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Influence Study of the Antimony Element Sb on the Tribological and Mechanical characteristics of the Al-11% Si Alloy

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ABSTRACT

Aluminum alloys are widely used in various industrial applications due to their low weight and favorable mechanical properties. Consequently, extensive research has been conducted to further enhance these properties. In this study, the Al-11%Si alloy was modified by adding varying amounts of antimony (Sb) metal powder: (0.05, 0.1, 0.2, 0.3, and 0.4 wt %), to enhance the mechanical characteristics including the tribological and tensile behavior. The mechanical properties of the modified alloys were thoroughly evaluated. The optimal mechanical performance was achieved with the addition of 0.3% and 0.4% Sb. The casting process involved melting a measured amount of the Al-11%Si alloy at 720 °C in an electric furnace. Antimony powder was then introduced into the melt, which was stirred at 250 r.p.m. for 5 minutes at three stages to form a vortex and ensure uniform dispersion of the modifier. The melt temperature was carefully monitored and controlled using a thermocouple before being poured into a carbon steel mold. Several tests were conducted on the modified alloys, including microstructural analysis, hardness, tensile strength, surface roughness, and wear resistance assessments. The addition of the antimony element (Sb) was found to significantly refine the microstructure and transform the morphology of silicon particles from a flake-like or lamellar form to a more fibrous structure. Furthermore, Sb additions of 0.05%, 0.1%, and 0.2% wt improved micro hardness (Hv), yield strength (YS), and ultimate tensile strength (UTS), while simultaneously reducing surface roughness (Ra) and wear-rate (Wr).

1. Introduction

Aluminum-silicon (Al/Si) alloys are attractive materials in the mechanical, aerospace, motorizes and industries, primarily due to their energy efficiency, light weight, wear-resistant, and thermal conductivity behavior. These latter characteristics are precisely why collecting data on the wear and friction properties of these materials is significant [1]. Several manufacture requests, such as the wear-resistant environments and locomotive manufacturing, are of interest to super-eutectic aluminum-silicon alloys. On the other indicator,

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these alloys have few drawbacks [2]. The demand for lightweight, high-performance structural materials has made Aluminum–Silicon alloys pretty candidates for the locomotive, aerospace, and consumer product industries, leading to the development and emergence of Aluminum–Silicon alloy-based metal alloy composites [3, 4].

The commercial importance of aluminum-silicon (Al/Si) alloys lies in their low shrinkage and high fluidity in casting and welding applications, as well as their good corrosion resistance and high specific strength. These alloys are increasingly used in locomotive applications to reduce weight and improve fuel economy. Eutectic Aluminum-Silicon alloys have exceptional casta-bility and wear resistance and are suitable for the manufacture of pistons and other critical components [5],[6]. Ultra-eutectic aluminum-silicon alloys are commonly used in the engineering applications due to their wear-corrosion resistance, low coefficient of thermal-expansion, high specific-strength, and cast-ability. Ultra-eutectic aluminum-silicon alloys are increasingly being used as an alternative to gray-cast iron in locomotive components, such as pistons, brake discs and cylinder heads. The size, shape and distribution of the principal and eutectic phases of silicon are related to the mechanical behaviors results of super-eutectic Aluminum-Silicon alloys [7].

Hardness can be improved by reinforcing silicon (Si) particles, that enhance the tribology properties of aluminum-silicon alloys. These alloys are increasingly used due to their numerous requests in automobiles, such as compressor-switches, pistons, engine-blocks, cylinder-liners and various other engineering fields [8]. Further enhancement in the mechanical-behaviors of aluminum-silicon alloys can be attained through modification treatments with antimony, sodium, and strontium [9,10]. By adding sodium, strontium, or antimony (Sb) modifiers to aluminum-silicon alloys, the silicon particle shape changes from a coarse needle-shaped to a fibrous or lamellar shape, which enhances the mechanical properties [11]. Upon addition of modifying elements such as Sb and other, the eutectic-silicon phase becomes a very fine and fibrous silicon network which further improves the mechanical of the alloys [9,10].

