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The Influence of Full Annealing Process Combined with Repetitive Hammering on the Mechanical Properties of AISI 316 Steel

Destri Muliastri*, Slamet Raharjo
Department of Mechanical Engineering, Bandung State Polytechnic
Gegekalong Hilir Street, Ciwaruga Village, West Bandung Regency, West Java, Indonesia
*E-mail: destri.muliastri@polban.ac.id

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Abstract

AISI 316 stainless steel is a metastable austenitic steel known for its high corrosion resistance, excellent strain hardening capability, and good formability. Its austenitic microstructure can transform into α-martensite under plastic deformation such as Dynamic Plastic Deformation (DPD). The main alloying elements—chromium (16–18%) and nickel (10–14%)—contribute to its mechanical strength and corrosion resistance. However, in certain industrial applications that demand both high mechanical strength and corrosion resistance, conventional strengthening methods like cold working may trigger phase transformations that reduce its corrosion resistance. Therefore, alternative methods are needed to improve mechanical properties while maintaining the austenitic structure. Previous studies have explored strain hardening using deformation methods such as repetitive hammering, but research on the combined effects of annealing and repetitive hammering on AISI 316 is still limited. This study aims to analyze the mechanical properties and microstructural changes of AISI 316 after annealing and after a combination of annealing and repetitive hammering. The treatment involved full annealing at 1050°C for 30 minutes, followed by hammering 30, 60, and 90 times. An additional treatment was conducted with annealing followed by 30 hammering repetitions at the same temperature. A 5 kg iron load was used during hammering. Tests conducted include Optical Emission Spectroscopy (OES), micro-Vickers hardness testing, tensile testing, microstructure analysis, strain measurement, and thickness reduction. The untreated specimen had a hardness of 269.3 VHN, which decreased to 165.2 VHN after annealing. Repetitive hammering increased hardness to 213.4, 228.5, and 251.4 VHN for 30, 60, and 90 repetitions, respectively. These results indicate that repetitive hammering following annealing significantly improves the hardness of AISI 316 without altering its austenitic structure. This study confirms that combining annealing with dynamic plastic deformation offers an effective alternative strengthening method for AISI 316 stainless steel.

Keywords: AISI 316 ; dynamic plastic deformation; full annealing; repetitive hammering

Abstrak

Baja AISI 316 merupakan baja tahan karat austenitik metastabil yang dikenal memiliki ketahanan korosi tinggi, kemampuan pengerasan regangan yang baik, serta mudah dibentuk. Mikrostruktur austenitiknya dapat berubah menjadi α-martensit melalui perlakuan deformasi plastis seperti Dynamic Plastic Deformation (DPD). Kandungan unsur paduan utama seperti kromium (16–18%) dan nikel (10–14%) memberikan kontribusi terhadap sifat mekanik dan ketahanan korosi yang unggul. Namun, pada aplikasi industri tertentu yang membutuhkan kombinasi antara kekuatan mekanik tinggi dan ketahanan korosi, metode pengerasan konvensional seperti cold working dapat menyebabkan transformasi fasa yang menurunkan ketahanan korosi tersebut. Oleh karena itu, diperlukan metode alternatif yang mampu meningkatkan kekerasan tanpa mengganggu fasa austenitiknya.Beberapa penelitian telah membahas pengerasan regangan menggunakan metode deformasi seperti penempaan berulang, namun kajian mengenai kombinasi perlakuan anil (annealing) dan penempaan berulang terhadap baja AISI 316 masih terbatas. Penelitian ini bertujuan untuk menganalisis sifat mekanik dan perubahan mikrostruktur baja AISI 316 setelah perlakuan anil dan kombinasi dengan penempaan berulang. Perlakuan dilakukan melalui proses full annealing pada suhu 1050°C selama 30 menit, dilanjutkan dengan penempaan sebanyak 30, 60, dan 90 kali. Selain itu, dilakukan juga kombinasi anil dan penempaan 30 kali pada suhu yang sama. Beban 5 kg digunakan selama proses penempaan. Pengujian meliputi OES, uji kekerasan mikro Vickers, uji tarik, analisis mikrostruktur, serta pengukuran regangan dan reduksi ketebalan. Hasil menunjukkan bahwa spesimen tanpa perlakuan memiliki kekerasan 269,3 VHN, yang menurun menjadi 165,2 VHN setelah annealing. Penempaan berulang meningkatkan kekerasan menjadi 213,4; 228,5; dan 251,4 VHN. Hasil ini menunjukkan bahwa kombinasi anil dan deformasi plastis dinamis efektif meningkatkan kekerasan AISI 316 tanpa mengubah struktur austenitiknya

Kata kunci: AISI 316; deformasi plastis dinamis; full annealing; penempaan berulang

1. Introduction

Stainless steel is a type of steel that contains at least 10.5% chromium and a maximum of 1.2% carbon (ISO 15510). The chromium content forms a passive chromium oxide layer on the surface, providing resistance to oxidation and corrosion. In addition, stainless steel has other valuable characteristics such as good weldability, energy absorption, resistance to abrasion and erosion, high reflectivity, and toughness at elevated temperatures [1]. One widely used type is AISI 316 stainless steel, which offers greater corrosion resistance than AISI 304/304L, especially in oxidizing acidic environments like nitric acid. The presence of molybdenum in AISI 316 also enhances its performance in sulfur-containing conditions [2].

