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Checking The Residual Stresses In Carbon Steel Pipe Girth Welds Before And After Heat Treatment

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Abstract
This study investigates the effectiveness of post-weld heat treatment (PWHT) in relieving residual stresses (RS) in ASTM A53 Grade B carbon steel pipe girth welds. Two sample pipe spools were fabricated using metal gas welding techniques. Residual stresses were measured in both the as-welded condition and after PWHT using the Xstress 3000 G3 Portable X-ray Diffractometer, which employs non-destructive X-ray diffraction and the d–sin²ψ method for high-precision stress analysis. PWHT was applied to assess its influence on residual stress distribution across various depths and locations within the weld zone. The measured stress profiles were compared with residual stress guidance provided in BS 7910 and the UK nuclear industry's R6 procedure. Results indicate that PWHT significantly reduces the magnitude of residual stresses, thereby enhancing the structural integrity and expected service life of the welded joints.

Keywords
Post- weld heat treatment (PWHT), Residual stress, ASTM A53 Grade B, Girth welds, X-ray diffraction, d–sin²ψ method, BS 7910, R6 procedure, Weld life extension

INTRODUCTION

Residual stresses (RS) are internal stresses retained in materials following manufacturing processes such as welding, even in the absence of external loads. In welded components, these stresses are primarily induced by rapid thermal expansion and contraction, phase transformations, and plastic deformation during the welding cycle [1], [2]. Tensile residual stresses, particularly in and around the weld zone, are of critical concern as they can significantly reduce fatigue life, increase susceptibility to crack initiation and propagation, and compromise the overall structural integrity of components such as pressure vessels and pipelines [3], [4].

To mitigate these adverse effects, post-weld heat treatment (PWHT) is commonly employed. PWHT is a thermal process designed to relieve residual stresses, improve metallurgical stability, and enhance the mechanical performance and service life of welded structures [5]. The effectiveness of PWHT depends on several factors including the material type, heat treatment parameters, weld geometry, and the method used to assess residual stress [6].

While advanced techniques such as neutron diffraction and synchrotron X-ray diffraction offer high-resolution, deep-penetration stress mapping [7], their high cost and limited availability restrict their widespread use in routine industrial applications. In contrast, X-ray diffraction (XRD) using portable systems offers a more accessible, non-destructive means of surface residual stress evaluation [8]. This method, particularly using the d–sin²ψ approach, is well-suited for industrial steels and has gained acceptance for quality assurance in welding processes [9].

This study investigates the effect of PWHT on residual stress relaxation in ASTM A53 Grade B carbon steel pipe girth welds a commonly used material in medium-pressure piping systems. Two sample pipe spools were fabricated using standard metal gas welding techniques. Residual stress measurements were carried out using a portable Xstress 3000 G3 X-ray diffractometer before and after furnace-based PWHT. The resulting stress profiles were analyzed across selected surface locations and compared with established structural integrity assessment standards such as BS 7910 and the R6 procedure [10]. The objective is to evaluate the efficacy of PWHT in stress reduction and its potential to enhance the structural performance and reliability of welded carbon steel pipelines.

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EXPERIMENTAL MATERIAL AND PIPE DETAILS

Material Selection

ASTM A53 Grade B carbon steel was chosen for this study due to its extensive application in pipeline systems used for transporting fluids, gases, and chemicals. It is widely utilized in the oil, gas, and petrochemical sectors because of its favorable mechanical properties, including good strength, ductility, and excellent weldability. The material's common usage in pressure piping systems makes it a suitable candidate for investigating the effects of welding and post-weld heat treatment on residual stress behavior. Analyzing residual stresses in ASTM A53 Grade B pipe girth welds offers practical relevance, as these stresses directly influence the long-term performance, safety, and reliability of pipeline infrastructure in service. The material selection ensures that the findings of this research can be directly applied to industrial operations and contribute to improved welding practices in critical pipeline applications. The dimension of sample and chemical composition of material shown in table 1 and 2 respectively.