In order to successfully develop and apply aluminum alloy manufactures, the microstructural factors such as form, grain size, bushing arm spacing, and distribution of principal and secondary phases, which directly affect the mechanical and tribological performance of the materials, must be effectively well-ordered by adding some important alloying elements such as antimony element Sb and others [12], [13], [15].

The main friction coefficients governing the friction and wear behavior of reinforced aluminum composites can be generally classified into two groups: mechanical/physical factors and material-related factors [14, 16]. Detailed tribological analyses, which include variations in mechanical and physical parameters—such as sliding velocity and vertical load—have shown that increasing the reinforcement content raises the transition load to severe wear. Among material factors, the volume partition of strengthening has the greatest impact on wear opposition, a result well documented in scientific studies. However, corrosion rate variations in aluminum and silicon alloys, as a function of volume partition, are also influenced by the shape and size of the reinforcement particles [17, 18, 19]. In this effort, the characteristics of a amended Aluminum-Silicon alloy (11%) were investigated. various proportions of antimony (Sb) were added to investigate its influence as a reformer on its tribological and tensile mechanical properties.

The tribological properties of these alloys depend on a number of mechanical behaviors associated with the material (such as hardness, roughness, and corrosion), as well as the microstructure (size, shape, type, composition, and distribution of microscopic components).
[20], [21], [22], [23], in addition to the service conditions such as load, sliding speed, temperature, environment and counter face [24], [25],[26]. Tensile tests refer to any method which involves loading a specimen in uniaxial tension until failure , where tensile-test is one in which a force is supplied to sample of a Aluminum-11% Silicon alloy in increases and the corresponding extension of the specimen noted [27]. Several mechanical properties can be evaluated from tensile-tests including the yield strength YS, ultimate tensile strength UTS, total elongation, and reduction in cross-sectional area. A general set of practices for conducting tensile tests is provided by ASTM Standard [28], [29], [30].

Therefore, this study aims to evaluate the effect of antimony Sb element on aluminum -11 % silicon alloy by evaluating the tribology properties, tensile and deformation behavior of Aluminum-silicon alloys at ambient temperature. The impact of this metal (Sb) on the mechanical behavior of the used Aluminum -11% Silicon alloy was discussed. Based on the derived results, hardness, roughness, wear, stress-strain curves were plotted, and the values of YS, UTS, elongation to failure, and strain hardening exponent were attained. For this purpose, all samples were evaluated at different addition ratios from 0.05% to 4% . Based on the data obtained from the tests, the curves were plotted, and the values of these properties were obtained.

According to previous studies, a study by Farahany et al. [31] revealed that the addition of Antimony Sb and Bi can modify eutectic silicon into a micro-flake form. Instead of a fibrous or coral-like form, eutectic silicon typically forms lamellar upon the addition of Antimony, reducing porosity in castings. Thus, the addition of both Sb and Bi offers opportunities to improve the request characteristics of silicon-aluminum alloys [32]. According to a study by Flores et al. [33], the addition of antimony Sb encourages microstructural vagaries in Aluminum-Silicon 319 alloys, resulting in Eutectic-Silicon appearing in a lamellar form. Based on the results of these studies, the influence of antimony on morphological modification of silicon may be associated to a alteration in the silicon growth pattern. The existence of intermetallic Al and Sb particles in frequent contact with eutectic silicon may induce silicon nucleation, which is triggered by this intermetallic phase. This leads to improved mechanical properties of the alloy due to the microscopic modification of eutectic silicon. The results of these studies showed a relative enhancement in ultimate tensile strength UTS from approximately 185 MPa to 195 MPa, elongation to failure from 1.5% to 3%, and Brinell-hardness values from 77 HB to 84 HB with an increase in Sb content of up to 0.25%.

Extra-study by Medlin and Bolibruchova [34] demonstrated the modification of the mechanical and microstructure characteristics of 319 aluminum alloy used in cylinder head production through the effect of added Antimony. The amendment method was carried out using Antimony element Sb as the main alloy (Al-10% Sb). According to the study results, the ultimate tensile strength point UTS reached its highest rate, 229 MPa, with a maximum elongation of 1.5% for the antimony-modified alloys. antimony was found to change the shape of the Eutectic-Silicon from imperfectly round to perfectly round, improving mechanical properties. Therefore, alloying elements are important factors in modifying the mechanical properties of alloys. The addition of both Bi and Sb offers opportunities for improvement and deserves further study to enhance the application properties of aluminum-silicon alloys. In fact, there are other alloying elements in addition to antimony that act as modifiers. As indicated by previous studies, strontium (Sr) and sodium (Na) function as effective modifying elements [35-38].

