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Research Paper

The Material Science Behind Repetitive Hammering, Solution Annealing, and Tempering on Hadfield Steel

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Abstract

The Hadfield steel used in this study contained 11 to 14% Mn and 1.1 to 1.4% C. Hadfield steel that underwent heat treatment showed insignificant differences in microstructure and hardness. On the other hand, Hadfield steel that was subjected to heat treatment combined with repetitive hammering exhibited changes in microstructure, as indicated by the presence of more and denser slip lines in accordance with an increased amount of deformation. The hardness value of the Hadfield steel also significantly increased. The slip lines discovered in the Hadfield steel that underwent solution annealing and tempering followed by repetitive hammering increased in number and appeared more compact than in the Hadfield steel without tempering. Additionally, the hardness value of the Hadfield steel with tempering was higher than that of the Hadfield steel without tempering. The strain values and thickness reduction results showed that the Hadfield steel subjected to tempering had higher strain and thickness reduction than the Hadfield steel without tempering. Higher strain and thickness reduction leads to higher hardness.

Keywords: *hadfield steel; heat treatment; repetitive hammering; solution annealing; strain hardening.*

Introduction

Hadfield steel is a type of austenitic manganese steel that exhibits high toughness and wear resistance, making it a popular choice for a wide range of industrial applications, including in aerospace, automobile, and mining industries. The high levels of manganese in Hadfield steel contribute to its toughness and hardenability, while chromium, nickel, and molybdenum provide resistance to corrosion and wear. The carbon content gives the steel its strength and hardness, while silicon acts as a deoxidizer and helps to improve the steel's toughness. Table 1 below shows the composition analysis of Hadfield steel.

Table 1 Material composition.

Element	Percentage by Weight
Carbon	1,05 – 1,35%
Manganese	11,0 – 14,0%
Silicon	0,30 – 0,90%
Chromium	1,50 – 2,50%
Nickel	0,30 – 0,80%
Molybdenum	0,10 – 0,25%
Phosphorus	0,07% max
Sulphur	0,04% max

Despite the high toughness and wear resistance characteristics, Hadfield steel faces several issues in its application. The properties of Hadfield steel can be further enhanced through mechanical and thermal treatments such as repetitive hammering, solution annealing, and tempering. These processes induce microstructural changes in the steel, which can significantly affect its mechanical and physical properties. For instance, the hardness value of Hadfield steel is low in railroad nose frogs, i.e., around 20 HRC when treated only

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by hardening with water media (quenching). Low hardness is usually associated with poor wear resistance and plastic deformation, which can reduce the component's lifespan. To enhance the wear resistance and strength of components, such as nose frogs on railroads, explosive hardening is required to harden the material's surface (Liu *et al.* [1]). Industries that use components made of Hadfield steel often encounter problems due to the steel's brittle nature and low toughness and ductility values, which are influenced by carbides and intermetallic compounds. Therefore, heat treatment engineering is necessary. Heat treatment is carried out to dissolve the carbides into the austenite phase through a process known as solution annealing. Solution annealing involves heating the specimen to the austenite phase, followed by rapid cooling to achieve a uniform solid solution (Agunsoye *et al.* [2]).

One of the important factors that affect the mechanical properties of heat-resistant steels, including Hadfield steel, is their strain-hardening behavior. In a recent study by Maruschak *et al.* [3], the strain-hardening behavior of heat-resistant steel was investigated using indentation testing. The results showed that the steel exhibited a significant increase in hardness and yield strength with increasing indentation depth, indicating the presence of strain hardening. The findings of the study by Maruschak *et al.* [3] are particularly relevant to the present work, they investigated the material science behind the effects of repetitive hammering, solution annealing, and tempering on the microstructure and mechanical properties of Hadfield steel.