Table 1. Sample dimension

	External Diameter (mm)	Internal Diameter (mm)	Length (mm)	Thickness (mm)
Pipe dimension	63.5	59.4	140	4

Table 2. Chemical compositions of the material

Material	C (%) Carbon	Si(%) Silicon	Mn(%) Manganese	P (%) Phosphorous	S(%) Sulphur	Nb(%) Niobium
Parent Metal	0.30	0.045	1.30	0.05	0.045	0.06
Filler Metal	0.06	0.45	0.90	0.025	0.035	0.15

Welding Process

The Metal Inert Gas (MIG) welding technique was employed for this study, following standard manufacturing practices. Welding was performed using an ER70S-3 wire electrode, selected for its compatibility with carbon steel and stable arc characteristics. Prior to welding, the pipe ends were prepared by machining a V-groove at the joint interface to ensure proper penetration and high weld quality.

Two pipe sections were aligned and securely tack welded at four equally spaced points around the circumference to maintain alignment during welding. The welding sequence began with the root pass, followed by successive filler passes. Each pass was deposited after allowing adequate cooling under ambient conditions to maintain structural integrity. Inter-pass temperature was closely monitored throughout the process and kept within the recommended range to avoid overheating, reduce residual stresses, and prevent metallurgical inconsistencies. Temperature data were recorded at each stage to confirm compliance with predefined welding parameters.

This controlled welding procedure was designed to minimize distortion, avoid weld defects, and achieve a consistent, high-quality weld joint with favorable mechanical properties suitable for further residual stress analysis. The properties of material and filler metal as shown in table 3.

Table 3. Mechanical properties of the material

Material	Tensile strength (Mpa)	Yield strength (Mpa)	Yieldratio	Elongation(%)
Parent Metal	415	240	18	40

Filler Metal	520	425	13	23

X-RAY DIFFRACTION MESUREMENT

Residual stress measurements in the girth-welded carbon steel pipe samples were conducted using the Xstress 3000 G3 Portable X-ray Diffractometer manufactured by Stresstech. This non-destructive instrument utilizes the X-ray diffraction (XRD) technique to determine surface residual stresses with high accuracy. The measurements were based on the widely accepted d–$\sin^2\psi$ method, which calculates strain by analysing the diffraction peak shifts at varying tilt angles (ψ), allowing for precise determination of stress components.

The device's modular design includes interchangeable X-ray tubes, such as Cr-Kα radiation sources, and an adjustable 2θ angle configuration, enabling flexibility for different material types and depth profiling within the penetration limits of XRD. The portable nature of the system allows for convenient deployment in both laboratory and field environments, reducing setup time and enhancing operational efficiency.

Data acquisition and analysis were performed using the integrated XTronic software, which automates the measurement process and ensures consistent and accurate interpretation of stress distribution. This setup provided reliable surface residual stress data across selected points on the weld and adjacent base material, forming a critical part of the assessment of post-weld heat treatment effectiveness.

POST WELD HEAT TREATMENT (PWHT)

To relieve the residual stresses induced by the welding process, post weld heat treatment (PWHT) was carried out on the welded ASTM A53 Grade B pipe samples. The treatment was performed in a muffle furnace using a controlled heating and cooling cycle. The specimens were gradually heated to 600 °C and held at this temperature for 1 hour, allowing sufficient time for stress relaxation through thermal diffusion and microstructural recovery.

The heating rate was maintained at approximately 100 °C per hour, and after soaking, the samples were furnace-cooled to room temperature at a controlled rate to avoid thermal shock or distortion. This PWHT cycle was selected based on standard practices for carbon steel pipes and ensured uniform heat distribution throughout the weld, heat-affected zone (HAZ), and base metal. The objective was to reduce tensile residual stresses and improve the metallurgical stability and service performance of the welded joint.

X-RAY DIFFRACTION (XRD) RESULTS

The residual stress measurements were conducted using the Xstress 3000 G3 Portable X-ray Diffractometer, employing the non-destructive X-ray diffraction (XRD) technique based on the d-$\sin^2\psi$ method. The measurements were taken on the same ASTM A53 Grade B pipe sample before and after Post Weld Heat Treatment (PWHT) to evaluate the effectiveness of stress relief. Measurements were carried out at key locations on the pipe surface the weld centre (WC), heat-affected zone (HAZ), and base metal (BM). The test direction was axial, consistent across all readings. The result shown in table 4.