2. Experimental System

2.1. Specimen Provision Procedures

A commercial-eutectic alloy Aluminum-Silicon, known for its excellent bearing features, low factor of thermal expansion and high fluidity was used as the base alloy in this study. These types of alloys are commonly employed in various industrial applications, particularly in the manufacturing of engine pistons. The chemical composition of the used alloy is showed in Table.1. In this work, the base alloy was subjected to a modification process, by adding various weight percentages of antimony element Sb% (0.05 %, 0.1 %, 0.2 %, 0.3 % and 0.4 %) in order to determine the optimum addition ratio that gives well-characteristics, through microscopic examination, hardness-test, wear rate-test, surface roughness-test and tensile-test. A deliberated quantity of the base alloy was melted at (720) °C in an electric furnace, after which Antimony-Powder (Sb) was carefully introduced using an appropriate technical procedure. The melt was agitated inside the furnace at (250) r.p.m for (5) minutes at three periods to make a vortex, ensuring uniform dispersion of the modifier antimony element Sb. The temperature was verified and monitored with a thermometer before the melt was poured into suitable mold a carbon steel mold.

Table .1 shows the chemical composition of the selected alloy

Si	Cu	Fe	Zn	Mg	Mn	Ti	Al	Sum.
11.2 01	0.93 1	0.84 2	0.71 5	0.44 7	0.18 5	0.01 78	85. 6	99.99 9

The specimens were equipped for main examinations. Initially, models were prepared for microstructural examination using grinding paper with different particle sizes (200, 400, 800, 1000, and 1200) Microns. The surface was then ground using polishing cloths and Al_2O_3 suspension. The surface was then etched with a suitable solution consisting of 0.5% HF and 99.5% water to obviously reveal the microstructures.

On the other hand, the micro-hardness values of each sample were deliberated, and three hardness measurements were performed for each sample, taking into account the average hardness of the sample, using a Vickers hardness tester for the selected samples. The Vickers hardness number was calculated using the following equ.1 [15]. The testing machine was supplied by the Department of Production and Metallurgical Engineering at the University of Technology.

$$Hv = 1.8544\ [L/(Dv)2] \quad (1)$$

where:

L : The applied load = 300 g

Dv : Middling diameter of the length of the two diagonals of a rhombus.

A pin-on-disc wear tester was used, featuring a carbon-steel disc with a hardness of 35 HRC and an average rotation speed of 510 rpm. The wear specimen prepared for testing was a cylindrical 10 mm in diameter and 20 mm in length. After placing the specimen in the designated position in the holder, it was ensured that the surface of the specimen was in proper contact with the steel disc before testing each specimen. The periodic calibration and maintenance are performed by grinding the disc in the contact area using 500- and 1000-micron sandpaper to maintain a consistent roughness level and cleaning the disc of any remnants from the previous test sample after each inspection. The wear-ratio (Wr) of the specimens was considered by determining the weight of each specimen before the start of the test (Wi), and then determining the weight after the test (Wf). The wear amounts were calculated in units of (cm3/cm3) as shown in the following equations (2) and (3). The specified relative error for measuring the test results was (0.0001 g). The applied test load and the sliding time used to evaluate the wear-ratio were (10) N and (15, 30, and 45) minutes, respectively.

$$\text{Wear-ratio}\,Wr = [Wi - Wf]/2\pi R n dpr T \quad (2)$$

$$\Delta W = Wi - Wf \quad (3)$$

where:

Wr : Wear-ratio (cm3/cm)

Wi: The weight of sample before the wear-test (gm).

Wf: The weight of sample after the wear-test (gm).

R : The distance from the center of the steel-disc to the sample-center (cm).

n : The cycle number for the steel-disc = 510 r.p.m.

dpr: The real density of the tested sample (gm/cm3).

