

Effect of Cryogenic Treatment on the Microstructure and Mechanical Properties of ARC- Welded D2 Tool-Steel Joints Fabricated from Recycled Leaf Spring Scrap

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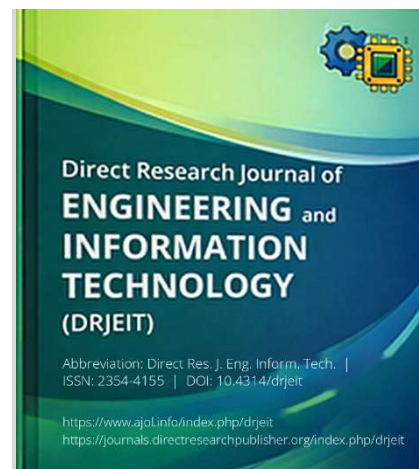
Research Article

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ABSTRACT

Cryogenic quenching media have been identified as one of the quenchants suitable for the enhancement of the properties of steel during heat treatment, yet the scope of its application by manufacturing industries for the fabrication of structural components is limited. In this study, the effect of cryogenic treatment using liquid nitrogen on the microstructure, tensile strength, hardness, impact strength, fatigue strength, toughness of an Arc-welded D2 tool steel joints fabricated from a recycled leaf spring material were investigated. The choice of the leaf spring steel material was as a result of continuous failure of a leaf spring used on a water tanker welded and quenched in air under normal room temperature. Samples for each property test were cut from the recycled leaf spring material obtained from the water tanker and the joints were fabricated using Arc-welding. Chemical composition of the recycled leaf spring steel material was determined using optical emission spectrometry (OES) technique. Scanning electron microscopy (SEM) was used to determine the microstructure of the recycled leaf spring material before and after the cryogenic treatment. Sixteen samples (two samples for tensile strength, hardness, impact strength and fatigue strength respectively) were produced for the mechanical properties' tests. Eight of the samples were quenched in air under room temperature while the other eight samples were further subject to cryogenic treatment by quenching in liquid nitrogen (at -196°C) in a canister for 45 minutes. Results of the chemical analysis showed that the leaf spring material is a high carbon, high chromium cold worked tool steel material, a ledeburite. The microstructure of the test sample before the cryogenic treatment was highly defined by a massive volume fraction of hard carbides, an austenite. After the cryogenic treatment, there was evidence of elimination of this retained austenite into hard martensite precipitates ultra - fine secondary carbides and relieved micro - stresses across the weld zone. The tensile strength, hardness, impact strength, fatigue strength, modulus of elasticity and percentage elongation of the control samples were evaluated as 649.4MPa, 85.0HRB, 85J, 70MPa, 2020MPa and 32.2% respectively. For joints further subject to cryogenic treatment the tensile strength, hardness, impact strength, fatigue strength, modulus of elasticity and percentage of elongation were obtained as 1063.9MPa, 108.7.5 HRB, 100J, 95.5MPa, 2960.55MPa and 36.85%. From the results it is clear that cryogenic treatment improved the properties of the leaf spring material. Thus, machine components made from high carbon steel can be subject to cryogenic treatment in order to enhance their properties.



Keywords: High carbon steel, Welded Joints, Cooling media, Cryogenic treatment, Microstructure, Mechanical properties Efficiency, Sustainability

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INTRODUCTION

In most manufacturing industries, welding is one of the most important fabrications finishing process. The discovery and the application of welding as a fabrication method for structural parts is as old as the discovery iron by man. It is a joining technique which involves the fusion of the metal-based parts to produce a permanent joint. Different welding methods have been developed and used for different applications in industries for the fabrication of ships, cars, aircrafts, machine tools, doors, windows, just to mention but a few. Some of the commonly known welding methods include Gas welding (which uses oxygen and acetylene gases), Shield Metal Arc Welding (SMAW), Resistance welding, Tungsten inert gas (TIG) (Khurmi and Gupta, 2015)

