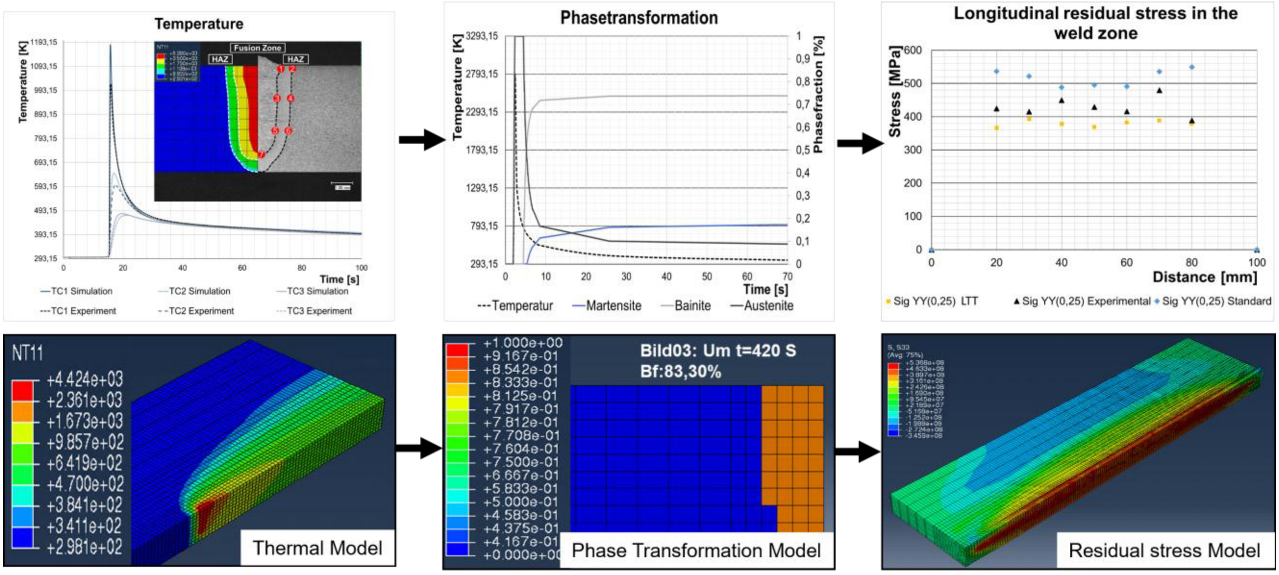

**Figure 4:** Comparison of residual stress measurements for conventional LTT wires

The results show a clear difference in residual stress distribution and temperature fields when phase transformation is included in the simulations compared to when it is neglected. Incorporating phase transformation leads to a more accurate prediction of residual stress, highlighting its significant influence. In addition, in-situ EDXRD measurements during laser beam welding confirmed the transformation behavior of LTT materials. The results show that the delayed martensitic transformation occurs during the cooling stage and is closely linked to local thermal conditions. This provides direct experimental evidence that transformation-induced strains interact with thermally induced stress during welding. The results demonstrate that residual stress development is governed by a strong coupling between thermal, metallurgical, and mechanical effects, emphasizing the importance of a thermo-metallurgical approach for accurate prediction and understanding of the LTT effect, **Figure 4**.

In Phase 3, the focus shifted from understanding the LTT effect to its application for active residual stress and distortion control. The results show that alloy composition and process conditions can be combined in a targeted manner to improve the final stress state of the weld.