T : The sliding period (min) = 20 minutes.

The cylindrical-tensile test bars were produced out of the directionally solidified rods and prepared according to ASTM-B557M-10 [10]. MICRO-Computer controlled universal testing Machine WDW 200E were used. A cylindrical tensile test sample was used about a diameter of 10 mm and a length of 100 mm , the geometry and dimensions of the specimen are presented in Fig. 1

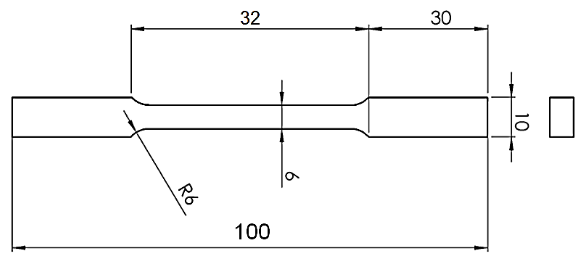

Figure .1 shows the geometry and measurements of the specimen tensile-test.

The Surface Roughness Examination, a roughness measurement instrument used of all samples treated is "Digital Surface Roughness Tester Pocket surf (Mahr)" . It is used to measure the average roughness (Ra) for the workspaces after and before addition of the Sb element. This instrument measures the roughness of required area by automatic scanning with fine needle and takes the average for all scanned areas.

3. Results and Discussion

3.1. Modified Micro-structure

The Figures 2 to 7 present the microscopic images of the unmodified and amended Aluminum-11% Silicon alloys microstructures. The morphology of the silicon-phase in Aluminum-Silicon alloys is influenced by factors such as the temperature gradient (G), the solidification front velocity (R), and the alloy's chemical composition. The addition of alloying elements increases the (G/R) ratio, which helps suppress constitutional undercooling of the aluminum phase by the silicon phase resulting in faceted silicon growth from the eutectic. In contrast, reformers like antimony element (Sb) reduce the G/R ratio, facilitating the refinement of the silicon phase and promoting better integration with the aluminum phase, as described by Guthy [39]. The Figures (2-7) illustrate the impact of antimony addition on the micro-structure of aluminum-silicon alloys. Increasing the antimony percentage from 0.05% to 0.4% reveals a finer microstructure. This is due to the influence of antimony in increasing the eutectic-concentration, resulting from the increased surface area of the silicon-phase, as well as the modification of eutectic-silicon from a flaky to a fibrous form. This behavior is attributed to the Impurity-Induced Twinning (I.I.T.) mechanism, whereby antimony atoms tend to adsorb at the growth interfaces of silicon during solidification. Such adsorption causes localized distortion of the silicon crystal lattice, promoting the formation of multiple twin planes within the crystal. As a result, the preferred directional growth of silicon flakes is suppressed, encouraging the development of a short, branched fibrous structure. Cumulative the % Sb to 0.3% and 0.4% resulted in a stable accuracy of the microstructure as shown in Figures (5,6 and 7). This behavior is attributed to the attainment of an optimal modification condition, in which the antimony content (Sb) is sufficient to induce effective twinning without causing the formation of undesirable secondary phases, in agreement with previous literature [40].

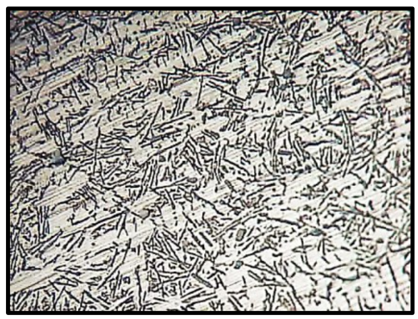

Figure. 2 shows the microscopic images of the unmodified Aluminum-11% Silicon alloys at 0 % Sb and 125 X

