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The Relationship of Surface Roughness and Hardness of BiSn Solder Alloys due to the Variation of Sn Content

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Abstract: ***In the current research, we evaluated surface roughness and hardness of five BiSn alloys (20, 30, 40, 50 and 60% Sn) bearing in mind the effect of Sn content on such surface and mechanical properties. In the framework of the prepared samples characterization, SEM was utilized to interpret the relationship between the surface and the hardness properties.Tin-bismuth alloys could be an alternative to lead-based solders for low-temperature uses.However, very little is known abouttheir manufacturability and durability. This article focuses on the relation between the surface roughness and hardness for the prepared alloys.***

Keywords: surface roughness; hardness; BiSn alloys; SEM images

1. Introduction

Bismuth-tin alloys are widely used in many applications: for lapping thin film magnetic heads[1], anchor shafts in permanent magnet rotors, locator members in aircraft assembly fixtures, metal parts in glass, magnets in fixtures,cores for electroforming,potting electronic components and holding jet turbine ending blades for machining[2,3]. The alloys of bismuth with other easily fusible metals are of value in possessing remarkable low melting points although not possessing especially good mechanical properties. If we alloy bismuth (M. P. 270 °C) with lead (M. P. 327 °C) in suitable proportions we can get a eutectic mixture melting as low as 127 °C, far below the melting point of either pure metal. Similarly, if we alloy bismuth with tin (M. P. 232 °C) in the eutectic proportions, an alloy melting at 133 °C is obtained [3].Tin has a high ductility and can easily work. Plastic deformation does not produce any appreciable strain hardening.This is because ofrecrystallization temperature is below room temperature. Tin and its alloys may be separated into four general categories:

(1) Plain alloys
(2) Solders
(3) Babbits
(4) Special applications

The plain alloys of tin are as follows: pure tin is used mostly for electrowinning and in chemical compounds: straits tin and hard tin are used for foil and collapsible tubes. Straits tin is also used for the tin plate and pipe[4].

Tin-bismuth are promising alloys. They may be an alternative to lead-based solders for low-temperature applications. However, very little is known about their manufacturability and durability[5]. The Sn-Bi eutectic alloy nanoparticle formed from the tetragonal phase of tin and the rhombohedral phase of bismuth [6].

Thisarticle presents an attempt to find out the relationship of surface roughness and hardness of BiSn solder alloys due to the variation of Sn content. This is done by evaluating surface roughness and hardness of five BiSn alloys (20, 30, 40, 50 and 60% Sn). Surface roughness, often shortened to roughness, is a measure of the texture of a surface.It is quantified by the vertical deviations of a real surface from its ideal form. If these deviations are large, the surface is rough; if they are small the surface is smooth. Roughness is typically considered to be the high frequency, the short wavelength component of a measured surface.

Surface roughness plays an important factor in product quality. It is an essential character in many applications such as:micro-optics and mold parts. It is alsoconsidered as an important feature of practical engineering surface due to its direct influence on the mechanical and physical properties of a part in the machine [7]. In manufacturing roughness is undesirable, but is is expensive to control. Decreasing the roughness of a surface will usually increase exponentially its manufacturing costs. This main challenge between the manufacturing cost of a part and its performance in the application.

Surface roughness has a great attention for many years [8]. It has formulated an important design feature in many situations such as parts subject to fatigue loads, precision fits, fastener holes, and aesthetic requirements. Beside tolerances, surface roughness is one of the most critical

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constraints for the selection of machines and cutting parameters in process planning [9].Also, in order to determine the strength of a material hardness tests were used. The definition of the hardness can be regarded as the resistance of solids structures to permanent indentation or penetration.Changes in hardness are considered as the state of the setting reaction of a material [10]. In a previous study, effect of the Bi content on the mechanical properties of an Sn-Zn-Al-Bi Solder Alloy was observed [11].