Cold working refers to plastic deformation carried out below the metal's recrystallization temperature, preventing the formation of new grains during the process. This increases dislocation density within the crystal structure, leading to strain hardening (higher strength and hardness) but often reducing ductility and increasing residual stresses. Because no recrystallization occurs, deformation-induced microstructural features (e.g., slip lines, twin boundaries) are retained until subsequent heat treatment. In austenitic stainless steels such as AISI 316, cold working at room temperature may also trigger partial transformation from austenite to martensite ($\gamma \rightarrow \alpha'$) depending on the strain level and chemical composition, which can reduce corrosion resistance if martensite forms in significant amounts. Repetitive hammering at room temperature essentially falls under cold working; thus, controlling the strain per blow and the accumulated strain is crucial to avoid undesirable phase transformations [3].

Hot working, in contrast, is performed at temperatures above the material's recrystallization point, allowing recrystallization to occur simultaneously with deformation (dynamic or static recrystallization). Because new grains form during or shortly after forming, the effects of strain hardening are not accumulated as in cold working—resulting in a material that remains relatively ductile and easy to shape, with lower residual stresses and potentially beneficial grain refinement. In AISI 316, hot working within the austenite stability range minimizes the risk of martensitic transformation and avoids the corrosion resistance loss caused by excessive cold work; however, excessive high-temperature exposure can lead to the precipitation of secondary phases (e.g., chromium carbides at grain boundaries) that may impair intergranular corrosion resistance if not properly controlled (sensitization) [3].

Materials with twinning structures are known to possess excellent mechanical properties, such as high conductivity, mechanical stability, and unique crystallographic configurations. In austenitic stainless steels like AISI 316, deformation twinning can occur under high strain rates, leading to symmetrical atomic arrangements within the grain structure. These twin boundaries not only block dislocation motion but also serve as effective slip planes, resulting in a favorable combination of strength and ductility [4]. This makes AISI 316 a promising candidate for further enhancement to meet industrial demands requiring both mechanical performance and corrosion resistance.

However, AISI 316 still faces limitations in mechanical strength for certain critical applications, particularly in the aerospace industry, where components like actuators, fasteners, and landing gear require extreme tensile strength and durability. Conventional strengthening methods such as cold working can lead to phase transformation from austenite to martensite, potentially reducing corrosion resistance. Therefore, alternative approaches are needed to improve strength and hardness while preserving the austenitic phase. One such method is the combination of full annealing—to optimize the initial microstructure and reduce residual stress—followed by strain hardening through repetitive hammering.

Previous studies have explored strain hardening via repetitive hammering on austenitic steels [5] but the results showed only marginal improvement—typically modest increases in hardness and mechanical strength—possibly due to suboptimal initial conditions or process parameters. More recent work on strain hardening in austenitic grades (e.g., AISI

316L) has demonstrated more substantial effects. For instance, in severe plastic deformation (high-pressure torsion) applied to additively manufactured 316L, hardness values reached up to 600 HV, indicating drastic hardening, though often accompanied by phase changes or residual stresses. Other studies on repeated impact or strain-rate loading (cold rolling with sudden strain-rate jumps) have shown notable increases in strength through adiabatic heating and dynamic strain hardening, though exact values vary with conditions . This research aims to address that gap by analyzing the mechanical properties and microstructural evolution of AISI 316 after annealing and after a combination of annealing and repetitive hammering. The study seeks to demonstrate that this treatment sequence can effectively enhance strength without inducing undesirable phase changes, and to provide deeper insight into the relationship between strain rate, hardness improvement, and microstructural stability.

2. Material and Method

This research uses experimental testing. The samples are divided into five parts, each of which will undergo different treatments. OES testing is conducted first before the samples receive any treatment. Table 2.1 shows the detailed process that will be performed on each sample.

Table 2.1 Sample Description

Code	Treatment
1xx	Control
2xx	Full annealing (Holding time 30 minutes) T=1050ºC
3xx	Cold workingFull annealing (Holding time 30 minutes) T=1050ºC Repetitive hammering 30x hammering
4xx	Cold working Full annealing (Holding time 30 minutes) T=1050ºC Repetitive hammering 60x hammering
5xx	Cold working Full annealing (Holding time 30 minutes) T=1050ºC Repetitive hammering 90x hammering

Cold working in this study refers to plastic deformation of the AISI 316 samples performed at room temperature prior to heat treatment. The process was conducted by manually applying compressive blows using a hammer, inducing strain hardening without exceeding the recrystallization temperature of the material. This stage increases dislocation density and introduces microstructural features (e.g., slip lines, twin boundaries) that influence the outcome of subsequent annealing and repetitive hammering treatments.

2.1 Equipment's and Materials

The equipment used in this research includes a furnace, measuring cylinder, stand, grinding machine, sanding machine, polishing machine, digital scale, PVC pipe, and a 5 kg weight. The materials used in this research are AISI 316, glycerin, nitric acid, and hydrochloride acid.

