

Residual stress analysis during pulse MIG welding of steel: A Review

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ABSTRACT

Residual stresses are internal forces that remain within a material after the completion of the welding process. These stresses primarily arise from the non-uniform heating and cooling cycles that occur during welding operations. This review presents a comprehensive overview of the current understanding of residual stress formation in steels subjected to pulse Metal Inert Gas (MIG) welding. The influence of various pulse MIG process parameters on the magnitude and distribution of residual stresses, and their subsequent impact on weld quality and structural performance, is critically examined. Furthermore, different experimental and numerical techniques for measuring and predicting residual stresses—such as X-ray diffraction and finite element analysis—are systematically reviewed. The paper also highlights post-weld treatment methods aimed at mitigating residual stresses and improving the overall integrity of welded joints. Various researchers recommended heat treatment, mechanical stress relief and controlled cooling to control residual stresses in weld specimen. Finally, the study identifies existing research gaps and outlines future directions to guide the development of more reliable and stress-minimized weldments.

Keywords: Pulse MIG welding, residual stress, steel, process parameters

INTRODUCTION

Metal Inert Gas (MIG) welding, also referred to as Gas Metal Arc Welding (GMAW), is a fusion welding technique in which a continuous consumable wire electrode is supplied through a welding torch into the molten weld zone. It is among the most extensively used welding methods across industries due to its high productivity, versatility, welding adaptability and ease of automation. A shielding gas—commonly argon or a blend of argon and carbon dioxide—is delivered through the torch to prevent atmospheric gases such as oxygen, nitrogen, and moisture from contaminating the weld pool [1]. The process offers several advantages, including high welding speed, smooth operation, precise heat control, and the ability to produce defect-free, high-strength joints. MIG welding is applicable to a wide range of metals, including carbon steel, stainless steel, and aluminum [2]. Furthermore, welding parameters such as current, voltage, wire feed rate, and travel speed play a critical role in determining the mechanical and metallurgical quality of the weld, thereby ensuring efficiency and reliability in industrial applications [3].