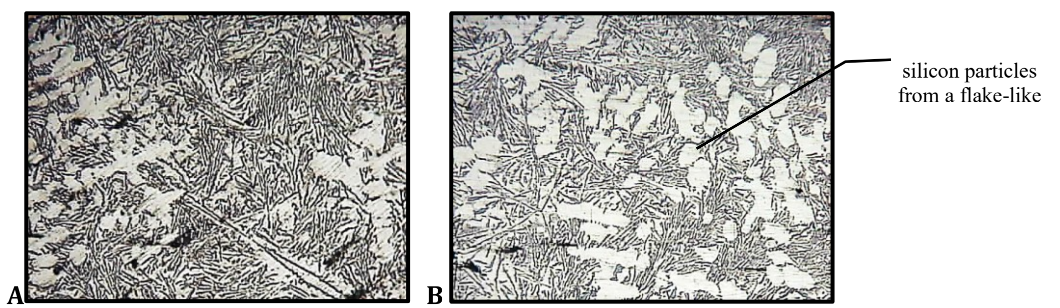

Figure. 3 shows the microscopic images of the amended Aluminum-11% Silicon Alloys, A: 0.05 % Sb at 125 X and B: 0.1 % Sb at 125 X

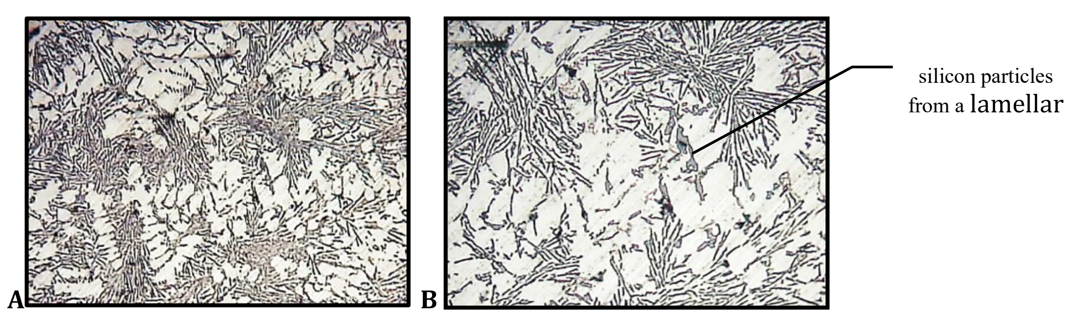

Figure. 4 shows the microscopic images of the amended Aluminum-11% Silicon alloys at 0.2 % Sb , **A**: at 125 X and **B**: at 250 X

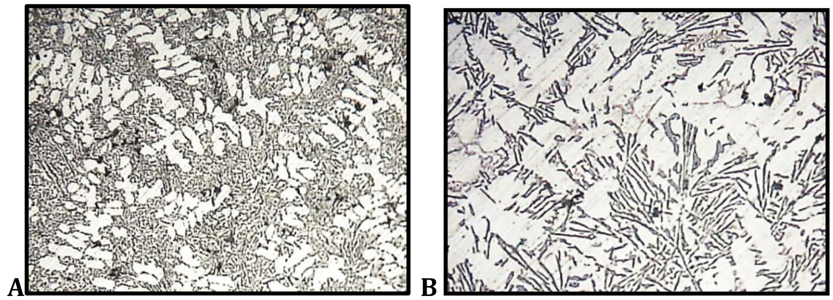

Figure.5 shows the microscopic images of the amended Aluminum-11% Silicon alloys at 0.3 % Sb, **A**: at 125 X and **B**: at 250 X