Though different types of welding methods exist, the one that is in common use in most developing countries like Nigeria for steel parts fabrication is the Arc and oxy-acetylene gas welding. Arc welding is in common use for the fabrication of structural parts such as metal doors, windows, roofs, vehicle bodies. Due to the numerous areas of the applications of metals as structural materials, different joint designs have been developed and used, some of which are: The single and double fillet lap joints, groove joints and butt joints (Mohammad *et al*, 2023). Preparing a perfect welded joint to attain high durability of the structural part in service remain a big challenge because the welding process is influenced by many parameters such as the types of materials being welded, joint design, environment, heat concentration, welding method, cooling medium, just to mention but a few. These factors if not properly controlled can lead to the formation of coarse microstructure of the welded joint and this can cause premature failure.

Review of relevant literature has reported that the rates of cooling of welded joints can greatly influence the strength of joints. Therefore, many cooling media such as air, water and oil of different classes have been in use for the preparation of welded joints but the commonly used cooling medium for welding has been water. There is need to study the effect of other cooling media on mechanical properties such as hardness, impact strength, tensile strength, and fatigue strength of the arc welded joints. (Ahmed *et al*, 2024). Today's welders are expected to understand the type of forces being applied to the weldment and to determine the best joint design to prevent these forces from causing a structural failure. An improper configuration of the of weld joint can cause weld and material defects, such as cracking or breakage and skilled welders must know how to adjust variables and the use of correct cooling medium to avoid these defects. Ahmed *et al*, 2024 noted that quenching media has a great effect on the mechanical properties of a welded joint by mitigating the effects of heat induced distortion of weldments. In this study, the effect of cryogenic cooling medium on the microstructure and mechanical properties of an arc welded D2 steel (high carbon steel) was investigated.

The liquid nitrogen (Cryogenic fluid) used to produce deep cooling of the arc welded joint was chosen as a result of continuous failure of a leaf spring used on a heavy - duty water tanker.

Materials and Equipment

The materials include: D2 Tool steel obtained from leaf spring of the water tanker, gauge 10 electrodes (which are heavily alloyed with chromium, molybdenum and vanadium which form carbides in the weld pool allowing the weldment area to match the original tool steel), liquid nitrogen (cryogenic fluid). The equipment used include: Arc welding machine, Elec-metric universal Tensile testing machine, Rockwell- Hardness testing machine. Fatigue testing machine, Impact testing machine, Optical emission spectrometry (OES) equipment, Scanning Electron microscope (SEM) equipment, cutting and grinding disc

Method

Determination of chemical composition and microstructure

Samples for chemical composition and microstructural examination as shown in (Figure 1) were cut from the recycled spring material using cutting disc. Chemical composition was determined using optical electron spectroscopy (OES) as performed by Kritika *et al*, (2015). The samples were grinded by rubbing against series of silicon carbide papers with increasingly finer grit to expose the surface for observation. Nital etchant (a mixture of nitric acid and alcohol) was used for etching the samples in order to reveal hidden microstructural features. A rotating disc with a soft cloth and diamond or alumina slurry was used to polish the samples in order to achieve a scratch free mirror – like surface. For determination of chemical composition, a high voltage electrical spark was applied to the metal sample to vaporize atoms and measuring the specific wavelengths of light they emit. The data obtained was processed with a computer to calculate the precise elemental concentration based on calibration standards. The microstructural examination was carried out by using a Scanning Electron Microscopy (SEM) equipment as performed by (Mangai *et al*, 2024). This was done by firing a focused beam of high energy electrons at the sample's surface and detecting the resulting signals to build a magnified, high – resolution image.