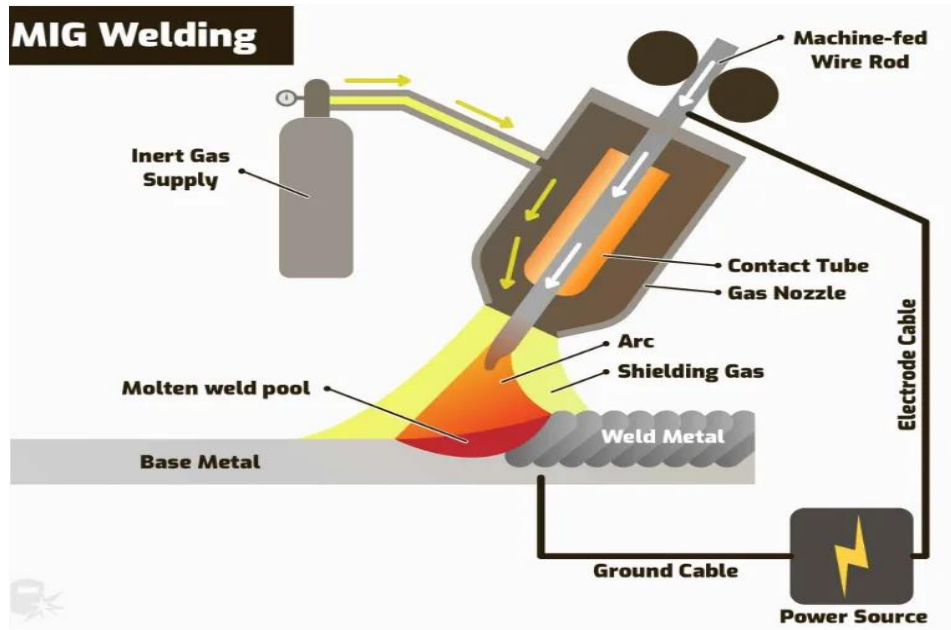


Fig.1. MIG welding setup

Pulse Metal Inert Gas (MIG) welding is an advanced variant of the conventional MIG or Gas Metal Arc Welding (GMAW) process, developed to achieve greater precision in controlling heat input and metal transfer. In this technique, the welding current alternates between a high peak current and a low background current. The peak current is sufficiently high to detach a single molten droplet from the electrode and transfer it across the arc, while the background current sustains the arc with minimal heat generation [4–6]. When applied to steel welding, the Pulse MIG process offers several advantages over traditional MIG welding, including reduced spatter, lower thermal distortion, and improved regulation of weld bead geometry and penetration. The controlled heat input makes it particularly suitable for welding thin or heat-sensitive steels—such as stainless steels and high-strength low-alloy (HSLA) steels—minimizing the risks of burn-through, excessive distortion, or warping [7].

Residual stresses are internal stresses that remain within a material after the completion of the welding process. In welded joints, these stresses primarily develop due to the non-uniform heating and cooling that occur during welding. As the molten metal solidifies and cools, it tends to contract; however, the surrounding material constrains this contraction, resulting in the formation of tensile and compressive stresses within the weld and heat-affected zones. The rapid thermal cycles associated with welding induce both distortion and residual stresses in the weldment. Such stresses and distortions can lead to dimensional inaccuracies during fabrication and pose significant safety concerns during service. Therefore, accurate prediction and effective reduction of residual stresses are essential to enhance the structural integrity and quality of welded components [8]. In thin-section structures, welding often intensifies these effects, producing considerable distortion and residual stresses [9]. Typically, regions near the weld experience high tensile stresses, while compressive stresses are generated in areas farther from the weld zone [10].

PULSE MIG WELDING PROCESS PARAMETERS

One of the most critical stages in the design and fabrication of welded structures is the selection of an appropriate welding process and filler consumables. These factors govern the thermal distribution and chemical composition of the welded joint, which in turn influence weld integrity through their effects on microstructure and residual stress development [11]. The mechanical properties of the weld zone and the overall quality of the welded joint depend significantly on the optimization of welding parameters and the choice of shielding gas [12]. Weld bead geometry is highly sensitive to process variables such as welding speed, current, voltage, arc travel rate, and shielding gas flow rate and composition [13].

Experimental investigations have demonstrated the impact of these parameters on weld quality. For instance, AISI 1018 mild steel specimens welded in a V-butt configuration using MIG welding were analyzed to study the effects of current, voltage, and preheat temperature. The welds were evaluated using X-ray radiographic testing, and the tensile properties—specifically ultimate tensile strength and percentage elongation—were used to assess weld quality. Optimization of process parameters through the grey-based Taguchi method revealed that preheat temperature had the most significant influence on

tensile properties, followed by welding current and voltage [14]. Thus, according to the P-GMAW method, homogeneous mixing of the weld pool is achieved, improving the joint quality and reducing the total heat dissipation[15]. Similarly, automated MIG welding experiments on ASTM A106 Grade B steel pipes have been conducted to examine the influence of process parameters on weld quality and performance [16].