The present study involved a combination of experimental and analytical techniques, including microstructural characterization, mechanical testing, and finite element analysis, to investigate the changes induced by various treatments of Hadfield steel. The results of this study provide insight into the underlying mechanisms of the observed changes and contributes to the development of optimized heat treatment protocols for Hadfield steel. Research on high strain rates in Hadfield steel has been ongoing for over forty years. Due to its low hardness in application, heat treatment engineering is carried out to increase Hadfield steel's hardness value, followed by rapid plastic deformation. Higher strain rates during deformation cause slip and twinning in the material. Slip creates more dislocation, while twinning further impedes the free path of the dislocation movement, resulting in increased stress flow. This behavior is known as high strain hardening and is described by De Cooman in [4]. Overall, the present study represents a significant contribution to the field of materials science and engineering, with potential applications in the development of high-performance materials for the aerospace, automobile, mining, and other industries.

Materials and Methods

The material used in this study was Hadfield steel containing 12.41% manganese and 1.13% carbon. The experimental methods employed included heat treatment and repetitive hammering. Various heat treatment variations were performed using solution annealing, normalizing, and solution annealing followed by tempering at different temperatures (100, 300, and 500 °C). For the repetitive hammering treatment, samples from the solution annealing and tempering processes as well as samples from the solution annealing process without tempering were subjected to different stroke variations (30, 60, 120, and 210) with a load of 5 kg.

The tests performed for characterization were as follows.

Hardness Test

A hardness test is a type of mechanical test that measures a material's resistance to deformation, such as bending, scratching, or indenting. The test was conducted using Rockwell hardness on the HRC scale with a major load of 150 kgf. To conduct a Rockwell hardness test using the HRC scale, a standard Rockwell hardness testing machine is required, along with a diamond cone-shaped indenter and an anvil. The test sample is placed on the anvil and the indenter is pressed into the material with a predetermined amount of force. The depth of penetration is then measured and used to calculate the Rockwell hardness number. The HRC scale ranges from 20 to 70, with higher numbers indicating a harder material.

Metallographic Test

Metallographic testing is a type of material analysis that involves examining the microstructure of a metal or alloy. The purpose of this testing is to understand the properties and performance of the material as well as to identify any defects or abnormalities that may affect its performance. Metallographic testing involves the preparation of a thin cross-section of the material, which is then viewed under a microscope. This allows for the identification of the various phases and constituents present in the material as well as the distribution and size of grains, inclusions, and defects.

Optical Emission Spectroscopy (OES) Test

Optical emission spectroscopy (OES) is a type of material analysis that is used to determine the chemical composition of metals and alloys. The test involves heating a sample to a high temperature, causing the atoms in the material to emit light. The light is then analyzed using a spectrometer, which separates the light into its individual wavelengths, allowing the identification and quantification of the elements present in the sample. OES is a powerful and accurate method for analyzing the chemical composition of metals and alloys, and is widely used in industries such as manufacturing, aerospace, and automotive industries.

Scanning Electron Microscope (SEM) Test

Scanning electron microscopy (SEM) is a type of microscopy that is used to produce high-resolution images of the surface of a material. SEM works by focusing a beam of electrons onto the surface of a sample, which causes the emission of secondary electrons that are detected, which is used to produce an image. The resulting images provide detailed information about the surface topography as well as the composition and distribution of materials on the surface. SEM can be used to investigate the microstructure and morphology of materials.

Results and Discussion

OES Test

The following table is the result of the optical emission spectroscopy (OES) test.