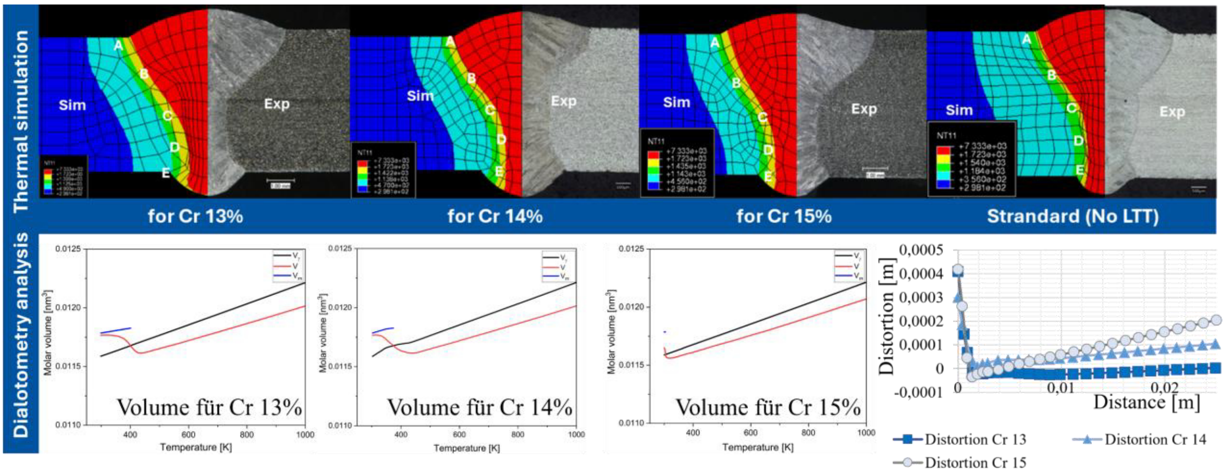

**Figure 5:** Calibrated equivalent thermal models for different Cr% along with dilatometry and distortion analysis.

The impact of chromium content on the LTT effect was examined across weld metal compositions containing 13%, 14%, and 15% Cr, **Figure 5**. The findings reveal a significant correlation between phase transformation characteristics, residual stress profiles, and the specific composition. In the instance of 13% Cr, the martensitic transformation initiates around 160.7 °C and concludes at 50.99 °C, yielding a substantial martensite fraction of approximately 72%. Consequently, this engenders considerable volume expansion during the cooling process, thereby generating compressive residual stress within the weld seam, which is indicative of a pronounced LTT effect. In contrast, at 14% Cr, the martensite start temperature decreases to around 70.5 °C and the martensite fraction drops to ~33%. The transformation is less pronounced and extends below room temperature, resulting in reduced transformation-induced strain and therefore weaker stress compensation. With a chromium content of 15%, the martensite start temperature drops to about 34 °C, and the amount of martensite formed decreases significantly (by about 16%). As a result, the martensitic transformation is largely suppressed, which reduces the LTT effect and increases the residual tensile stress. The findings suggest that a chromium concentration of approximately 13% yields the most favorable LTT characteristics, as it facilitates adequate martensite development at a critical point in the cooling process, thereby inducing compressive stress. Elevated chromium levels diminish the efficacy of the LTT effect, a consequence of transformation being delayed or inhibited, which underscores the significance of precise alloy design in managing residual stress and distortion.

Further the numerical model was extended to include coupled thermo-metallurgical-mechanical behavior along with the influence of an additional heat field, allowing both metallurgical and thermal contributions to residual stress development to be evaluated.

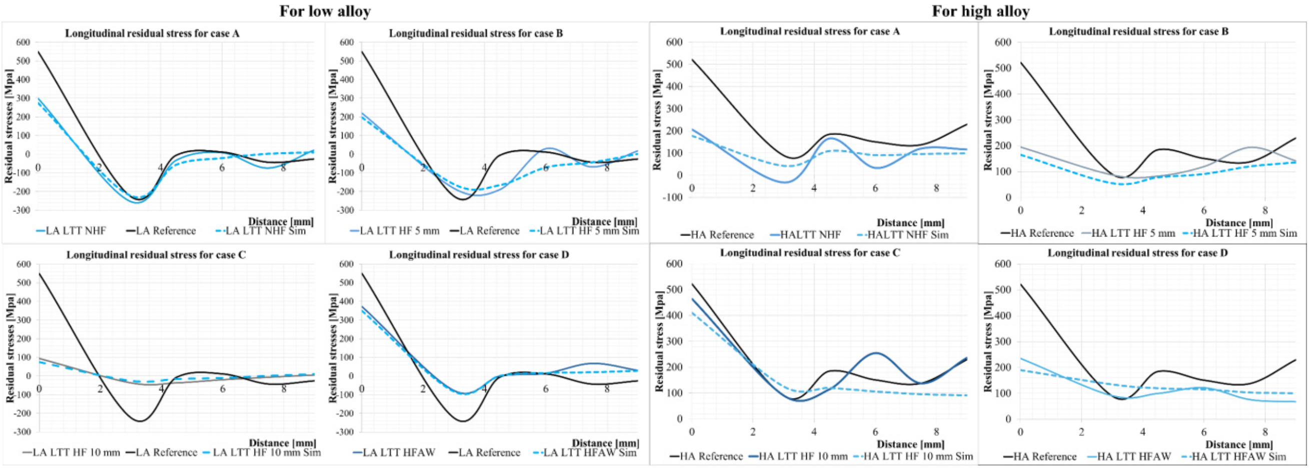

**Figure 6:** Residual stress comparison with and without LTT effect for both high and low alloy considering the heat fields where HA refers to high alloy and LA refers to low alloy.