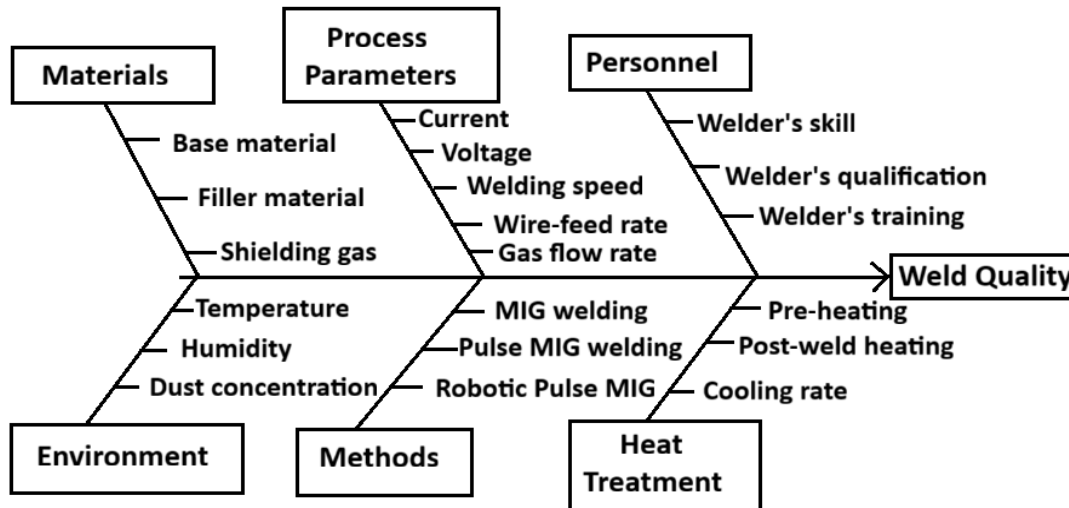


Fig.2. Cause and effect diagram of MIG welding.

Figure.2 shows all the factors that influence the quality of weld specimen fabricated using pulse MIG welding. Improper selection of pulse parameters can lead to several weld defects, such as irregular bead formation, lack of fusion, undercutting, burn-back, and stubbing. The Metal Inert Gas (MIG) welding process is influenced by various dynamic factors, including power source behavior, metal transfer characteristics, arc and droplet dynamics, and weld pool behavior. Effective control of these parameters is essential to minimize defects and enhance overall weld quality [17–20]. In pulse-MIG welding, achieving optimal performance typically involves using a high wire feed speed and trim, combined with a low welding speed and a short contact tube-to-work distance, which helps maximize dilution. Studies further reveal that the mechanical properties, arc configuration, and both macro- and microstructural features of the weld are significantly affected by the torch position, travel angle, and work angle [21, 22].

RESIDUAL STRESS ANALYSIS

During the welding process, non-uniform temperature distribution often results in the development of residual stresses, which can negatively impact the mechanical integrity of welded joints. These stresses and associated distortions primarily arise from the uneven distribution and mismatch of thermal and plastic strains within the weldment, frequently leading to dimensional inaccuracies and reduced service performance [23]. To alleviate residual stresses, large welded components are commonly subjected to post-weld heat treatment (PWHT) [24–26].

The influence of PWHT parameters on residual stress relaxation and the mechanical behavior of SMA490BW steel has been studied through mechanical testing and finite element analysis. Findings indicate that PWHT effectively reduces residual stress levels [27,28].

Numerous studies have explored the formation and prediction of residual stresses using both experimental and numerical approaches. It is widely recognized that residual stress formation is an unavoidable phenomenon in dissimilar metal welded joints [29–33]. A three-dimensional thermo-elastoplastic model has been utilized to predict the influence of geometric configurations on residual stress distribution, with X-ray diffraction (XRD) measurements confirming the accuracy of the model [34]. Additionally, the effect of heat input on residual stress magnitude and distribution in MIG-welded stainless steel 409M was analyzed using the hole-drilling stress relaxation method, revealing that higher heat input leads to increased residual stress levels [35]. Similarly, finite element simulations of hybrid laser-MIG welding of NV E690 steel demonstrated that higher heat input results in elevated peak temperatures, greater residual stresses, and increased weld distortions [36].

Other studies have addressed the effects of welding process parameters, boundary constraints, solid-state transformations, and multi-pass welding on residual stress formation, emphasizing the balance between computational accuracy and efficiency in modeling [37]. Weld repair analyses combining advanced computational modeling and experimental measurements demonstrated that repairs generally increase transverse residual stresses along the weld, particularly in

shorter repair lengths [38]. Comparative studies between non-destructive X-ray diffraction (XRD) measurements and numerical simulations have shown strong agreement, confirming the validity of numerical models for residual stress evaluation. Numerical analyses of pipe welds under varying preheat temperatures indicated that preheating effectively reduces post-weld residual stresses [39].