2.2 Research stages

1. OES AISI 316 testing

   OES testing is conducted before the samples undergo treatment to determine the chemical composition of the AISI 316 samples. The OES testing is performed using a machine of the type ARL 3460 Optical Emission Spectrometer.

2. Cold working process

   Prior to the heat treatment stage, the AISI 316 samples are subjected to cold working at room temperature. This process involves manually applying compressive blows using a hammer to induce plastic deformation without exceeding the material's recrystallization temperature. The cold working step increases dislocation density and introduces deformation-induced microstructural features (e.g., slip lines, twin boundaries), which are expected to influence the results of subsequent full annealing and repetitive hammering treatments.

   Cold Working Process Steps:

   - **Preparation of AISI 316 Sample**

     Prepare the AISI 316 sample in the desired form (plate, rod, or other shapes). Ensure the surface is cleaned of any dirt, oil, or oxides to avoid uneven deformation during the cold working process.
   - **Placement of the Sample on the Working Surface**

     Place the AISI 316 sample on a flat, hard working surface (such as a steel anvil or solid stone block). This surface should be able to withstand the applied force without deforming, ensuring that the sample can deform evenly.
   - **Hammering the Sample**

     This step is the core of the cold working process. Hammering is done by repeatedly striking the sample with a hammer, directly on the area intended for deformation. Each strike causes atomic shifts within the crystal lattice, resulting in plastic deformation of the material.

3. Full Annealing process

   The prepared samples undergo full annealing heat treatment at a temperature of 1050°C for a holding time of 30 minutes. This process is carried out inside a heating furnace. Subsequently, the samples are slowly cooled in the furnace atmosphere until they reach room temperature.

4. Repetitive Hammering Process

   The repetitive hammering process is performed after the specimen undergoes heat treatment, hammering process is a form of strain hardening behavior. To test the strain hardening behavior of AISI 316 steel, the samples are subjected to a 5 kg metal rod dropped from a height of 1 meter (Ep = 49 joules), diameter of PVC pipe 35mm and sample dimension is 100 mm x 30 mm width 5mm, repeated 30, 60, and 90 times after the full annealing process. Figure 3.1 illustrates the schematic of repetitive hammering.

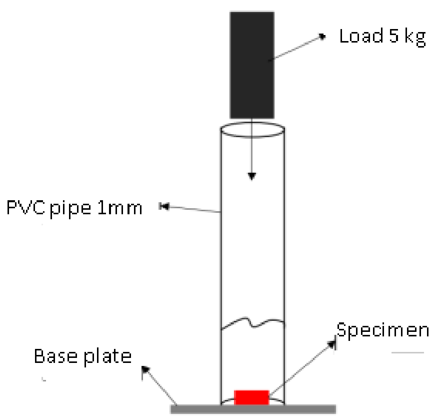

Figure 3.1 Illustration of Repetitive Hammering.

5. Tensile Testing Process

   Tensile testing is conducted to determine the yield strength and elasticity of AISI 316 samples before and after treatment. Prior to testing, the samples follow ASTM E8M standard dimensions.

6. Hardness Testing Process

   Hardness testing is performed using a Hardness Testing Machine employing the Vickers method. Hardness tests are conducted on the entire samples to compare hardness values before and after treatment.

3. Results and Discussion

3.1 OES testing results

The results of Optical Emission Spectroscopy testing of AISI 316 Steel samples are presented in Table 3.1

Table 3.1 OES Test Results for AISI 316

Elements	**AISI 316 (wt.%)**	**ASTM A240 (wt.%)**
Carbon	0,018	≤0,03
Mangan	1,643	≤2,00
Phospor	0,029	≤0,045
Sulfur	0,004	≤0,03
Silicon	0,4	≤0,75
Chromium	16,62	16,00-18,00
Nickel	10,62	10,00-14,00
Molybdenum	2,56	2,00-3,00
Copper	0,108	-

The results of Optical Emission Spectroscopy (OES) testing on AISI 316 stainless steel show that all alloying elements fall within the specification range of ASTM A240. With 16.62% chromium and 10.62% nickel, the material is confirmed to be austenitic stainless steel, providing excellent corrosion resistance and non-magnetic properties. The presence of 2.56% molybdenum enhances pitting corrosion resistance, particularly in chloride-rich environments, making AISI 316 superior to AISI 304. Furthermore, the low carbon content (0.018%) prevents chromium carbide precipitation, thereby avoiding intergranular corrosion and ensuring good weldability.

In addition to the major elements, trace amounts of manganese (1.643%) and silicon (0.4%) contribute to microstructural stability and improve deoxidation during melting. The low levels of phosphorus (0.029%) and sulfur (0.004%) are also beneficial, as they support good toughness and weldability. The detected copper content (0.108%), although not specified in ASTM A240, is minimal and does not significantly affect performance. In fact, previous studies suggest that small amounts of copper may improve resistance to stress corrosion cracking under certain conditions [6].