Table 4. XRD result

***Locatio*n**	**Direction**	**Residual Stress Before PWHT (Mpa)**	**Residual Stress After PWHT (Mpa)**
Weld Center (WC)	Axial	+296.7	+118.4
HAZ – Left	Axial	+245.3	+102.9
HAZ – Right	Axial	+231.6	+95.7

Base Metal (BM)	Axial	+98.2	+37.6

Comparison and Discussion

The XRD results confirm that Post Weld Heat Treatment (PWHT) significantly reduces tensile residual stresses across the weld center, heat-affected zones, and base metal. This stress relief improves the structural integrity of the welded joint by minimizing risks such as fatigue and stress corrosion cracking. The axial direction was selected for its relevance in pipeline loading. The absence of compressive stress is likely due to the surface-level nature of XRD measurements. Overall, PWHT proves to be an effective method for enhancing weld quality and performance.

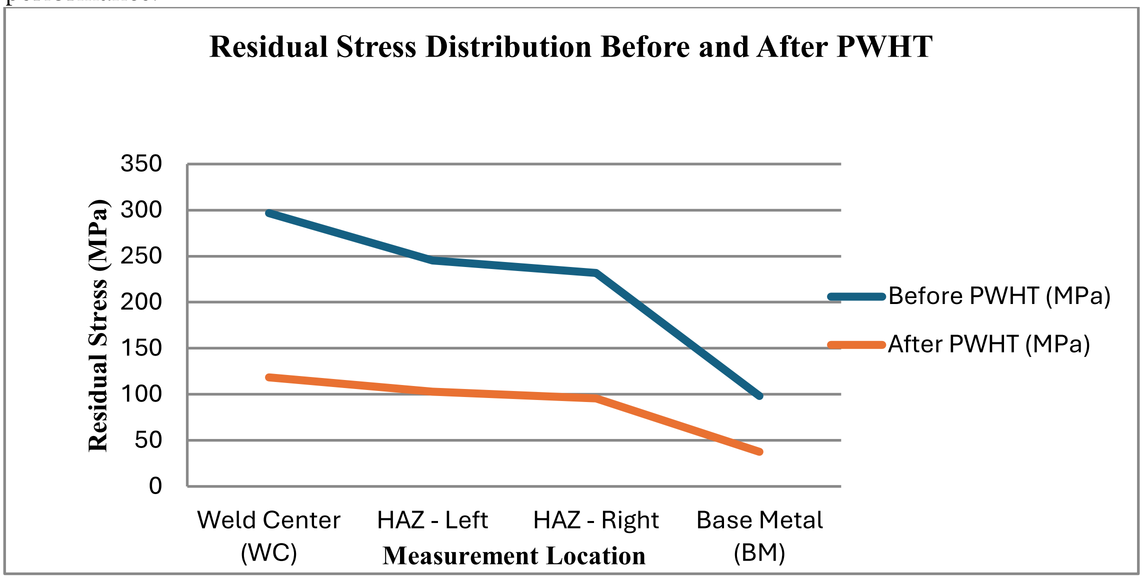

Figure – 01 The residual stress distribution before and after PWHT

Here is the simple line graph showing the residual stress distribution before and after PWHT. The graph clearly demonstrates a significant reduction in axial tensile residual stress at all measured locations—Weld Center, HAZ (Left & Right), and Base Metal indicating the effectiveness of PWHT in stress relief.

CONCLUSION

This study confirms the effectiveness of Post-Weld Heat Treatment (PWHT) in significantly reducing tensile residual stresses in ASTM A53 Grade B carbon steel pipe girth welds. Using X-ray diffraction via the d–sin²ψ method, substantial stress relief was observed at all critical zones weld centre, heat-affected zones, and base metal—when compared to the as-welded condition. The measured reduction aligns with safety margins suggested in BS 7910 and the R6 procedure, validating the use of PWHT for improving weld quality and structural reliability. Overall, PWHT not only enhances the fatigue resistance and service life of welded joints but also ensures compliance with industrial residual stress control standards.

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