In austenitic steel weldments, residual stresses and tensile property variations have been characterized with high accuracy using optimized mixed hardening models, which yielded the most reliable predictions [40]. The influence of base metal thickness on coating residual stresses was also investigated, with the optimal configuration exhibiting surface residual stress as low as 18 MPa. Such low residual stress levels in the top layer of multilayer deposits help mitigate corrosion-related issues such as stress corrosion cracking and corrosion fatigue [41]. Furthermore, the relationship between microstructural evolution and residual stress distribution has been explored, revealing that solid-state phase transformations significantly alter both the magnitude and distribution of residual stresses in welded specimens [42].

Estimating the residual stress in weldment is a challenging task [43]. The hybrid laser-metal inert gas (MIG) welding process was studied to solve problems associated with the MIG welding process, such as low welding efficiency, high residual stress and deformation, and serious loss of strength. Results show that compared with the MIG welded joint, the overall residual stress level of the hybrid-welded joint is lower [44]. The role of pulse parameters affecting the residual stresses of the weld joint has been studied by considering a summarized influence of pulse parameters. The use of a pulsed current MIG welding at proper pulse parameters gives lower residual stresses [45, 46]. X-ray Diffraction (XRD) analysis has been employed to evaluate residual stresses in dissimilar metal welding between the nickel-based superalloy Inconel 59 and austenitic stainless steel AISI 904L. The joints were successfully fabricated using Double-Pulsed Gas Metal Arc Welding (DP-GMAW) with ERNiCrMo-13 filler metal. The results revealed the presence of tensile residual stresses within the weld zone and compressive residual stresses in the surrounding regions [47].

Investigating the influence of residual stresses on fatigue performance has been shown to be essential for understanding the long-term reliability of welded structures [48]. The pulsing effect in welding alters the solidification time, which directly impacts the development and distribution of residual stresses [49]. Residual stress measurements on DMR-249A steel weld joints, conducted using both XRD and ultrasonic testing methods, indicated significant variations in stress magnitude across the weldments, with the highest concentrations observed near the fusion boundary [50]. Moreover, the application of combined treatments, such as a pulsed magnetic field and pulse current during pulse MIG welding, has been found to effectively reduce residual stress levels in steel samples [51]. Additionally, employing a low heat input during welding promotes a higher cooling rate, leading to improved tensile strength and lower tensile residual stress [52].

From the literature reviewed, it is evident that pulse MIG welding process parameters—such as welding current, voltage, welding speed, and preheat temperature—strongly influence the magnitude and distribution of residual stresses. Higher heat input generally increases tensile stresses and distortion, whereas optimized pulse parameters can minimize these effects through improved thermal control. Finite element modeling (FEM) has proven effective for predicting residual stress fields when validated with experimental methods like X-ray diffraction and hole drilling. Post-weld treatments such as thermal stress relieving and vibration-assisted processing further enhance dimensional stability. However, the specific influence of pulse MIG parameters on residual stress evolution and microstructural behavior remains insufficiently explored, necessitating further detailed experimental and analytical studies.

CONCLUSIONS

Residual stresses play a crucial role in determining the structural integrity, performance, and service life of welded steel components. From the reviewed literature, following conclusions are made:

- Pulse Metal Inert Gas (MIG) welding offers significant advantages over conventional MIG processes in controlling heat input and minimizing residual stress levels.
- The magnitude and distribution of residual stresses in pulse MIG-welded steel are strongly influenced by welding parameters such as pulse current, pulse frequency, duty cycle, wire feed rate, and welding speed.
- Various researchers recommended heat treatment, mechanical stress relief and controlled cooling to control residual stresses in weld specimen.
- Overall, the review establishes that Pulse MIG welding is a reliable and efficient process for producing high-quality steel welds with reduced residual stress levels. However, further research is still needed to develop comprehensive predictive models, explore hybrid welding processes, and optimize parameter combinations for different steel grades and thicknesses under industrial conditions.

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