

Characterization of Mechanical Properties of ASTM A36 Steel After Cryogenic Treatment

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ABSTRACT

The use of ASTM A36 steel through the cold bending process is often faced with material durability due to the occurrence of fine cracks in the process. Fine cracks can increase the risk of corrosion so in the long run it can reduce mechanical strength. The method of repairing steel structures by conventional methods (quenching) has disadvantages such as distortion and cracking in the steel, thereby reducing ductility and other mechanical properties. Deep cryogenic treatment (DCT) emerged as an alternative to overcome the shortcomings of conventional methods in a more effective way so that it can improve the structure of steel without causing distortion and cracking in the steel. This study focused on the analysis of ASTM A36 steels that have been DCT treated, with variations in immersion time (0, 12, 36, 60 hours) followed by characterization of mechanical properties (bending strength, tensile strength, and impact) and physical properties (microstructure). Cryogenic treatment significantly improves the mechanical capabilities of steel through granular refinement and microstructural homogeneity. Mechanical properties indicate that the sample treated for 60 hours shows the smallest grain size with the highest tensile strength (392.4 MPa), and the largest modulus of elasticity (1752.6 MPa). However, the ultimate strain decreased from 19.47% to 36 hours to 18.31% at 60 hours, corresponding to a relative reduction of approximately 5.96%. The best bending strength (892.81 MPa) is achieved after 12 hours. Impact toughness also increased with a longer duration, peaking at 290.08 J for 60 hours. These results emphasize the important role of cryogenic treatment in optimizing ASTM A36 steel for structural applications, where the balance between strength, rigidity, and toughness is critical. However, long soaking durations can lead to diminishing results, such as reduced ductility and bending strength, which require optimization of cryogenic parameters.

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INTRODUCTION

ASTM A36 is a type of steel that is widely used in the construction and automotive fields. The market value of ASTM A36 steel in 2023 was USD 1156.7 million and is projected to rise to USD 1543.4 million by 2030 [1]. ASTM A36 steel has several advantages that make it a common choice in a wide range of construction and manufacturing applications such as maximum tensile strength of 400 – 552 MPa, elongation of 18% material can be processed by welding and manufacturing, affordable cost, wide availability, flexibility in application, can be obtained in a variety of shapes and sizes, good elasticity. The advantages of ASTM A36 steel make this material suitable for a wide range of constructions structure. In addition, ASTM A36 does not require additional heat treatment, thus simplifying the fabrication process and reducing costs. ASTM A36 steel heat treatment can improve the strength and toughness of steel, this method often incurs higher processing costs and complexities [2]–[5]. In the construction industry, the use of ASTM A36 steel through the cold bending process is often faced with problems related to structural integrity and material durability. The cold bending process, although it has efficiency for shape formation, can give rise to residual stress and fine cracking. This residual stress has the potential to degrade the structural stability and strength of the steel, while fine cracks can increase the risk of corrosion. This problem ultimately affects the mechanical properties of the material in the long term, which is a major challenge in ensuring the reliability and lifespan of the construction structure. In response, the construction industry has relied on a series of post-bending treatment methods, such as [6] annealing, normalizing, stress relieving, quenching, and tempering. These methods aim to reduce or eliminate the negative impacts of the cold bending process, but they have disadvantages related to high costs, long processing times, and the potential for distortion or cracking in the material, which reduces ductility and affects other properties of the material. In this context, [7] deep cryogenic treatment (DCT) is emerging as a promising alternative, offering potential solutions to address the shortcomings of conventional methods in a more efficient and effective way [8].

Cryogenic treatment emerged as an effective approach to improve the mechanical properties of ASTM A36, this process involves cooling the material to cryogenic temperatures, usually below -196°C , to convert the retained austenite into martensite and create fine carbide precipitation inside the microstructure. These microstructural changes lead to the refinement of the grain, increasing yield strength and toughness due to the Hall-Petch effect, where smaller grains inhibit dislocation movement and increase resistance to deformation. Cryogenic treatment also reduces internal pressure and improves microstructural homogeneity, collectively improving mechanical performance. However, the need for an appropriate duration to optimize the mechanical properties of ASTM A36 steel. The duration of immersion has a significant effect on increasing density and stabilizing micro strain. During cryogenic treatment there is a retained austenite transformation into martensite, the phenomenon can improve mechanical and electrochemical performance [9]–[11]. Cryogenic treatment significantly increases the martensite content in low-carbon steels, thereby improving surface hardness, wear resistance and toughness [12], [13].