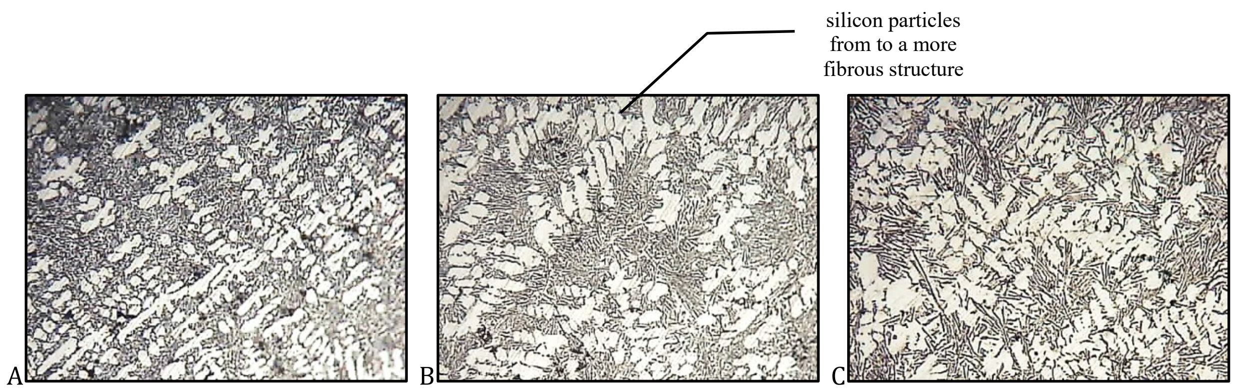

Figure. 6 shows the microscopic images of the amended Aluminum-11% Siliconalloys at 0.4 % Sb , A,B and C: at 125 X

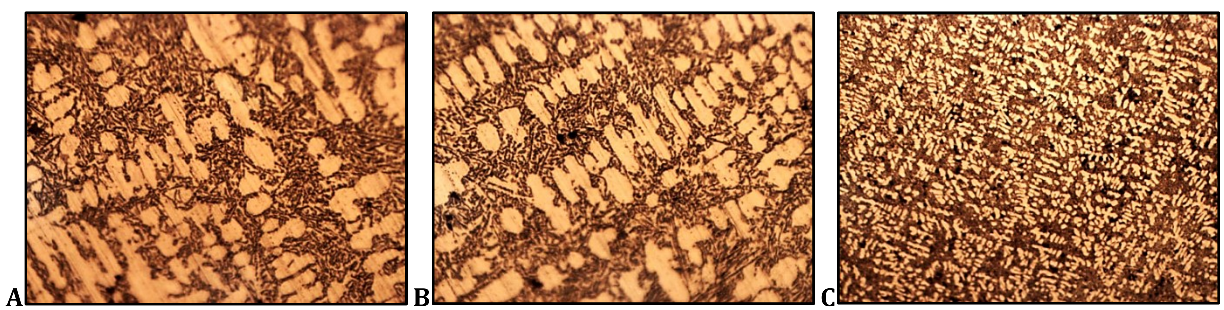

Figure.7 shows the microscopic images of the amended Aluminum-11% Silicon alloys at 0.4 % Sb , A and B: at 250 X and C: at 60 X

3.2. Micro-hardness Magnitude

Hardness is defined as a material's resistance to surface abrasion. Fig. 8 shows the hardness profiles of the samples after the modification process. As shown, the highest hardness values were recorded with the addition of 0.3% and 0.4% antimony. This improvement is attributed to the microstructure refinement, which reduces stress concentration around the faceted silicon in the second phase. This refinement results in the silicon transforming from a flaky to a fibrous form, improving mechanical properties. Furthermore, the added antimony element Sb, along with other alloying elements present, acts as a barrier to dislocation movement within the aluminum-silicon alloy used, contributing to the overall increase in mechanical characteristic.

3.3. Surface Roughness

Surface roughness is expressed as surface roughness rate (Ra) in unit μm. Fig.9 shows the change in surface roughness of the used alloy. The roughness test showed that when antimony element is added according to the proportions specified in this work (0.05%,0.1%,0.2%,0.3% and

0.4 %), the surface roughness increases significantly.

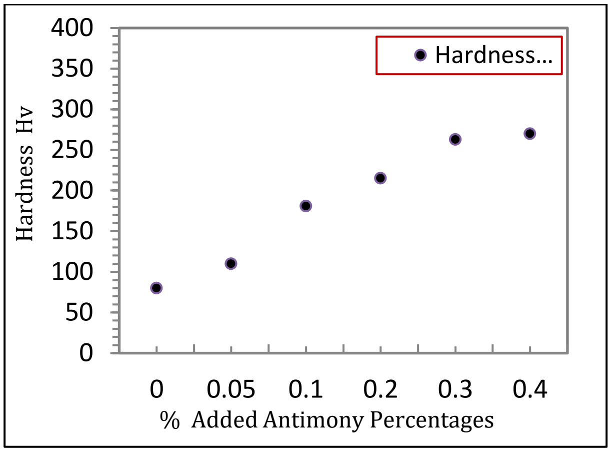

Figure. 8 illustrates the relationship between Vickers hardness and the amount of antimony added to the Al-11Si alloys.