Overall, the chemical composition analysis confirms that the steel specimen used is suitable for subsequent thermomechanical treatments such as annealing and repetitive hammering. The compliance with standards ensures that the key functional properties of AISI 316—mechanical strength and corrosion resistance—can be optimized without compromising the stability of its austenitic phase. These findings provide a strong foundation for understanding how further treatments affect the microstructural evolution and mechanical enhancement of the material.

3.2 Tensile Testing Resullts

The parameters obtained from the data processing of the tensile test include tensile strength, yield strength, elasticity, and elongation. Table 3.2 shows the calculated data from the tensile testing of the specimens.

Table 3.2 Tensile Test Data

No	Sample	Load max (kg)	Ultimate strenght (MPa)	Yield strenght (MPa)	Young Modulus (Gpa)	Elongation (%)
1	Control	1208	755,69	645	17,04	66,76
2	Full annealing 1050ºC Repetitive hammering 30x	1280	748,18	555	19,55	69,04
3	Full annealing 1050ºC Repetitive hammering 60x	1250	740,86	575	21,63	66,76
4	Full annealing 1050ºC Repetitive hammering 90x	1324	787,34	700	23,3	79,4

Based on the tensile test results, the specimen that underwent full annealing at 1050°C followed by 90 cycles of repetitive hammering exhibited the highest values of ultimate tensile strength, yield strength, and Young's modulus compared to the other specimens. This indicates that the large force or impact applied to the specimen resulted in a significant increase in strain hardening. The increased number of hammering cycles led to a higher dislocation density, which acts as a barrier to dislocation motion, thereby enhancing the material's strength. These findings are supported by [7] who reported that severe plastic deformation due to repeated impact can enhance mechanical strength through subgrain formation and dislocation entanglement.

The increase in Young's modulus from 17.04 GPa (control) to 23.3 GPa (90x hammering) suggests improved material stiffness. Although Young's modulus is generally not significantly affected by mechanical treatment, this enhancement may be attributed to a reduction in internal defects and microstructural refinement caused by dynamic recrystallization during deformation. This result is consistent with the findings of Tarto et al who stated that thermomechanical treatments can improve stiffness through grain orientation refinement and porosity reduction [8] .

In terms of ductility, the specimen with 90 cycles of hammering demonstrated the highest elongation, reaching 79.4%, surpassing both the control specimen (66.76%) and all other treated specimens. This increase in ductility indicates that recrystallization and dynamic recovery during the annealing process were effective in counteracting the embrittlement effects caused by work hardening. Thus, the combination of heat treatment and mechanical deformation not only improves strength but also maintains—or even enhances—the material's plastic deformation capability. This is supported by Allain et al who found that combining deformation and recrystallization processes can result in fine grain structures and twin boundaries that contribute to increased strength and ductility [9].

Overall, increasing the number of hammering cycles shifts the dominant deformation mechanism from slip and dislocation motion to twinning at higher impact energy levels. This explains why both strength and ductility can increase simultaneously in the 90x treatment. Hence, this treatment demonstrates the effectiveness of thermomechanical processing in enhancing the mechanical performance of metals without compromising any major property.

3.3 Hardness Testing Resullts

Microhardness testing is conducted to determine the hardness value of a material, which is the result of the treatment of full annealing combined with repetitive hammering . Hardness tests are conducted at three points for each variation using the vickers micro hardness method.

Table 3.3 Hardness Value

No	Sample	Hardness (HV) 1	2	3	Average
1	Control	261,4	271,9	274,7	**269,3**
2	Full Annealing	162,7	166,2	166,7	**165,2**
3	Full annealing 1050ºC Repetitive hammering 30x	211,5	214,5	214,2	**213,4**
4	Full annealing 1050ºC Repetitive hammering 60x	228,6	228,0	229,0	**228,5**
5	Full annealing 1050ºC Repetitive hammering 90x	271,0	239,2	244,0	**251,4**