The goal of this article is to focus on the variation of the roughness and hardness as a function of Sn content. Also to attempt to find acorrelation between the surface roughness and hardness for the five prepared alloys for the first time.

2. Experimental Work

$Bi_{80}Sn_{20}$, $Bi_{70}Sn_{30}$, $Bi_{60}Sn_{40}$, $Bi_{50}Sn_{50}$ and $Bi_{40}Sn_{60}$ alloys were prepared using tin and, bismuth with a purity better than 99.5 %. The alloys were melted in a muffle furnace .The productingotswere re-melted again in order to insure the homogeneity. These alloyswere prepared by single roller melt spinning technique with the aid of long ribbons of ~ 4 mmwidth and ~ 90 μm thicknesses., thewere cut into The final shape the samples was adopted for measurements by using double knife cuter.

It must be mentioned that, the phase diagram [12] (appeared in Figure 1) was considered during preparation of the samples understudy. Microstructure of used alloys was managed by usingShimadzu X-raydiffractometer, (Dx–30, Japan), Cu–Kα radiation with λ=1.54056 Å at 45 kV and 35 mA and Ni-filter, in the angular range 2θ ranging from 0 to 100° in continuous mode with a scan speed 5 deg/min and scanning electron microscope (JEOL JSM-6510LV, Japan).

It worth mentioning that, EDAX for the five samples, was done. This step is important in order to ensure the presence of the starting materials in the product samples without any impurities. However, to avoid the figures crowed we present one sample of the EDAX charts as appeared in Figure 2.

In the present work, we undertook two experiments. The first experiment has managedthe effects of variation of the Sn content on the surface roughness with the aid optical profiling system, manufactured by (Contour GT-K1, Bruker, Billerica, MA, USA).Figure 3 shows the used optical profiling system.As described in ASME B46.1 [13], the profiling system based on a technique of streamlined interface and intuitive workflow. Both white and green lightsinterferometry are available in this system. The profiling system, Figure 3, shows the three-dimensional surface measurements which range frommillimeter-scale to nanometer scale with sub-nanometer resolution. The easymeasurement setup with the fast data acquisition combination together withthe small footprint, allow the Contour GT-K1 to provide 3Dsurface metrology performance. In the present work, Ra is the average of five absolute values of the profile heightdeviations from the mean line, recorded within the evaluation length.The Ra valueswere taken as the arithmeticmean line calculated by theanalyzer. The five values were considered andrecordedfor each specimen at five differentlocations. In this way the roughness value wasrecorded.

Next experiment is the hardness which was done with the aid of a digital Vickers micro-hardness tester, (model: United Tru-Blue II/18USA) for the five prepared samples. The hardness testeris illustrated in Figure 4. Five indentationswere recorded for each specimen, and the micro hardness value was obtained as the average of thesefive readings.TheVickers hardness (HV) of BiSn samples were measured as recommended in ASTM E92-04 [14]. The measurements were conducted along the longitudinal planes of the samples.

One can sum up the experimental work as follows:-

- Preparation of the understudy five BiSn samples ($Bi_{80}Sn_{20}$, $Bi_{70}Sn_{30}$, $Bi_{60}Sn_{40}$, $Bi_{50}Sn_{50}$ and $Bi_{40}Sn_{60}$).
- Characterization the product samples with the aid of X-ray/EDAX and SEM analysis.
- Study surface roughness as a function of Sn content.
- Investigate hardness as a function of Sn content.
- Find co-relation between surface roughness and hardness.