Preparation of the V-Butt welded joints

Samples were cut from the leaf spring material and prepared according to the V-butt joint design shown in (Figure 2). The edges of the cut pieces were shaped to ensure good penetration, fusion, and smoother weld bead. Shield metal arc welding (SMAW) was used to produce the



Figure 1: Samples for microstructural examination

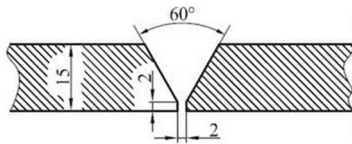


Figure 2: (a) V- butt joint design



(b) Cut V-butt joint



(c) Welded V-butt joint

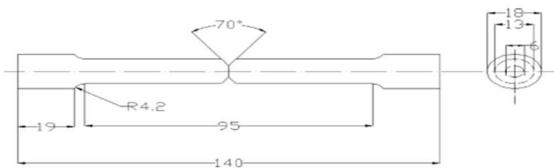


Figure 3: Tensile strength test specimen

joints for the different property test using welding current of 130A, voltage of 25v, and speed of 4. 25 mm/s. After welding, the specimens were allowed to cool in air at room temperature and subsequently quenched in liquid nitrogen for 45 minutes in a cannister.

Tensile Strength Test

Specimens were prepared according to the standard specifications for tensile strength test as shown in (Figure 3) by machining. The tensile tests were carried out on a computer-controlled versatile machine (SANS testing Machine Co., LTD, Shenzhen, China, Model: WAW-

1000) which has a capacity of 100 tons with velocity of 13.5 mm/minute. First, one specimen was fixed on the machine and a uniaxial tensile load was applied when the machine put on until the specimen failed or broke at the weld joint along the gauge length. Ultimate tensile strength, modulus of elasticity, and Elongation were recorded in a Microsoft Excel Datasheet of a computer attached to machine. This test procedure was repeated for all the specimens and the results recorded.

Hardness Test

The hardness test of the produced joints was carried out

using the Rockwell Hardness (HRB) testing method according to ASTM E3. The test specimen was placed on an anvil of the hardness tester (Wolpert Amsler type v-tester, Model: D-6100, Germany A square). In this study. The base pyramidal diamond indenter was impressed on the surface using a load of 1Kg force over a period of 15s. The angle between the 2 opposite faces of the pyramid was 136°. The 2 diagonals of the trace left by the indenter was measured via an optical microscope. This procedure was repeated across the profile of the weldments (200mm) with a step size of 1mm from the weld center. Then the average of the hardness measured at 3 points along weldment was determined. The procedure was repeated for all the specimens (Figure 4).



Figure 4: Hardness test specimen

Impact Test

The Impact strength of on the produced specimens was carried out in accordance with standard test of ASTM E3 Charpy V-notched specimens. The specimen was fixed on an anvil of the machine (a calibrated impact testing machine, model is MAT21/ IT3U made by Brooks Inspection Equipment Ltd, Colchester, England), ensuring it was securely held in place, then a pendulum weight that has a potential energy of 300 J (i.e., impact load) was allowed to strike the specimen at the back of the V-notch. The energy absorbed by the specimen was read after the impact from a scale with a resolution of 2 J (which is an indicator of its toughness is red). This procedure was repeated to obtained the impact strengths of the specimens (Figure 5).



Figure 5: Impact strength test specimens

Fatigue Strength Test

The fatigue strength of the produced specimens of dimensions (Length = 80mm, end to end thickness= 10mm and gauge thickness = 5mm) were carried out using a

fatigue test machine. The specimen was fixed on the machine, ensuring it was securely held in place. A cyclic load to the specimen was applied, simulating the expected loading conditions in service. The loading conditions were axial and torsional and the stress levels for the test were determined, which can be constant amplitude or variable amplitude. The cycling frequency was set, which affected the test duration and results and the test duration was determined, which was specified in number of cycles or until failure occurred (Figure 6).



Figure 6: Fatigue test specimen

RESULTS AND DISCUSSION

Chemical composition of the recycled leaf spring material

The chemical composition of the recycled leaf Spring material is as presented in (Table 1). From the chemical composition of the recycled leaf spring material the spring material has high concentration of carbon (1.45%), chromium (11.8%), Manganese (0.808%), Silicon (0.38%), Molybdenum (0.011%) and Iron (84.0%). Based on the composition, the leaf spring material can be classified as a high carbon high chromium (HCHCr) cold - worked tool steel specifically aligning very closely with the AISI D2/DIN.1.2379 family of steels. The defining trait of this alloy is its combination of 1.45% Carbon and 11.8% Chromium which places it on the edge of being considered as a semi stainless tool steel leaving it vulnerable to corrosion under harsh conditions but highly protected compared to standard carbon steel (Hediye, 2025).