Cryogenic treatment is used to improve the mechanical properties of metals such as hardness, wear resistance, and dimensional stability. The stages of the cryogenic process consist of (1) Gradual cooling, i.e. the material is cooled slowly from room temperature until it reaches the desired cryogenic temperature using liquid nitrogen (about -196°C) or liquid helium (about -269°C); (2) Soaking aims to keep the material at cryogenic temperature for a certain time; (3) Reheating after immersion makes the material temperature slowly return to room temperature so as to prevent cracking or deformation due to sudden temperature changes [14]. The *soaking* stage which is carried out for 12 to 36 hours (depending on material specifications) at a temperature of around -196°C is important in ensuring that the phase transformation and carbide precipitation occur optimally. Meanwhile, the post-cryogenic tempering stage is important to relieve internal stress due to martensitic transformation and facilitate the formation of a more balanced microstructure between hardness and toughness [15].

Cryogenic treatment is known to have a significant influence on the impact properties (toughness) of metal materials, including low-carbon steels such as ASTM A36. This process involves cooling the material to ultra-low temperatures (approx. -196°C), which can improve the homogeneity of the microstructure and reduce the internal residual stress. The cryogenic treatment of ASTM A36

improves the micro strength and stability of the structure but also affects the toughness of the material in a complex way. The increase in impact energy occurred due to the improvement of carbide distribution and the decrease in residual stress, other results showed a decrease in impact properties due to increased hardness and brittleness tendency after the transformation of austenite into martensite. Therefore, the cryogenic effect on impact properties is highly dependent on the process parameters and initial microstructural conditions [16].

METHOD

The research employed an experimental method with descriptive analysis. The study was conducted on ASTM A36 steel, a low-carbon structural steel primarily composed of iron (Fe), with a carbon content of approximately 0.25–0.29%, manganese (Mn) of 1.30%, silicon (Si) of 0.28%, copper (Cu) of 0.20%, phosphorus (P) of 0.040%, and sulfur (S) of 0.05%, based on reference composition data. These chemical elements may influence the mechanical behavior and microstructural response of the material to cryogenic treatment. The steel was subjected to cryogenic treatment for durations of 0, 12, 36, and 60 hours, followed by an evaluation of its mechanical properties (tensile strength, bending strength, and impact energy absorption) and microstructural characteristics. The research steps that will be carried out are to prepare the material to be used, namely ASTM A36 steel. The next stage is to carry out the cryogenic process by soaking it with nitrogen in a tube that has been maintained at a temperature of -183°C, at the soaking stage the soaking process is carried out with a specified duration of 0, 12, 36 and 60 hours. After soaking, the temperature is normalized at room temperature of 21 °C. The next step is to test the mechanical properties, namely ultimate tensile strength (MPa), bending strength (MPa) and absorb energy impact (J), and physical properties (microstructure).

The mechanical properties of ASTM A36 steel were evaluated through tensile, bending, and impact tests conducted at room temperature. Tensile testing was performed using a JTM Computer Servo Universal Testing Machine (UTM) in accordance with ASTM E8, employing dog-bone-shaped specimens to determine tensile strength and elongation. Bending tests were conducted using the same UTM following ASTM E290, while impact testing was performed using a Gotech Charpy Impact Testing Machine in accordance with ASTM E23, employing standard notched specimens to evaluate impact energy absorption. The experimental data were analyzed using a quantitative descriptive approach by presenting numerical and visual results to evaluate the effects of cryogenic soaking duration on mechanical properties (UTS, bending, and impact energy absorption). The results were further compared with findings from previous studies to support the interpretation of the experimental outcomes and provide a basis for future research.