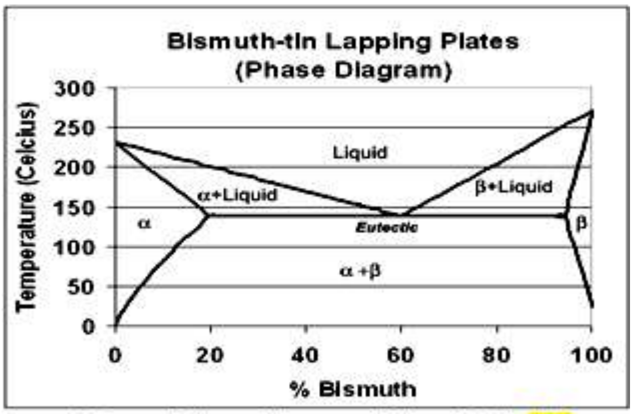

Figure 1: Phase diagram of Bismuth-Tin [**]

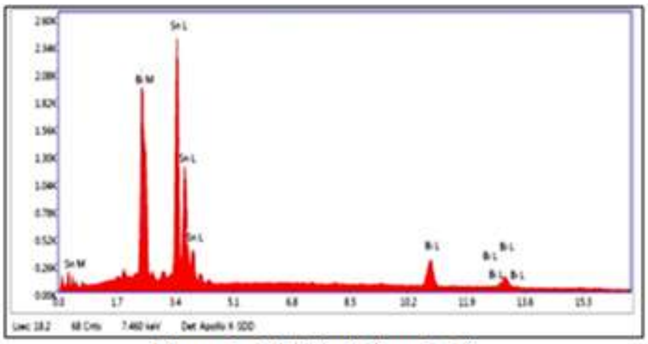

Figure 2: EDAX of Bismuth-Tin

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Figure 3: Profiler used for roughness work

Figure 4: Hardness tester

3. Results and discussion

In the present work; after characterizationof the five samples, we managed two experiments. First, the experimentwas done to determine the samples roughness and follow their variation due to the changein Sn content (from 20-60%).In the present paper, we spotlight on the effect of variation of Sn percentage on the alloys and their role played on the surface roughness. In order to do that and avoid the disputation reported earlier, we kept al the pre-mentioned parameters constant. In this way, the only observed variation of the roughness is argued to the effect of variation of Sn.

Variation of the surface roughness against the change in Sn content is depicted in Figure 5 in the form of histograms. The results indicate that the surface roughness decreases with the increase of Sn content till the percentage of Sn reaches 60% where it abruptly increases. According to Figure 5,the hardness values are dramatically increased.When Sn becomes 50%, the samples lose 50% of their roughness. The smallest values of surface roughness were obtained when the ratio between BiandSn becomes 1:1.

The highest value of R_a was obtained when the alloys contained Bi40% and Sn 60% *i.e.*$Bi_{40}Sn_{60}$.

It must be mentioned that thesurface roughness measurements were carried out at room temperature and were taken at five different adjacent placeson each sample to obtain the average value.Figure 6 supports the above-obtained data with the aid of the profiler texture images.

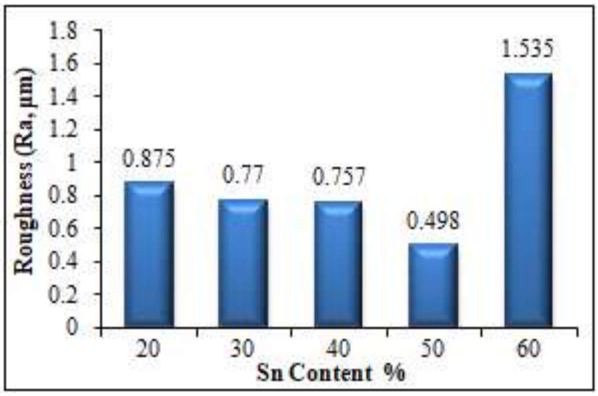
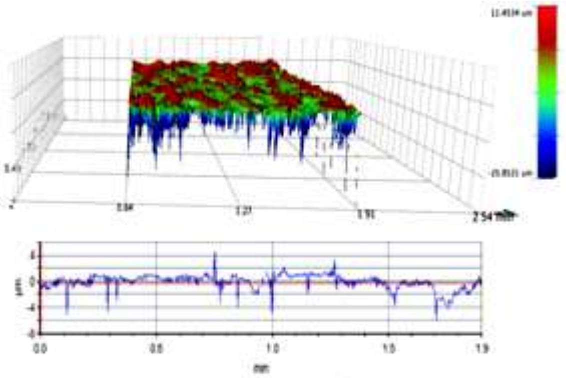
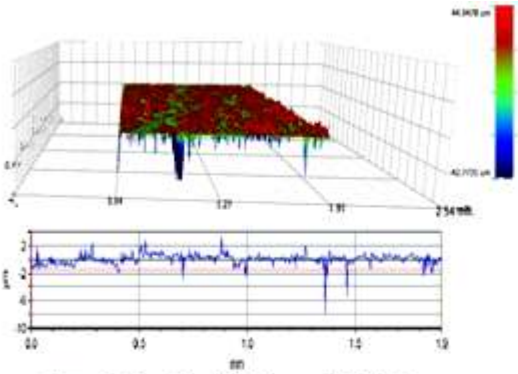