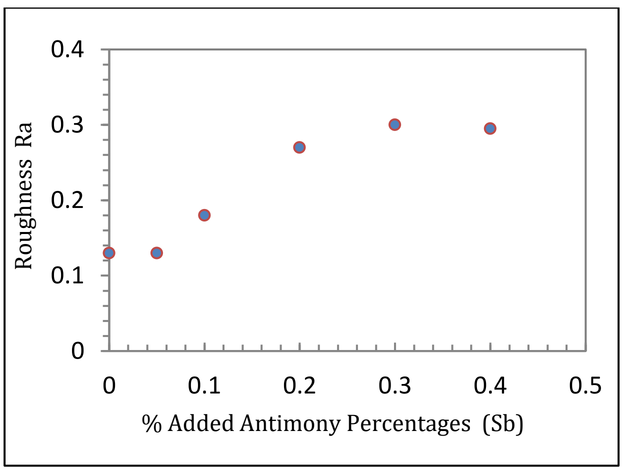

Figure. 9 shows how roughness (Ra) varies with antimony content in Al-11Si alloys.

3.4. Wear Rate

Figure (10) shows the relationship between the corrosion rate and the percentage of added antimony. From these figures, it can be seen that the wear-rate reduced with increasing antimony content, reaching lower levels compared to the basic alloys. This is due to further improvement in the micro-structure and positive hardness results, At antimony contents of 0.3 % and 0.4 %, the specimens exhibited the lowest wear rates under a constant 10 N load across durations of 15, 30, and 45 minutes. This enhanced wear performance correlates with improved mechanical properties—namely increased hardness and a refined microstructure due to antimony addition.

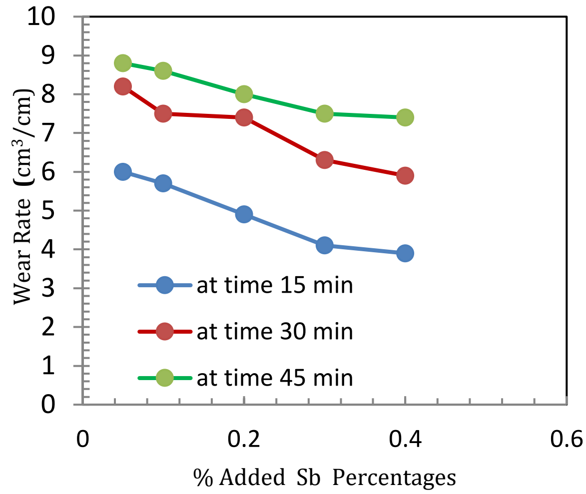

Figure. 10 shows the relationship between added Sb% and wear rate under a 10 N applied load.

3.5. Tensile Behavior

Alloying elements have varying amounts of influence on the mechanical properties of alloys depending on the amount and quality of addition of these alloying elements, and as shown in Figures 11,12 and 13, the behavior of mechanical characteristics (yield strength point YS, ultimate tensile strength point UTS and hardening exponent N) is observed, where the change in YS, UTS and N is observed for each selected class of antimony addition percentage on an aluminum-silicon alloy. This improved performance in mechanical properties during tensile testing is due to improved metallurgical characteristics, specifically increased hardness and improved microstructure, thanks to the addition of these specific proportions of antimony element Sb.

This effort highlights the tribology and mechanical behavioral of Al-11%Si alloy, which are important properties of aluminum-silicon alloys. However, there are other chemical physical and mechanical properties, and we suggest conducting a subsequent study to examine the effect of alloying elements on these properties.