RESULTS AND DISCUSSION

The mechanical properties of ultimate tensile strength, bending strength, and absorb energy impact are best in nitrogen immersion for 60 hours (392.40 MPa), 12 hours (891.78 MPa), and 60 hours (290.08 J). Table 1 shows that there are conditions where the results of ultimate tensile strength and absorb energy impact show the same response, where the lowest value is at 12 hours immersion and the highest value is at 60 hours. Meanwhile, the bending strength value shows a response that is inversely proportional to the ultimate tensile strength and absorb energy impact values.

Table 1. Duration of critical treatment (hours) on the results of tensile test, bending test and impact test

Hour	Ultimate Tensile Strength (MPa)	Bending Strength (MPa)	Absorb Energy Impact (J)
0	381.3	856.87	286.96
12	379.9	891.78	279.95
36	384.1	884.60	288.20
60	392.4	627.72	290.08

Ultimate tensile strength and absorb energy impact measure the toughness of a material and tend to follow the same pattern as they are influenced by the microstructure of the material. In contrast to bending strength, which is more influenced by the stress distribution factor in the cross-section, and the elasticity-plasticity properties of the material so that it shows the opposite trend. The results of the ultimate tensile strength and absorb energy impact showed that 12-hour immersion in the cryogenic process was less good than 0, 36, and 60-hour immersion, this occurred because the bond between the grains was not very strong and the residual stress distribution was uneven. At 60 hours immersion, the residual voltage can be evenly distributed, and the microstructure transformation becomes smoother so that the UTS value increases and the energy impact absorb also increases [17].

Bending strength depends not only on tensile strength, but also on stiffness (modulus of elasticity), stress distribution, and plasticity behavior of the material. A 12-hour immersion in the cryogenic process showed UTS and low impact indicating a relatively rigid material with a more limited plastic strain resulting in a high bending strength value. At 60 hours of immersion, the increase in UTS and impact indicates that the material is more ductile, so that during the bending test more energy is absorbed through plastic deformation, but the bending strength decreases. So, it can be concluded that the bending strength is more influenced by the stiffness and deformation distribution, so that the trend can be inversely proportional to UTS and impact.

The tensile test results showed that soaking time of 60 hours was the best immersion with values of 392.4 MPa (ultimate tensile strength) and 1752.6 MPa (modulus elasticity). Meanwhile, the tensile test results without cryogenic treatment were 381.3 MPa (ultimate tensile strength) and 1547.8 MPa (modulus elasticity). The increase in tensile strength at 60 hours immersion is due to granule refinement and increased in density, thereby increasing resistance to deformation. These results support previous findings that cryogenic treatments increase tensile strength at the expense of ductility, particularly with prolonged immersion treatments [18], [19].

The decrease in bending strength occurred at 60 h (T60) with a value of 627.72 MPa. This was due to excessive carbide sharpening and residual stress accumulation, which weakened the material's ability to withstand bending loads. This improvement reflects the refinement of the initial microstructure and the relaxation of tension, which increases the bending resistance. Prolonged exposure (60 hours) results in a significant reduction in bending strength of up to 627.72 MPa, caused by carbide sharpening and residual stress accumulation. Over-treatment of cryogenic treatment can also lead to brittleness of microstructures, which reduces the material's ability to withstand bending loads [20]–[22].

Trends based on Table 4 show that prolonged treatment improves toughness by refining the granule structure and improving the uniformity of the microstructure, which distributes the impact load more effectively. Energy absorption initially decreased, from 286.96 J to 279.95 J at

Table 2. Duration of cryogenic treatment on tensile test results

Hour	Ultimate Tensile Strength (MPa)	Ultimate Strain (%)	Modulus Elasticity (MPa)
0	381.3	18.18	1547.8
12	379.9	18.52	1573.0
36	384.1	19.47	1616.9
60	392.4	18.31	1752.6

Table 3. Duration of cryogenic treatment on specimens measuring 225.3 mm² upon the results of the bending test

Hour	Area (mm ²)	Maximum Force (N)	Bending strength (MPa)	Break Displacement (mm)
0	225.30	6894.76	856.87	56.80
12	225.30	7175.67	891.78	51.08
36	225.30	7117.84	884.60	50.13
60	225.60	7080.66	627.72	50.52

12 h immersion, this was due to incomplete structural homogenization. Energy absorption increased with prolonged treatment, reaching 290.08 J at 60 hours. This improvement reflects a finer grain structure and improves the uniformity of the microstructure, which distributes the impact stress more effectively and improves toughness. The observed changes are in line with the Hall-Petch effect and research showing that fine-grained microstructures improve the ability to absorb and eliminate impact energy [23]–[25].