Figure 5: Variation of the roughness against the change in Sn content



Sample No. (2): 30% Sn and 70% Bi



Sample No. (1): 20% Sn and 80% Bi

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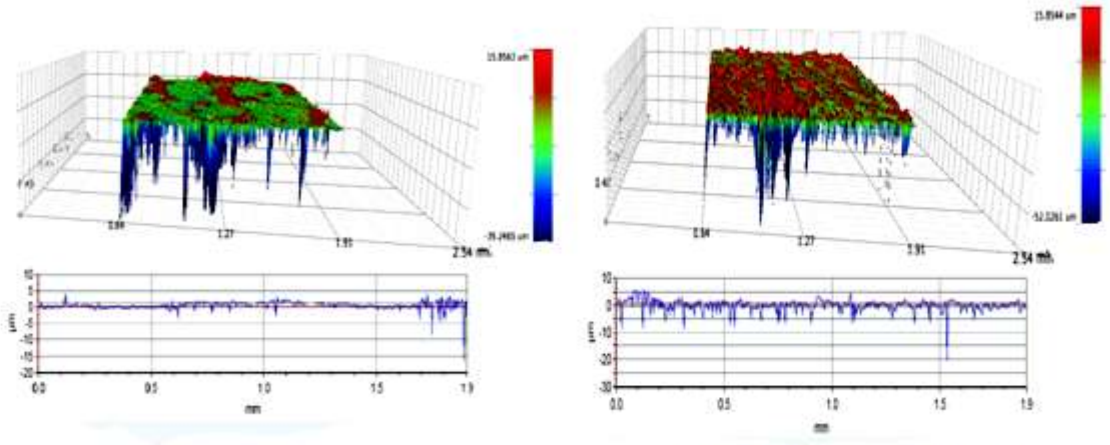
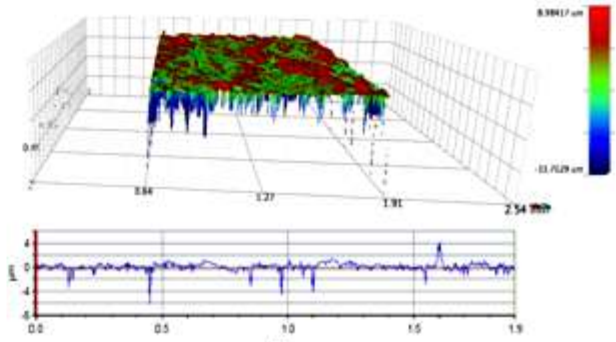