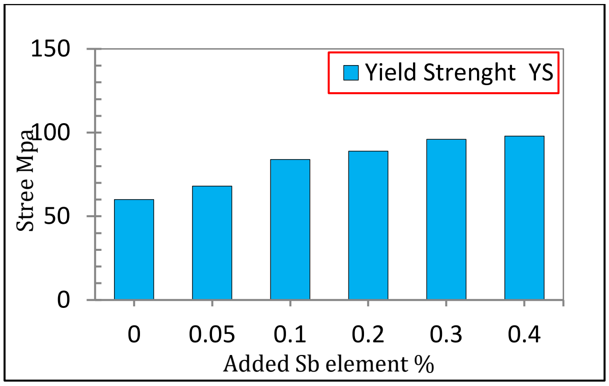

Figure. 11 shows how yield strength varies with added Sb% in the selected Al-11Si alloy.

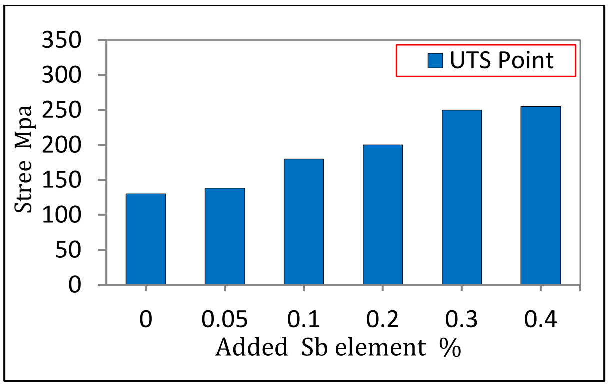

Figure. 12 shows how UTS changes with added Sb% in the selected Al-11Si alloy

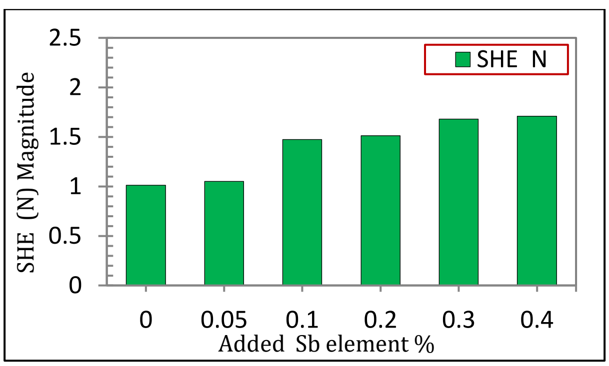

Figure. 13 shows how the strength hardening exponent (SHE) varies with added Sb% in the selected Al-11Si alloy

4. Conclusions

This study demonstrates that controlled antimony (Sb) modification is an effective approach for improving the overall performance of Aluminum–11%Silicon alloys. The findings indicate that (Sb) additions up to (0.4) wt.% play a critical role in altering the eutectic solidification behavior, leading to a refined and more stable micro-structure characterized by the transformation of eutectic-silicon from a Coarse Flake-Like morphology to a Fine-Fibrous form. This micro-structural modification represents the primary mechanism governing the observed improvements in material performance.

The refined eutectic structure significantly enhances the mechanical and tribological behavior of the alloy. Enhancements in hardness (Hv), tensile strength (T.S.), and wear resistance (Wr) are directly linked to the increased uniformity and stability of the modified micro-structure, which reduces stress concentration sites and promotes more homogeneous load distribution during mechanical loading and sliding conditions. Consequently, the alloy exhibits superior resistance to deformation and wear. From the perspective of applications and testing in this effort, the results indicate that the optimal antimony (Sb) content is between (0.3% - 0.4%) by weight. At this percentage, the alloy achieves an best balance between high tensile strength T.S. , improved hardness Hv, and enhanced tribological performance. These results highlight the potential of modifying antimony (Sb) alloys as a practical and effective strategy for improving aluminum and silicon alloys used in engineering components where mechanical integrity and corrosion resistance are critical factors.

Generally, the study provides meaningful insight into the role of antimony (Sb) as a permanent modifier and contributes to a better understanding of Composition–Microstructure–Property relationships in hypoeutectic-Aluminum-Silicon alloys, offering guidance for alloy design and industrial applications.

Nomenclature

YS yield strength
UTS ultimate tensile strength
Ra surface roughness
Wr wear-rate
Hv micro hardness

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Conflicts of Interest

There is no conflict of interest.

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