The results of the microstructure showed that there was an influence of cryogenic treatment on the microstructure, from the average result of the grain size, the longer the cryogenic treatment the grain size also decreased. The results of the microstructure are shown in Figure 2, from a sample of ASTM A36 steel that underwent cryogenic treatment at varying durations (0, 12, 36, and 60 hours) showing grain refinement and homogeneity. Untreated samples showed coarse-grained microstructures with relatively large grain sizes and irregular distribution. After 12 hours of cryogenic treatment, the grain size decreased, although some heterogeneity remained. Significant improvements were observed at 36 hours and a more uniform distribution. The most delicate and homogeneous structure is achieved at 60 hours.

Table 4. Duration of cryogenic treatment on specimens

Hour	End Angle (degree)	Absorb Energy Impact (J)	Specific Impact Energy (MJ/m ²)	Maximum Force (N)	Melt Stress (MPa)
0	-11.2	286.96	2.87	5615.60	56.16
12	-18.35	279.95	2.80	4712.39	47.12
36	-9.4	288.20	2.88	6401.00	64.01
60	-5.67	290.08	2.90	6685.70	66.86

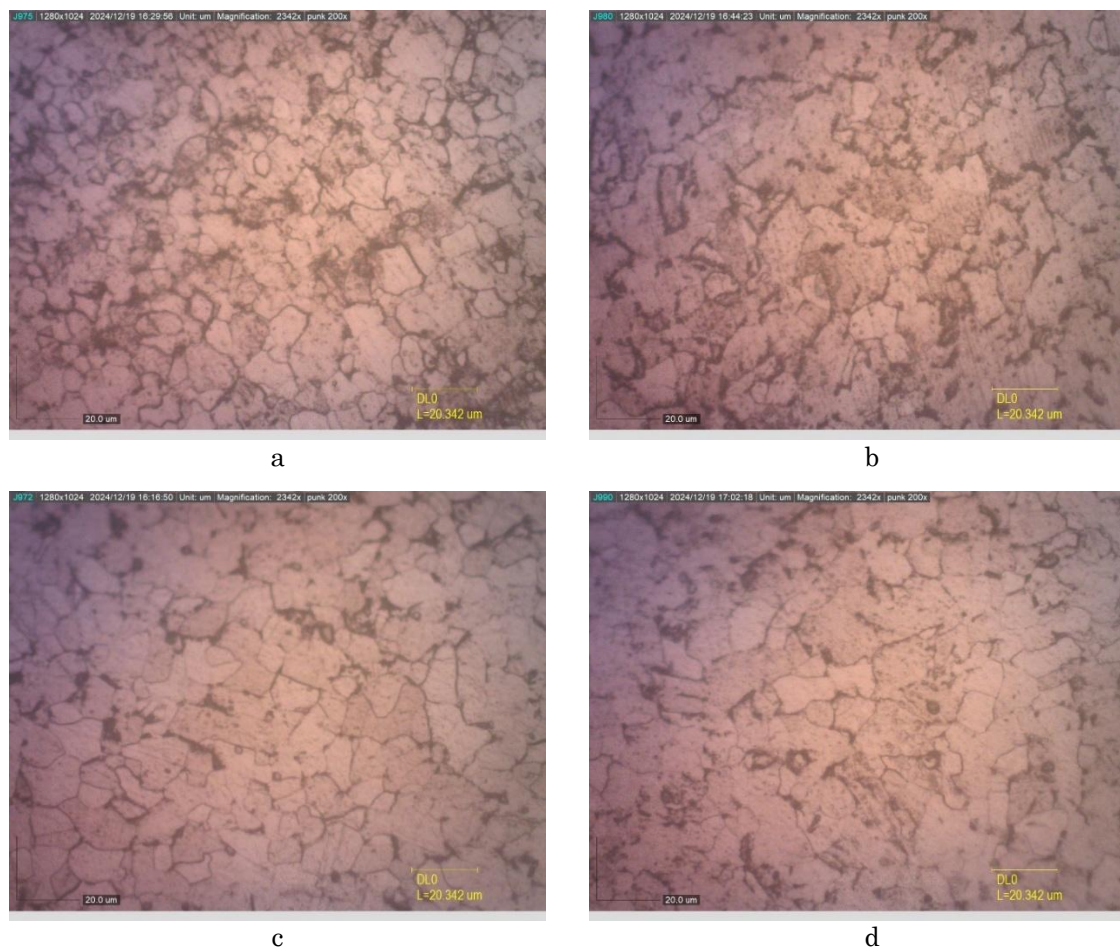


Figure 1. Micro photographs at the duration of critical treatment (a) 0 hours, (b) 12 hours, (c) 36 hours, (d) 60 hours

Cryogenic treatment may influence the microstructural characteristics and mechanical properties of ASTM A36 steel. The microstructural observations reveal variations in grain morphology and grain-boundary characteristics following different cryogenic treatment durations (Figure 1). The observed microstructure is predominantly characterized by ferrite and pearlite, with lighter regions corresponding to ferrite and darker regions associated with pearlite. These microstructural variations may be related to changes in dislocation arrangements and internal stresses during cryogenic exposure, although the transformation of retained austenite into martensite and the occurrence of dynamic recrystallization cannot be confirmed from optical micrographs alone. To quantitatively evaluate grain-size variations, the optical micrographs were analyzed using the linear intercept method based on ASTM E112, with measurements calibrated against the 20 μm scale bar provided in each image. Grain size was estimated by determining the mean intercept length from the intersections between test lines and visible grain boundaries. The specimen subjected to 60 hours of