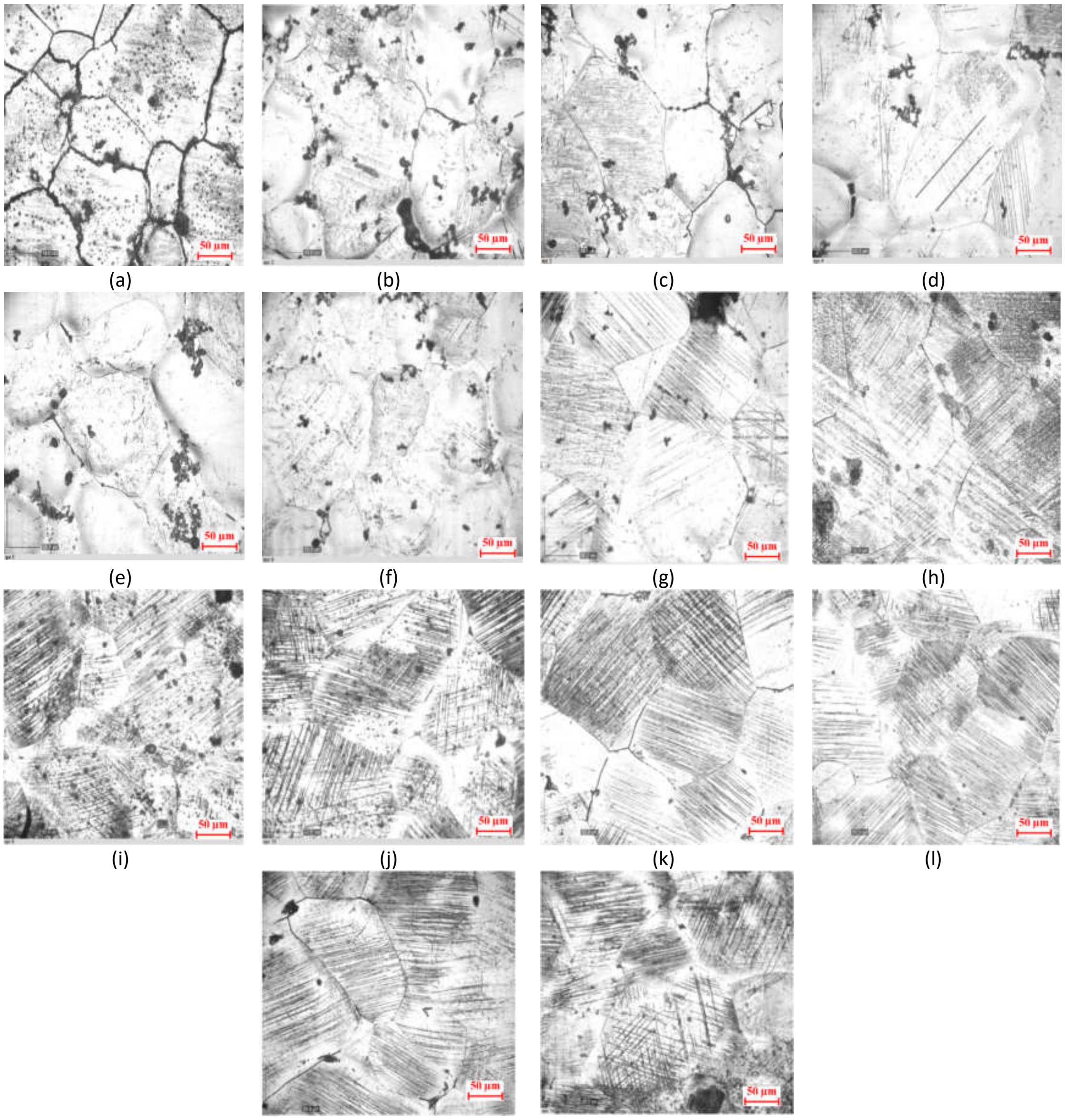
Table 2 OES test results.

Elements	Contents (%)
C	1.130
Si	0.324
S	0.005
P	0.048
Mn	12.418
Ni	0.037
Cr	2.706
Mo	0.006
V	0.008
Cu	0.026
Sn	0.002
Al	0.003
Fe	(balancer)

Hadfield steels typically consist of 10 to 14% manganese and 1.0 to 1.4% carbon. Additionally, alloys such as Cr, Mo, Si, Al, N, and V are often added to enhance the properties under varying conditions. These alloys can provide improvements such as increased strength, abrasion, corrosion, and impact resistance (Lindroos *et al.* [5]).

Effect of Repetitive Hammering on Microstructure

Metallographic tests were performed on fourteen samples, each subjected to a different type of treatment.