Table 1: Chemical composition of the scrap of the leaf spring

C (%)	Si (%)	S (%)	P (%)	Mn (%)	Cr (%)	Ni (%)	Cu (%)	Mo (%)	Ti (%)	Sn (%)	Fe (%)
1.45	0.38	0.011	0.05	0.808	11.8	0.07	0.1	0.011	0.0	0.0	84.0

Microstructure of fabricated joints

The microstructure of the air-cooled joint shown in (Plate I) shows that there is carbide dissolution and segregation with retained Austenite formation at the welded joint. The primary carbide (N_4C_5) did not dissolve homogeneously due to local segregation of Chromium which occurs at the dendrite boundary during solidification. Fadzillah *et al.* (2018) in a paper on the microstructural evolution of AISI D2 tool steel welded joint during direct partial remelting explained that the joint typically features a globular semi –

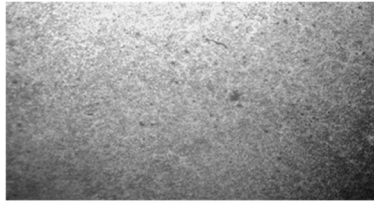


Plate I. Microstructure of air cooled joint.



Plate II. Microstructure of cryogenic treated joint.

solid transition zone or a brittle dendritic fusion zone with coarse primary carbides depending on whether specialized techniques like direct partial remelting or conventional fusion welding arc is used.

Also, when the steel welded joint undergoes cryogenic treatment by subjecting to quenching at -196°C (temperature of liquid nitrogen) it drastically modifies the unstable microstructural regions left behind by high heat input of welding. The microstructure undergoes critical transformation which significantly alters its mechanical behavior because D2 steel has a high carbon alloy content such as chromium. Welding creates a high unstable highly stressed microstructural zone as shown in (Plates I & II). Subjecting the welded joint to cryogenic treatment process alters the microstructure by complete transformation of retained austenite to martensite, precipitation and refinement of secondary carbides and relief of weld - induced residual stresses. (Hediye, 2025). These in turn improve the mechanical properties of the welded joint

Mechanical Properties of the Joints

The mechanical properties of the fabricated joints using air and liquid nitrogen as quenching media are as presented in (Table 2). From (Table 2) it is shown that the tensile strength of the welded butt joint quenched in liquid nitrogen is higher than that of the control specimen by 67.16%.

Table 2: Mechanical Properties

Mechanical property	Quenching Medium	
	Air cooled	Liquid nitrogen (-196°C)
Tensile strength (N/mm^2)	649.4	1085.6
Hardness (HRB)	85.0	108.7
Modulus of elasticity (N/mm^2)	2020.0	2960.5
Elongation (%)	32.2	36.8
Impact strength	85.0	100.0
Fatigue strength (N/mm^2)	70.0	95.5

Also, hardness, modulus of elasticity of the welded, percentage of elongation, impact and fatigue of the welded joint quenched in liquid nitrogen showed significant improvement over the control specimen. From this results it can be concluded that the microstructure of the samples quenched in liquid nitrogen are finer than that of the control specimen and this leads to higher properties. This confirms the theory behind the used of liquid nitrogen as a quenching media which enhanced finer microstructure due

to slow cooling of the welded joint (Xiuying *et al*, 2024). Also, the mechanical properties (Tensile strength, Hardness, Impact strength, Fatigue strength) of the butt welded joint for cooled in air and liquid nitrogen are presented in (Figures 7-12).