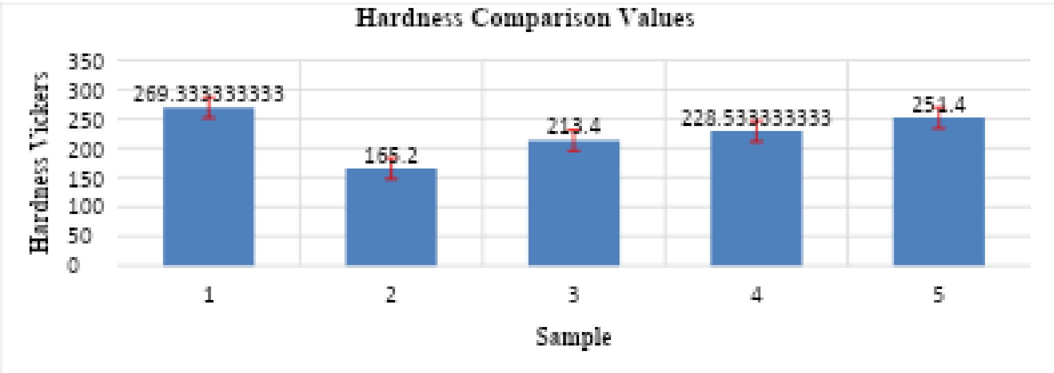

Figure 3.2 Hardness comparison graph

Microhardness testing using the Vickers method was performed to evaluate the influence of full annealing and repetitive hammering on the hardness of the material. The control specimen, which did not undergo any post-processing heat treatment, exhibited a relatively high average hardness of 269.3 HV. This high value is attributed to the strain hardening effect from prior cold working, where dislocation density and internal stress increase due to plastic deformation. In contrast, the specimen subjected to full annealing at 1050°C showed a significant reduction in hardness to 165.2 HV, indicating successful recrystallization and recovery of ductility. The specimens that received additional treatment in the form of repetitive hammering after full annealing 30x, 60x, and 90x demonstrated gradual increases in hardness: 213.4 HV, 228.5 HV, and 251.4 HV, respectively. These values correspond to hardness increases of 22.6%, 38.3%, and 52.2% compared to the fully annealed sample. The increase in hardness with more hammering cycles confirms that plastic deformation was reintroduced, initiating strain hardening mechanisms such as dislocation multiplication, slip formation, and twinning.

According to Allain et al. [9], an increase in dislocation density and the activation of twinning as a deformation mode are closely related to the stacking fault energy (SFE) of the alloy. In materials with moderate to low SFE, such as austenitic steels, the propensity for twinning is higher, which enhances the strain hardening rate and contributes to a more significant increase in hardness. The progressive rise in hardness observed in this study aligns with these principles, as repetitive hammering likely promoted both dislocation interactions and twin boundary formation. Furthermore, as described by

Callister and Rethwisch [10], the reintroduction of plastic deformation after annealing effectively reverses the softening effects of recrystallization by impeding dislocation motion, leading to improved hardness and strength. This suggests that repetitive mechanical deformation can be an effective post-annealing process to tailor mechanical properties, with the number of deformation cycles playing a critical role in determining the final hardness level.

The specimens that received additional treatment in the form of repetitive hammering after full annealing—30x, 60x, and 90x—demonstrated gradual increases in hardness: 213.4 HV, 228.5 HV, and 251.4 HV, respectively. These values correspond to hardness increases of 22.6%, 38.3%, and 52.2% compared to the fully annealed sample. The increase in hardness with more hammering cycles confirms that plastic deformation was reintroduced, initiating strain hardening mechanisms such as dislocation multiplication, slip formation, and twinning. These results are in line with the work of Zhang et al who emphasized the role of repetitive mechanical deformation in enhancing hardness through increased dislocation density [10] .

Overall, the microhardness data demonstrate that mechanical deformation following full annealing can progressively restore and even enhance the material’s hardness to levels approaching that of the cold-worked condition. Although the sample hammered 90 times did not fully match the control’s hardness, it came close, suggesting an effective reactivation of strain hardening. These findings are also supported by Xu et al who reported similar hardness improvements due to surface-level deformation and dislocation buildup. The correlation between deformation intensity and hardness underscores the importance of controlled mechanical treatment in tailoring material properties for engineering applications [11] .

3.4 Metalografi Testing Results

Microstructure observations of the sample were conducted before and after the sample received treatment. Observations were made using an optical microscope with 20x and 50x magnification. The following are the microstructure observations of the sample under various treatments.

3.4.1 Microstructure without treatment

Figure 3.4 shows the microstructure of as-received AISI 316 stainless steel, predominantly composed of an austenitic phase with elongated and angular grain shapes. This grain morphology indicates prior cold rolling during manufacturing, which introduces directional deformation. The clear and distinct grain boundaries suggest that the material has not undergone recrystallization. The elongated grain structure is a result of strain hardening, where dislocation density increases due to plastic deformation, thereby enhancing the material’s hardness and tensile strength. According to Callister et al such plastic deformation mechanisms hinder further dislocation motion and lead to work hardening in metallic materials [12].

In addition to austenite, fine dark precipitates can be observed along the grain boundaries, which are likely chromium-rich carbides ($M_{23}C_6$). These carbides typically form during slow cooling after hot working and can potentially lead to intergranular corrosion if the material becomes sensitized. While they can contribute to strengthening grain boundaries, excessive carbide precipitation may compromise corrosion resistance. This initial microstructure serves as a reference point for analyzing subsequent changes due to thermal or mechanical treatments, such as full annealing or repetitive hammering. Chen et al reported that cold-worked austenitic stainless steels exhibit elongated grain shapes and distorted structures prior to softening or recrystallization treatments [13] .