Sample No. (4): 50% Sn and 50% Bi

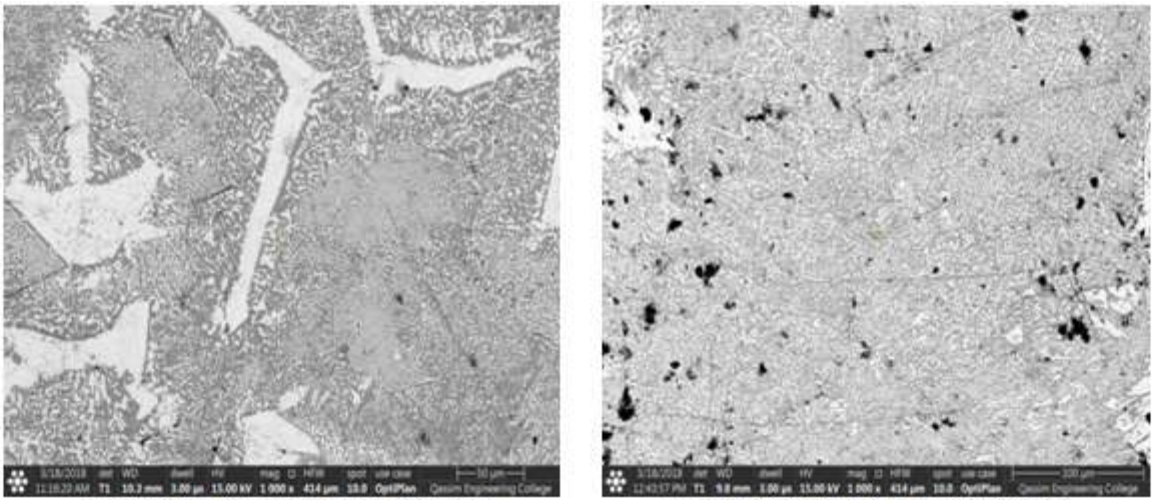
Sample No. (3): 40% Sn and 60% Bi



Sample No. (5): 60% Sn and 40% Bi

Figure 6: The profiler texture images for the five prepared samples

Now it is an established that the surface roughness changes as a result of the Sn content variation. This fact forces us to investigate the surface morphology of the five samples by means of the scanning electron microscopy (SEM). The results are indicated below in Figure 7.



Sample No. (1): 20% Sn and 80% Bi

Sample No. (2): 30% Sn and 70% Bi

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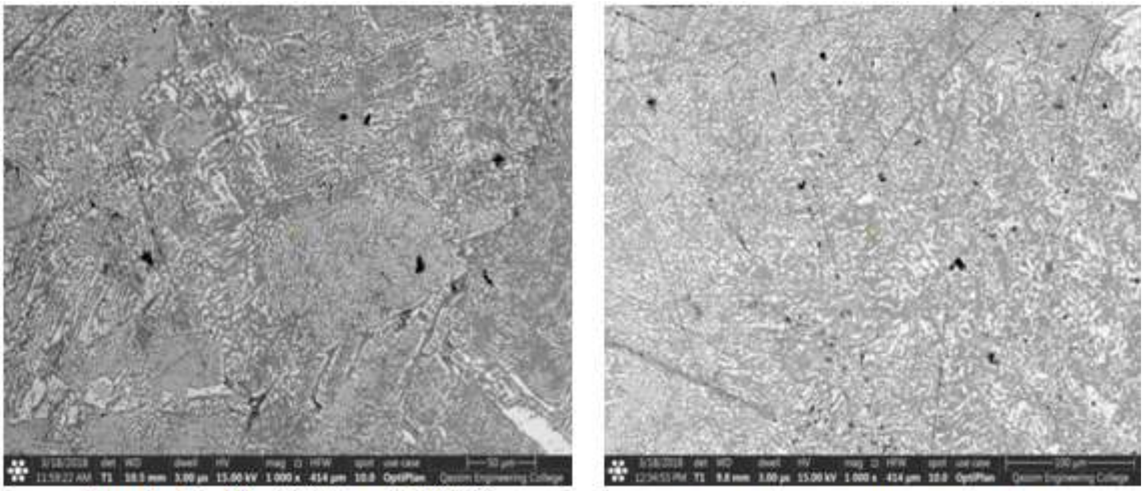
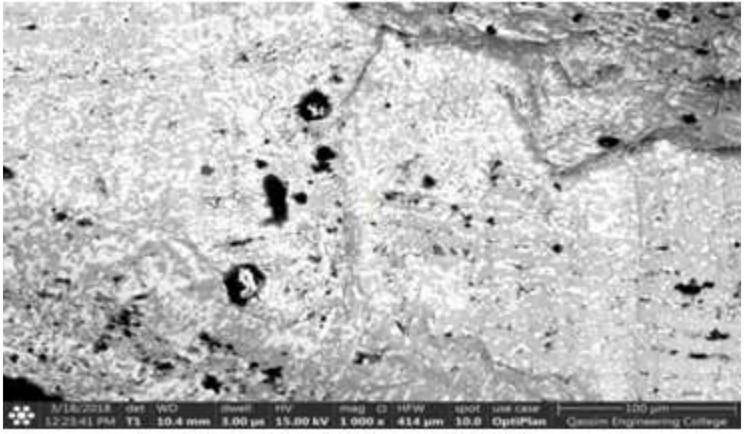