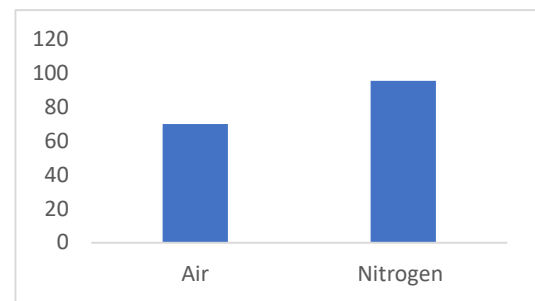


Figure 7: Tensile strength of butt joint cooled in air versus liquid nitrogen

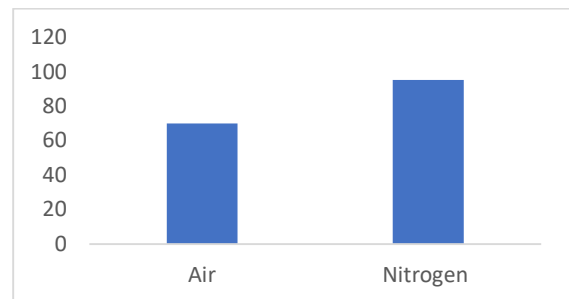


Figure 8: Hardness of butt joint cooled in air versus liquid nitrogen.

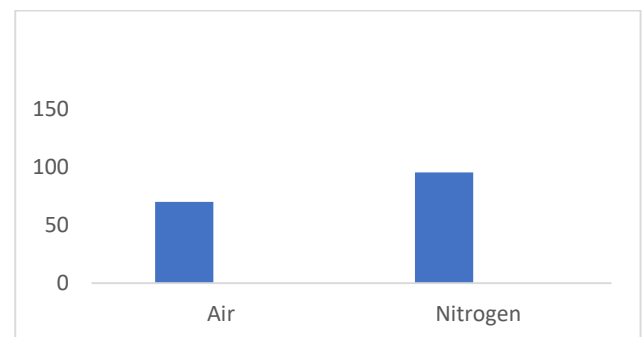


Figure 9: Modulus of Elasticity of butt joint cooled in air versus liquid nitrogen.

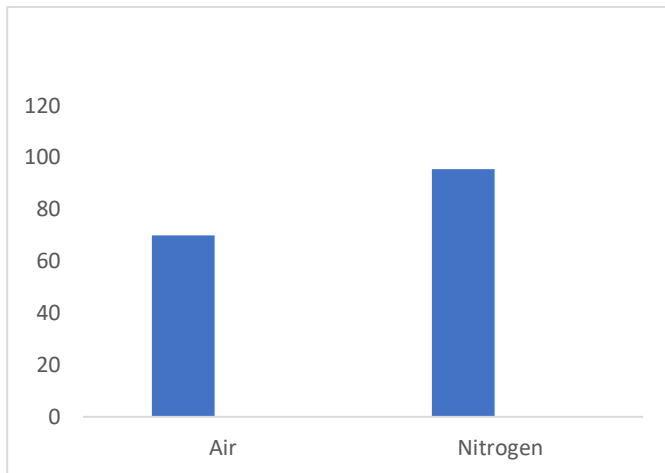


Figure 9: Modulus of Elasticity of butt joint cooled in air versus liquid nitrogen.