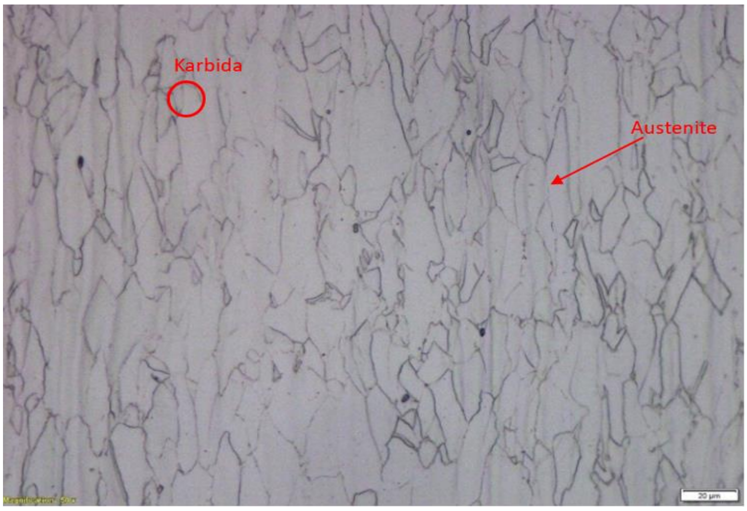

Figure 3.4 Microstructure without treatment

3.4.2 Microstructure with full annealing treatment

The microstructure shown in the image corresponds to AISI 316 stainless steel after full annealing, most likely conducted at around 1050°C. The image reveals equiaxed and uniformly distributed austenite grains, indicating that the material has undergone complete recrystallization. The absence of elongated grains, which were present in the as-received condition, confirms that the cold work-induced deformation has been eliminated by the annealing treatment. The well-defined grain boundaries and the rounded grain shapes are characteristic of a thermally softened structure. According to Callister et al annealing processes restore ductility by relieving internal stresses and reducing dislocation density, resulting in softer and more workable material [12] .

Additionally, fine dark precipitates dispersed throughout the matrix are visible, which are likely chromium-rich carbides ($M_{23}C_6$) formed during cooling after annealing. These precipitates are typically located along grain boundaries and within grains. When finely and evenly distributed, they can strengthen the grain boundaries without significantly compromising corrosion resistance. However, excessive or uneven carbide precipitation may increase the risk of intergranular corrosion. This microstructure demonstrates that the material is in a softened state, ideal for further mechanical processing such as forging or hammering. Motta et al notes that fully annealed austenitic stainless steels generally exhibit larger, randomly oriented grains formed through the recrystallization and grain growth process [14] .

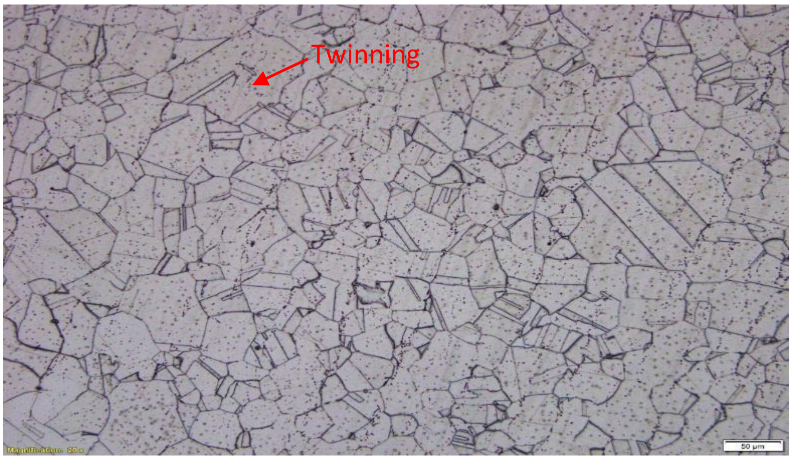

Figure 3.5 Microstructure with full annealing treatment.

3.4.3 Microstructure with full annealing treatment and repetitive hammering 30 times

Figure 3.6 shows the microstructure of an AISI 316 stainless steel specimen that underwent full annealing at 1050°C, followed by furnace cooling and 30 cycles of repetitive hammering. This combined thermal-mechanical treatment leads to a unique microstructural evolution. The microstructure reveals equiaxed austenite grains with the presence of mechanical twins, marked clearly in the figure. Twinning is a deformation mechanism that occurs when the material is subjected to shear stress beyond a certain threshold, especially in low stacking fault energy (SFE) materials like austenitic stainless steels. These twin boundaries are characterized by a mirrored atomic arrangement across a defined plane, formed through uniform shear movement of atoms in a direction proportional to their distance from the twin plane [13]

The formation of twin structures is significant as it contributes to strain hardening, especially after a prior annealed condition. Unlike dislocations that result in permanent lattice distortion, twin boundaries are coherent and possess low interfacial energy, making them more stable and less susceptible to corrosion initiation sites. Their presence improves strength without drastically compromising ductility. According Lu et al, twinning-induced plasticity (TWIP) enhances both strength and formability in austenitic steels by acting as a barrier to dislocation motion and increasing work hardening rates [15] . In the context of this study, the appearance of twins after 30 hammering cycles indicates that plastic deformation has reintroduced strengthening mechanisms, despite the prior softening effect of full annealing.

Furthermore, the mechanical twins play a role in influencing corrosion resistance, particularly along grain boundaries. Twin boundaries typically do not promote sensitization like high-angle grain boundaries, due to their low boundary energy and high atomic coherence. This can be beneficial in maintaining intergranular corrosion resistance, especially in environments where AISI 316 is often exposed, such as chemical processing or marine applications. Therefore, the presence of twins not only reflects the onset of mechanical strengthening but also suggests potential improvements in microstructural stability and corrosion behavior following moderate deformation post-annealing.