(a) (b) (c) (d)

(e) (f) (g) (h)

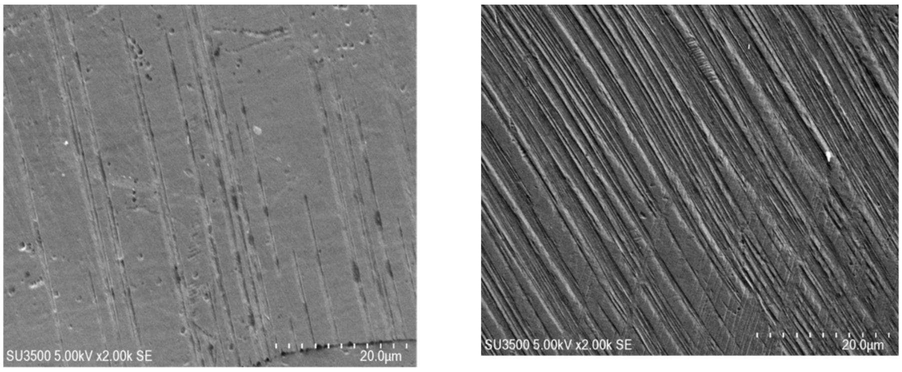
(i) (j) (k) (l)

(m) (n)

Figure 1 Microstructure: (a) no treatment, (b) solution annealing 1050 °C, (c) normalizing 1050 °C, (d) (solution annealing 1050 °C + tempering 100 °C), (e) (solution annealing 1050 °C) + tempering 300 °C), (f) (solution annealing 1050 °C + tempering 500 °C), (g) solution annealing and repetitive hammering 30 times, (h) solution annealing and repetitive hammering 60 times, (i) solution annealing and repetitive hammering 120 time, (j) solution annealing and repetitive hammering 210 times, (k) solution annealing and tempering 100 °C and repetitive hammering 30 times, (l) solution annealing and tempering 100 °C and repetitive hammering 60 times, (m) solution annealing and tempering 100 °C and repetitive hammering 120 times, (n) solution annealing and tempering 100 °C and repetitive hammering 210 times.

The microstructure of the Hadfield steel subjected to heat treatment, whether by solution annealing, normalizing, or tempering, exhibited the presence of carbide with austenite as its matrix. Meanwhile, the microstructure of the Hadfield steel subjected to repetitive hammering showed an increase in the quantity and density of slip lines as the level of deformation increases. Compared to a sample subjected only to solution annealing, the sample that underwent tempering had more slip lines.

Figure 2(a) shows slip lines with a wider gap and lower quantity in comparison to the slip lines displayed in Figure 2(b). Moreover, Figure 2(b) indicates that some of the slip lines have a different direction. This is due to a higher amount of deformation being subjected to the microstructure, which creates more slip lines. Greater strain rates will result in more twin deformation. Rapid deformation along with high strain rates can lead to twin deformation. This behavior is consistent with the findings of Bagherpour *et al.* [6].



(a) (b)

Figure 2 SEM image of microstructure of a sample subjected to solution annealing, then tempered at 100 °C and repetitive hammering: (a) 30 times, (b) 210 times.

Effect of Repetitive Hammering on Hardness

Figure 3 shows the hardness values of the samples subjected to heat treatment did not show any significant differences. This can be attributed to the fact that the microstructures of the samples treated with different methods had the same austenitic matrix and there was also the presence of carbides in all samples.

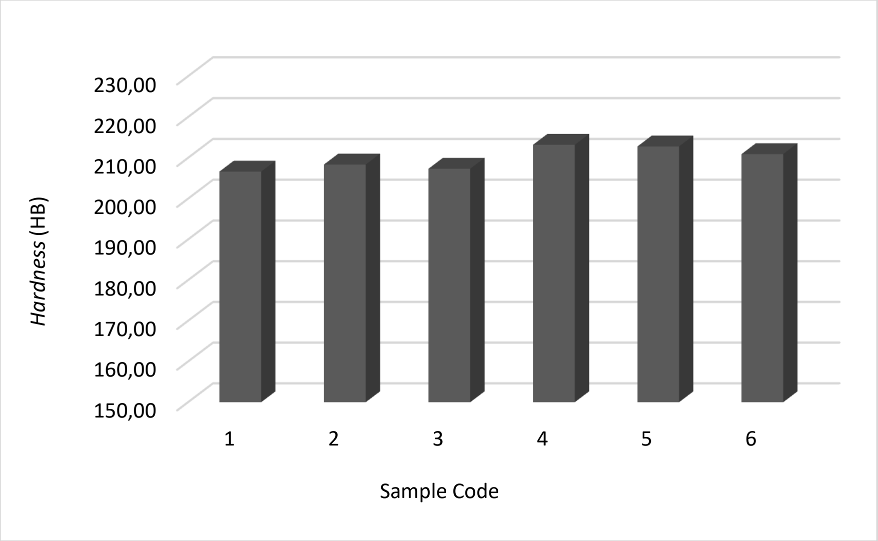


Figure 3 Hardness vs heat treatment (sample code): (1) no treatment, (2) solution annealing 1,050 °C, (3) normalizing 1,050°C, (4) solution annealing 1,050 °C + tempering 100 °C, (5) solution annealing 1050 °C + tempering 300 °C, (6) solution annealing 1050 °C + tempering 500 °C).