Sample No. (3): 40% Sn and 60% Bi

Sample No. (4): 50% Sn and 50% Bi



Sample No. (5): 60% Sn and 40% Bi

Figure 7: Scanning Electron Microscopy SEM for the five BiSn prepared samples

From the above microscopic images, we concluded the following:

- Figure 7 shows the presence of two types of structures: bismuth and tin phases exist in the BiSn alloys.
- Figure 7 reveals that bismuth grains, which have white color,are the major part of different size, shape, and orientations while the black color (large grain) represents tin as the minority.
- Figure 7 shows that the structures of the bismuth grains are lamellar while tin grains are of dendrite structure.
- This figure is helpful for the interpretation of figure 5 where surface roughness decreases with the increase in of Sn content. This can be understoodbecause it leads toa refinement grainsize with the increased homogeneity. This is acceptable if we considered the change of theaverage grain size in the five samples.
- Also, Figure 7 shows that the scanning electron micrograph of BiSn rapidly solidified alloy has a structure consisting of two phases, rhombohedra bismuth phase, and body-centered tin.

On the contrary to the $R_a$results, the hardness behavior, shows increasing the values monotonically up to a certain limit. This is indicated in Figure 8. As Sn increases from 20% to 50 %, samples become harder. However, when the alloys contain 60% Sn, they become less hard suddenly. The lowest hard sample is produced when the alloy contains 20% Sn. The hardest sample is that which contains 50% Sn. In addition, the results explained that the hardness was improved by the addition of Sn but until a certain limit.The increases of HV values after addition of Sn to 50% are regarded as a result of the generation ofdislocations. This is, in turn,increases dislocation density and formation of the ultrafine-grained structure.

For seeking of the relationship between hardness and surface roughness, we did a survey in the literature.A number of studies have investigated this relation and have dealt with the effects of the speed, feed, and depth of cut, nose radiusand others on the surface roughness.

The surface roughness and its relation with hardness models were developed by Wang and Feng [15], Grieve et al. [16], and Fischer and Elrod [17]. They concluded that the effect of cutting speed is insignificant. However, different conclusions were presented in work of Chandi-Ramani and Cook [18] Hasegawa et al. [19], Sundaram and Lambert [20], Miller et al. [21], Boothroyd and Knight[22].

Feng and Hu [23] examined the impact of working parameters on the surface roughness in their experiments. They showed that cutting speed had a significant impact on surface roughness.It is an established fact that fatigue life usually decreases as ductility decreases. Accordingly, BiSn might have a low resistance to thermomechanical fatigue.Pattanaik and Raman [24] showed that the tensile properties of BiSn alloys are dependent on strain rate and at low strain rates the solder becomes ductile. This result

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should be considered during thermomechanical fatigue applications [25].