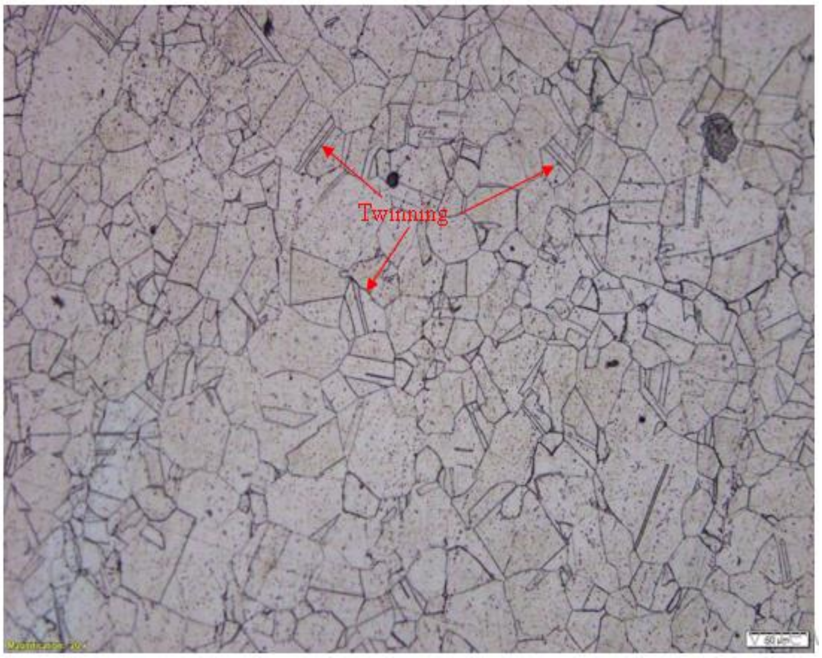

Figure 3.6 Microstructure with full annealing and repetitive hammering 30 times.

3.4.4 Microstructure with full annealing treatment and repetitive hammering 60 times

Figure 3.7 shows the microstructure of the AISI 316 specimen that underwent full annealing at 1050°C, followed by furnace cooling and then subjected to 60 cycles of repetitive hammering. The microstructure reveals notable features such as slip lines and twinning, both of which are characteristic deformation mechanisms in austenitic stainless steels. The appearance of slip lines in the austenitic matrix indicates that plastic deformation has occurred through the motion of dislocations along specific crystallographic planes. Austenitic stainless steels, due to their face-centered cubic (FCC) structure, are known for their high ductility and multiple slip systems, making them prone to dislocation slip under stress. The visible slip bands confirm that the repetitive hammering introduced sufficient strain energy to activate dislocation motion within grains.

Alongside slip lines, twinning is also observed, representing a secondary mechanism of plastic deformation. Twinning is typically activated in low stacking fault energy (SFE) materials under conditions of higher strain or lower temperatures. In this case, the combination of prior annealing and subsequent mechanical impact has led to the formation of deformation twins, which are visible as symmetrical features across twin planes. These twins act as effective barriers to dislocation motion, thereby contributing to strain hardening and increasing the strength of the material. As supported by Lu et al twinning in austenitic stainless steels enhances both strength and ductility by increasing work-hardening rates through the interruption of dislocation paths [15].

The presence of both slip and twinning mechanisms suggests a transition from simple plastic deformation toward more complex strengthening behavior. At this stage—after 60 hammering cycles—the material undergoes substantial microstructural refinement. Dislocation tangles and twin boundaries increase the resistance to further plastic deformation, which explains the progressive increase in hardness observed in mechanical testing. Additionally, the interaction between dislocations and twin boundaries can locally raise internal stresses, influencing crack propagation resistance and overall fatigue performance. These microstructural features are strong indicators that the material has moved beyond the recovery stage and is undergoing significant strain hardening.