Figure 4 demonstrates that the hardness of the Hadfield steel significantly increased due to repetitive hammering. The hardness value increased as the number of repetitive hammering increased. As shown in Figure 4, the hardness significantly increased from 30 to 120 repetitions, while at 120 to 210 repetitions, the hardness only slightly increased due to material saturation. The sample subjected to solution annealing, which had a hardness value of 208.37 ± 0.69 HB, was then subjected to 30, 60, 120, and 210 repetitions of hammering, resulting in an increase in hardness to 277.13 ± 5.63 HB, 315.00 ± 2.35 HB, 377.60 ± 4.02 HB, and 384.70 ± 7.60 HB, respectively. Meanwhile, the sample subjected to tempering, which had a hardness value of 213.20 ± 0.65 HB, was then subjected to 30, 60, 120, and 210 repetitions of hammering, resulting in an increase in hardness to 315.27 ± 0.99 HB, 357.8 ± 8.70 HB, 402.33 ± 3.77 HB, and 407.00 ± 3.43 HB, respectively. This suggests that the increase in hardness value as a result of repetitive hammering was higher in the tempered sample compared to the sample without tempering.

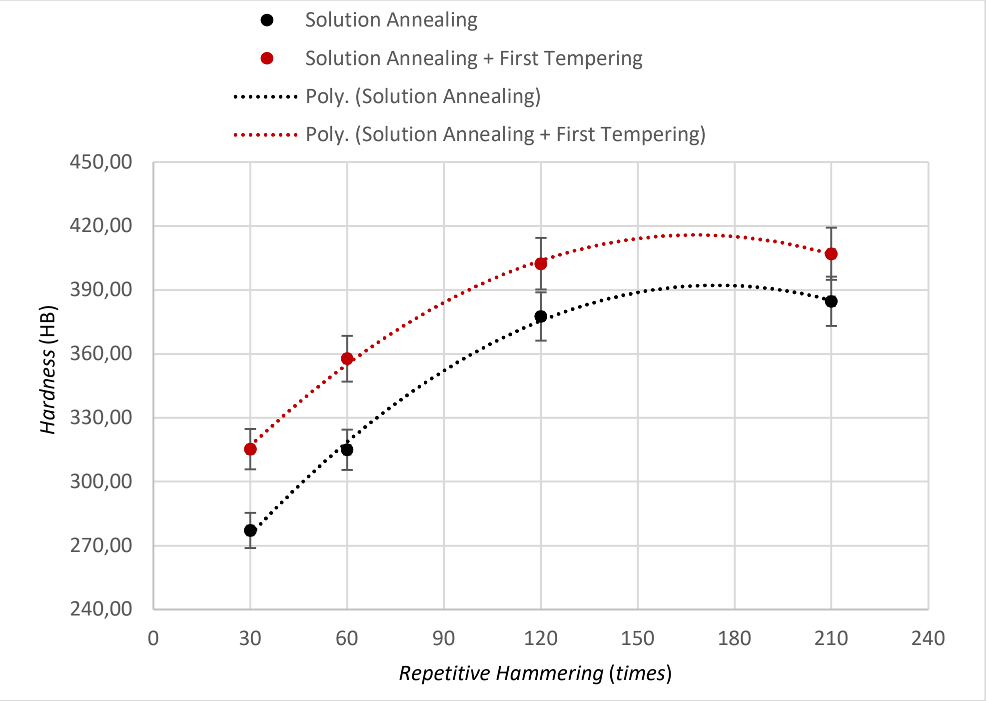
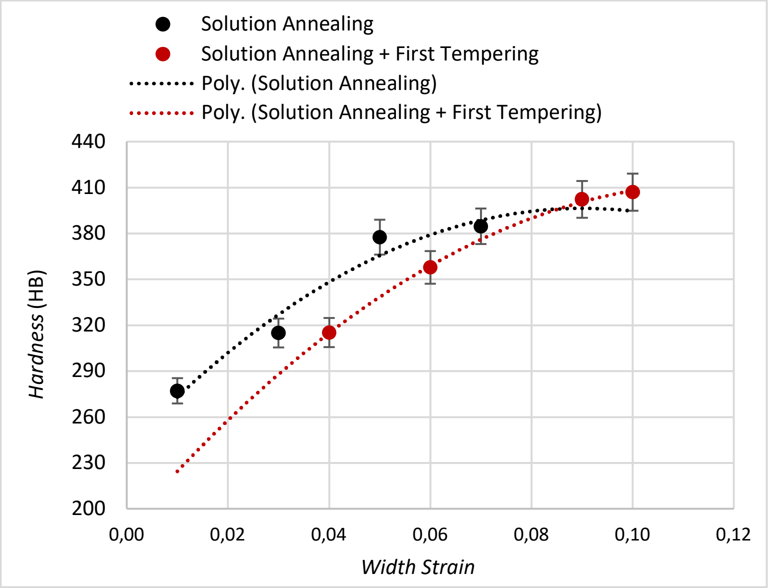