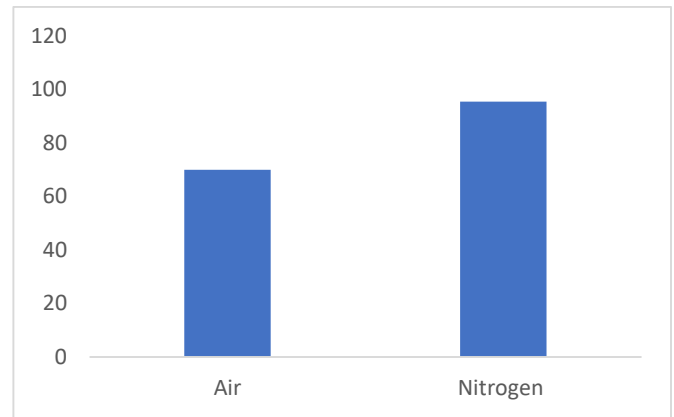


Figure 12: Fatigue strength of butt joint cooled in air versus liquid nitrogen

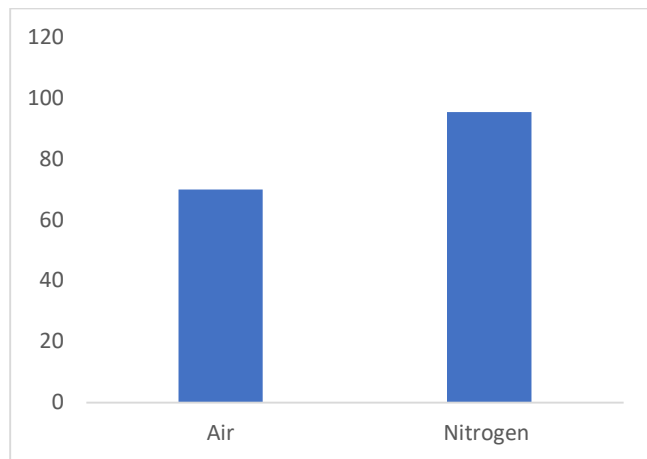


Figure 10: Percentage elongation of strength of butt joint cooled in air versus liquid nitrogen.

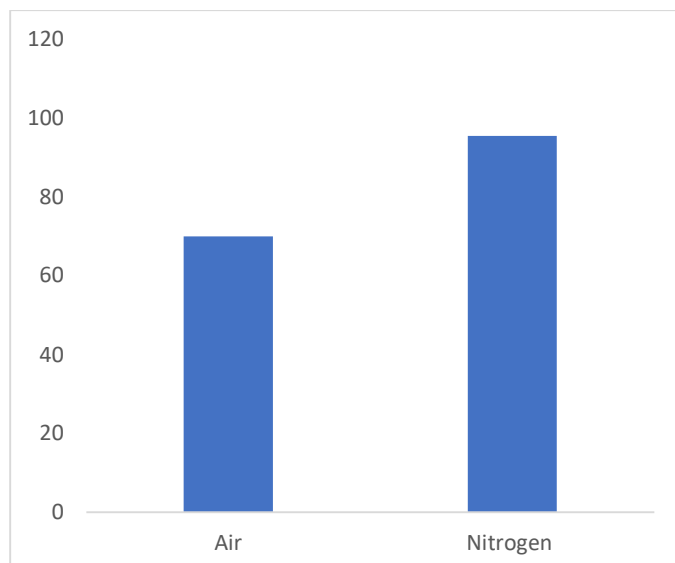


Figure 11: Impact strength of butt joint cooled in air versus liquid nitrogen.

Conclusion

Based on the findings of this study, it was concluded that the chemical composition analysis of the leaf spring revealed a relatively high carbon content of 1.45%, indicating that the leaf spring material is a high-carbon steel. Other major elements detected in the leaf spring were chromium (11.80%), silicon (0.38%), magnesium (0.011%), and iron (84.92%). The relatively high chromium and carbon contents may promote the formation of chromium-rich carbides during welding and subsequent cooling. These phases can influence the microstructure, hardness, strength, and wear resistance of the welded joint, depending on the welding conditions and cooling rate. The mechanical properties of the welded joints showed a clear improvement following liquid nitrogen treatment. The control specimens, which were allowed to cool naturally in air, recorded a tensile strength of 649.4 MPa, hardness of 85.0 HRB, impact strength of 85.0 J, fatigue strength of 70.0 MPa, modulus of elasticity of 2020.0 MPa, and percentage elongation of 32.2%. In comparison, the liquid-nitrogen-treated specimens recorded a tensile strength of 1063.9 MPa, hardness of 108.7 HRB, impact strength of 100.0 J, fatigue strength of 95.5 MPa, modulus of elasticity of 2960.55 MPa, and percentage elongation of 36.85%. The results therefore demonstrate that the liquid nitrogen treatment produced superior mechanical properties compared with the naturally air-cooled welded joints. Furthermore, microstructural examination showed that the welded joint subjected to liquid nitrogen treatment exhibited a more uniform phase distribution than the control specimen. The improved microstructural uniformity was associated with the enhanced mechanical properties observed in the liquid-nitrogen-treated joints. Therefore, the findings demonstrate that liquid nitrogen treatment can significantly influence the microstructure and mechanical performance of welded leaf-spring joints.

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