The results in **Figure 6** confirm that the LTT effect plays a key role in generating compressive stress in the weld seam through delayed martensitic transformation. At the same time, the applied heat field influences thermal strains and further improves the residual stress profile. For low-alloy steel, the optimal condition was achieved when the heat field was applied 10 mm behind the melt pool. The delayed martensitic transformation, occurring later in the cooling process and nearer to ambient temperature, effectively diminished the thermal contraction range. Consequently, stress compensation was enhanced, which in turn reduced peak weld stress by roughly 100 MPa and achieved an overall stress reduction of approximately 82% relative to the baseline scenario. Furthermore, the elimination of compressive stress within the heat-affected zone facilitated a more uniform stress distribution. For the high-alloy steel, the most effective strategy was to apply the heat field after completion of the welding process. This allowed the weld to cool naturally, enabling the LTT transformation to occur without interference. The subsequent heat input primarily contributed to relaxation of existing thermal stress rather than altering transformation behavior. As a result, the stress at the weld center decreased to about 220 MPa, and the stress distribution within the heat-affected zone became much more uniform. Consequently, the overall residual stress was reduced by roughly 58% compared to the initial weld. These observations highlight the substantial impact of the base material on the heat field's implementation. In low-alloy steel, the increased thermal conductivity promotes rapid cooling, thus making the transformation characteristics especially susceptible to additional heat. Conversely, high-alloy steel, distinguished by its lower thermal conductivity and metastable austenitic phase, demonstrates greater sensitivity to thermal variations, demanding precise control over the heat field's application. Therefore, the combined findings suggest that the most efficient reduction of residual stress is achieved through a combined approach, where metallurgical control, enabled by the LTT effect, is integrated with a carefully designed thermal strategy.

## 5 Summary

The present investigation establishes that a combined thermos-metallurgical strategy, particularly the application of low-transformation-temperature (LTT) materials, can be employed to manage residual stress and distortion in fusion welding. Throughout the three phases of the study, the development of residual stress was found to be controlled not only by thermal phenomena but also, and to a considerable extent, by phase transformation dynamics; these, in turn, are modifiable via alloy composition and processing parameters.

Phase 1 results confirmed that using LTT filler materials significantly reduced tensile residual stress. In some cases, this also led to compressive stress in the weld area. This effect is mainly due to a delayed martensitic transformation, which helps to counteract thermal shrinkage during cooling.

In Phase 2, numerical simulations combined with in-situ experimental validation demonstrated that accurate prediction of residual stress requires consideration of coupled thermal, metallurgical, and mechanical effects. The results highlighted the strong influence of chemical composition on temperature gradients, melt pool behavior, and phase transformation kinetics.

In Phase 3, the management of residual stress was successfully accomplished through a combined strategy that integrated alloy design and process techniques, notably the use of a heat field. The introduction of an auxiliary heat field, alongside an optimized alloy composition, resulted in significant stress reductions, specifically approximately 82% in low-alloy steel and 58% in high-alloy steel.

Furthermore, the impact of Cr–Ni composition was distinctly observed; a chromium content of approximately 13% exhibited the most favorable LTT behavior, attributable to adequate martensite formation and transformation-induced strain.

Higher chromium contents (14–15%) resulted in reduced martensite fractions and diminished stress compensation. The results also emphasized that the timing and placement of the heat field are crucial for maximizing the effectiveness of the LTT effect.

Overall, the study confirms that optimal residual stress reduction is achieved through an integrated approach, where metallurgical control via tailored alloy composition is combined with controlled thermal management, providing a reliable pathway for minimizing residual stress and distortion in welded components.

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## Conflict of Interest

The author declares no conflict of interest.

## Data Availability Statement

The data that support the findings of this study are available at [http://hdl.handle.net/21.11102/e66b83c7-a6b2-4134-9c73-cfb528332dec](http://hdl.handle.net/21.11102/e66b83c7-a6b2-4134-9c73-cfb528332dec) upon request.

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