Figure 4 Hardness vs repetitive hammering.

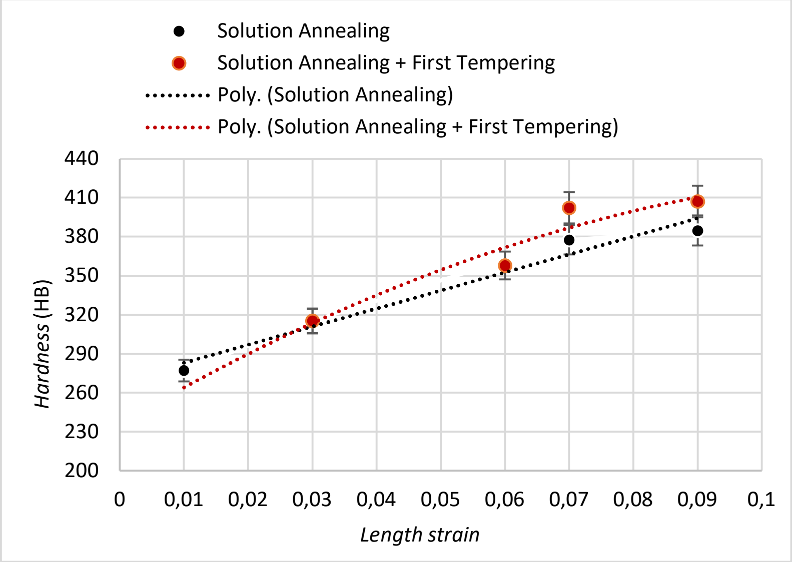
Deformation twinning readily forms when a sample undergoes deformation. Any hindrance to the dislocation's propagation will raise the critical stress. The formation of deformation twinning, however, counters this critical stress, thereby increasing the material's hardness. As per Yuan *et al.* [7], deformation twinning plays a crucial role in increasing the hardness of materials. Furthermore, there are other methods to increase the hardness of steel materials. As demonstrated by research conducted by Arifvianto *et al.* [8], all blasting treatments with various blasting particles increased the roughness and hardness of the steel surface. This intriguing phenomenon presents an opportunity for further investigation into the comparative analysis of diverse techniques aimed at augmenting the hardness of materials with a specific focus on steel materials.

Effect of Strain to Hardness Value after Repetitive Hammering

The samples that underwent tempering exhibited higher strain and hardness values than those without tempering after the same repetitive hammering, as shown in Figure 5. The initial length and width strains of the tempered sample subjected to thirty times of repetitive hammering were 0.03 and 0.04, respectively. These values were higher than those of the untreated sample with the same length and width strains of 0.01. This is attributed to the tempering process, which softens the matrix or induces a crystal structure of FCC that is more susceptible to deformation.