cryogenic treatment was previously reported to exhibit an average grain size of 7.19 μm ; however, this value and the conclusion that it represents the finest grain structure require confirmation through documented measurements across all treatment conditions (0, 12, 36, and 60 hours), including the number of analyzed fields and statistical variation. The Hall–Petch relationship suggests that grain refinement may contribute to increased yield strength by restricting dislocation movement; however, this mechanism cannot be conclusively established without verified quantitative grain-size data. Nevertheless, the specimen treated for 60 hours exhibited the highest ultimate tensile strength of 392.4 MPa, indicating that cryogenic treatment duration may influence the mechanical response of ASTM A36 steel. In carbon steels such as ASTM A36, after cryogenic treatment, a portion of the austenite phase γ [26]–[28] face-centered cubic/FCC) can be trapped and not completely transformed into α' (body-centered tetragonal/BCT) martensite. This is called retained austenite. The transformation of residual austenite to martensite occurs through a displacive transformation mechanism, meaning that carbon atoms do not have time to diffuse on a long scale, but the position of the lattice changes rapidly due to internal stress.

CONCLUSION

Cryogenic treatment significantly improves the mechanical capabilities of steel through granular refinement and microstructural homogeneity. The mechanical testing results indicate that the specimen subjected to 60 hours of cryogenic treatment exhibited the smallest grain size, the highest ultimate tensile strength (392.4 MPa), and the highest reported modulus of elasticity (1752.6 MPa). However, the ultimate strain decreased from 19.47% to 36 hours to 18.31% at 60 hours, corresponding to a relative reduction of approximately 5.96%. The best bending strength (892.81 MPa) is achieved after 12 hours. Impact toughness also increased with a longer duration, peaking at 290.08 J for 60 hours. These results emphasize the important role of cryogenic treatment in optimizing ASTM A36 steel for structural applications, where the balance between strength, rigidity, and toughness is critical. However, long treatment durations can lead to diminishing results, such as reduced ductility and bending strength, which requires optimization of cryogenic parameters.

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