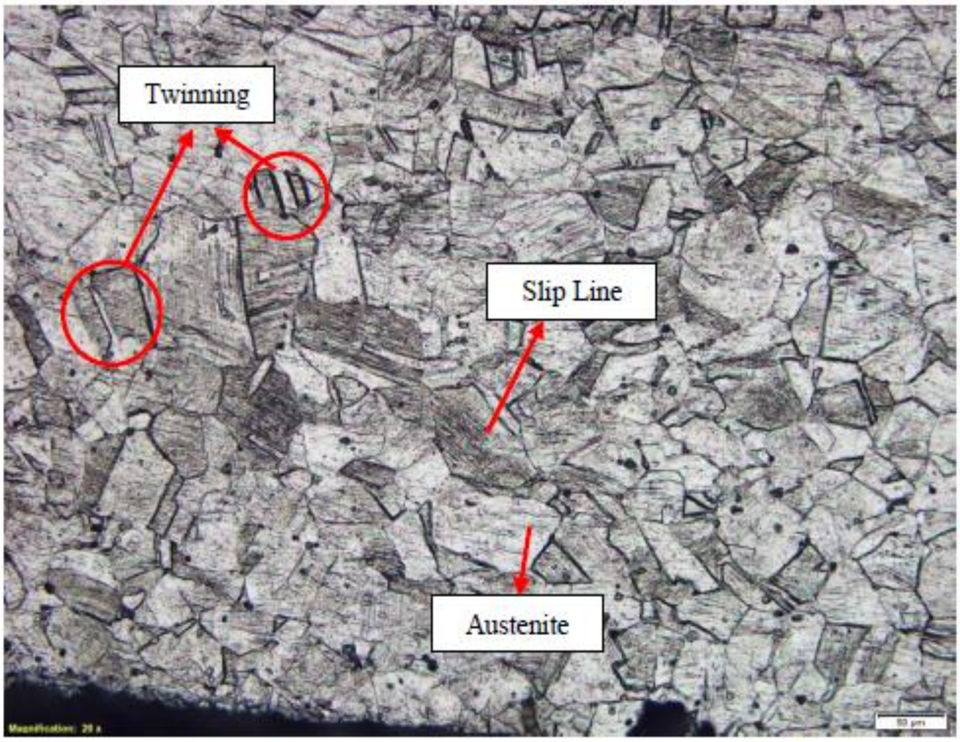

Figure 3.7 Microstructure with full annealing and repetitive hammering 60 times

3.4.5 Microstructure with full annealing treatment and repetitive hammering 90 times

Figure 3.8 displays the microstructure of the specimen that underwent full annealing at 1050°C, cooled inside the furnace to room temperature, followed by repetitive hammering with 90 strikes. The resulting microstructure reveals a higher density of deformation twins and a reduction in visible slip lines, indicating a shift in the dominant deformation mechanism. As deformation increases, the ability of the material to accommodate further strain via dislocation slip becomes more limited. Consequently, twinning becomes a more favorable deformation mechanism, particularly in low stacking fault energy (SFE) austenitic steels such as AISI 316.

Twinning is known to impede dislocation movement by acting as physical barriers, thereby increasing the resistance to plastic flow. This phenomenon enhances the strain-hardening capability of the material and improves mechanical properties such as strength and toughness. According to Allain et al. (2004), the number and thickness of deformation twins increase with plastic strain, and they contribute significantly to the flow stress by promoting dynamic Hall–Petch strengthening [12]. Moreover, the simultaneous presence of slip and twinning in the microstructure, albeit with fewer slip lines than in previous stages (30 and 60 blows), indicates a complex interaction between deformation modes at higher strains. As noted by Meyers et al. (2001), the transition to twinning-dominated behavior occurs as dislocation activity becomes saturated, necessitating alternative strain-accommodation mechanisms [13].

The refinement of the microstructure due to twinning and accumulated strain energy suggests that the material has reached a state of advanced strain hardening, where twin boundaries serve as new internal barriers. This condition results in an overall increase in yield and tensile strength, consistent with experimental results from mechanical testing. The observed microstructure is typical of work-hardened austenitic stainless steels subjected to high-strain deformation.

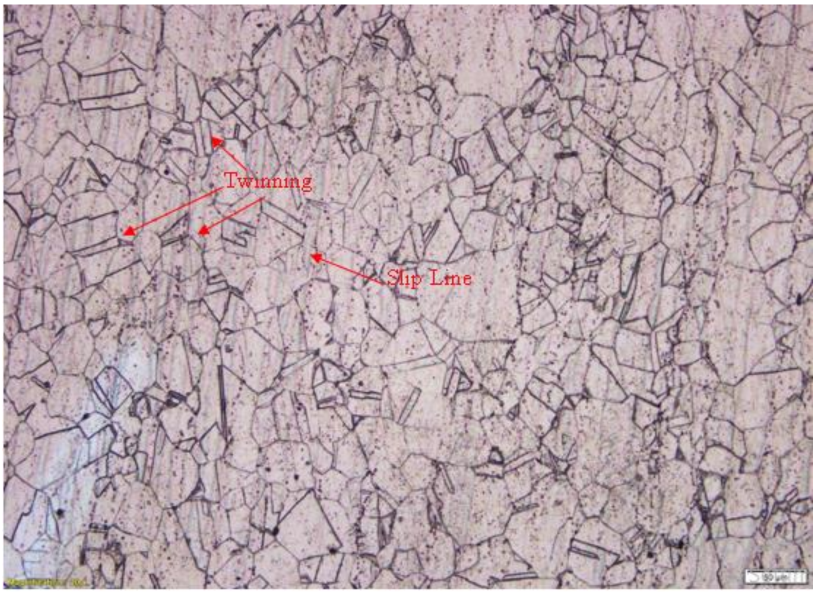

Figure 3.8 Microstructure with full annealing and repetitive hammering 90 times

4. Conclusion

The full annealing process at 1050 °C significantly reduced the hardness of AISI 316 from 269.3 HV to 165.2 HV by eliminating dislocations, relieving residual stresses, and producing more uniform grain structures, thereby enhancing the material’s ductility. Repetitive hammering after annealing resulted in microstructural evolution characterized by a combination of slip and twinning mechanisms at the early stage (30 blows), intensification of slip and twinning at intermediate strain (60 blows), and a predominance of twinning at high strain levels (90 blows). These microstructural changes contributed to the subsequent increase in hardness and tensile strength due to the strain hardening effect, while still maintaining a degree of ductility. The combination of heat treatment and repetitive plastic deformation can thus be employed to tailor the mechanical properties of austenitic stainless steel to meet specific application requirements.

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