(a)



(b)

Figure 5 Strain vs hardness: (a) width strain value vs hardness, (b) length strain value vs hardness.

Effect of Thickness Reduction to Hardness Value after Repetitive Hammering

The thickness reduction of the sample subjected to tempering was higher than that of the sample without tempering, due to the softer matrix of the tempered sample being more prone to deformation. Figure 6 illustrates that greater thickness reduction resulted in higher hardness values. For example, the sample with a hardness value of 407.00 ± 3.43 HB underwent a thickness reduction of 20.91%. This can be attributed to the fact that the tempering process softens the matrix, making it more susceptible to deformation and resulting in a higher degree of thickness reduction.

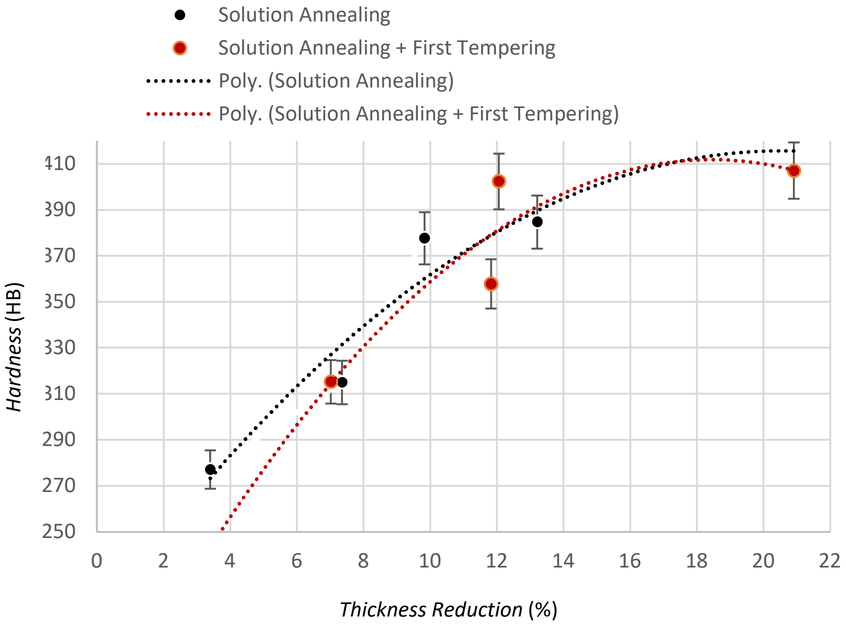


Figure 6 Thickness reduction vs hardness.

Conclusions

This research demonstrated that repetitive hammering of Hadfield steel without heat treatment did not result in any significant changes in the microstructure and hardness. However, the sample that underwent heat treatment followed by repetitive hammering exhibited significant changes in hardness, microstructure, strain value, and thickness reduction. The sample that underwent tempering before repetitive hammering showed higher hardness, strain, and thickness reduction values compared to the non-tempered sample. From a microstructural perspective, it was observed that greater deformation or repetitive hammering results in an increased number of slip lines, denser slip lines, and slip lines with various directions. The findings of this research are supported by previous research in this area, which also highlighted the benefits of these heat treatments on the mechanical properties of Hadfield steel. For example, the work by Liu *et al.* [1] has shown that explosive treatment can increase the hardness and wear resistance of Hadfield steel.

The findings presented in this paper demonstrate significant scientific novelty in the field of materials science and engineering. Specifically, this study has shown that repetitive hammering of Hadfield steel, when combined with an appropriate heat treatment, can result in significant changes in microstructure, hardness, and other mechanical properties. This represents a new and important insight into the effects of mechanical deformation and heat treatment on this type of steel. The results also revealed the importance of tempering before repetitive hammering, which can lead to even greater improvements in hardness, strain, and thickness reduction. This novel finding provides important information for the development of improved heat treatment protocols for Hadfield steel and other materials. Furthermore, the observations regarding the microstructure of the samples after repetitive hammering are novel and contribute to a better understanding of the deformation behavior of Hadfield steel. The increase in slip lines, denser slip lines, and slip lines with various directions provides new insights into the mechanisms of plastic deformation in this material.

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