The importance and significance of the pre-mentioned factors are in dispute.Carefullookto Figure 5, and Figure 8 reveals that the hardness is inversely proportional to the roughness. In this respect, we can interpret this situation by applying Taylor's equation [26].

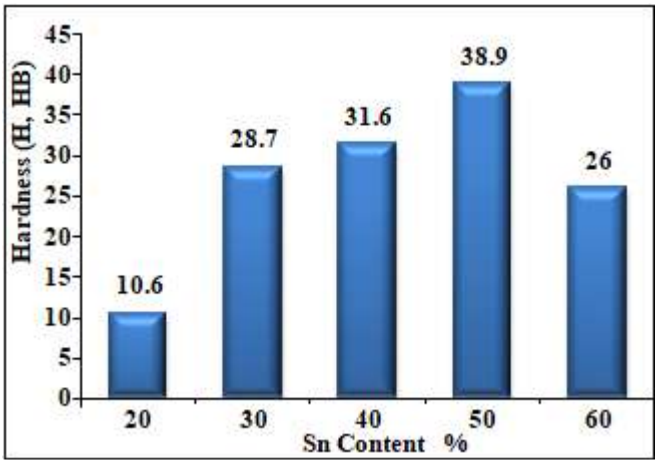

Figure 8: Variation of the hardness against the change in Sn content

TheTaylor's equation has the following form:

$$R_a=C*H^l*F^m*A^n*D^p*V^q*T^s \qquad (1)$$

Where:

R_a=surface roughness (the arithmetic average),
H = work piece hardness,
F =feed,
A =cutting tool point angle (180^0, major cutting edge angle–end cutting edge angle),
D =depth of cut,
V =cutting speed,
T =cutting time

A logarithmic formcan be used to convert Taylor's equation into the following linear form:

$$\text{Ln}R_a=\text{ln}C+l(\text{ln}H)+m(\text{ln}F) \qquad (2)$$

This equation can then be, in turn,simplified into the following linear mathematical formula:

$$\text{Ln}R_a=\text{Constant}\ (\text{ln}H) \qquad (3)$$

This was based on the fact that all parameters were held constant. Thisenabled us tostudy therelation between $R_a$and H as shown in Figure 9.

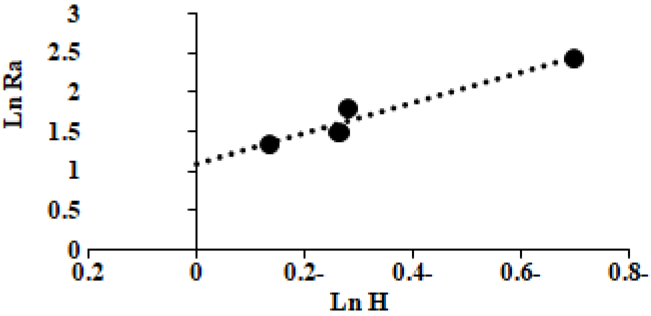

Figure 9: Relation between hardness and surface roughness

It is evident from the above figure that the relation between hardness and surface roughness is linear and justifies Taylor's equation entire the range of Sn variation from 20 to 50%. As for the sample when contain 60% Sn, it is evident from Figure 8 that is behaves in a different mode. Accordingly, it is avoided from Figure 9 to avoid the second expected mode of Taylors' equation (negative coefficient).

4. Conclusions

In the present study, the following conclusions can be drawn:

1) Different surface roughness and hardness values were obtained from BiSn Samples, and this finding is due to their different compositions.
2) The smoothest surfaces for all BiSnwere obtained when the BiSn contains 50%. ofSn.
3) While the roughest surface was obtained when the BiSn contains 60% of Sn.
4) The BiSn had the highest microhardness value 50% of Sn.
5) There is a clear correlation between surface roughness and hardness of BiSn.
6) Still, more experiments are necessary to study the effect of surface treatment (polishing, etching,…..) for changing the surface defects. This is, inturn, governs the surface roughness and hardness.

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