PREDICTION OF TENSILE MECHANICAL PROPERTIES OF TIN-BISMUTH ALLOYS BY VICKERS HARDNESS TEST

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in

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Atilim University

By

NURI ABURODESS ALSSID ALKILANI

JUNE 2018

PREDICTION OF TENSILE MECHANICAL PROPERTIES OF

TIN-BISMUTH ALLOYS BY VICKERS HARDNESS TEST

A THESIS SUBMITTED TO

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NURI ABURODESS ALSSID ALKILANI

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IN

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Approval of the Graduate School of Natural and Applied Sciences, Atılım University.

Prof.Dr. Ali Kara

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I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Prof. Dr. Engin S. Kılıç

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This is to certify that we have read the thesis "Prediction of Tensile Mechanical Properties of Tin-Bismuth Alloys by Vickers Hardness Test" submitted by "Nuri Alkilani" and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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ABSTRACT

PREDICTION OF TENSILE MECHANICAL PROPERTIES OF TIN-BISMUTH ALLOYS BY VICKERS HARDNESS TEST

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Mechanical properties under tensile are the most fundamentally used ones to predict the mechanical behavior of materials. However, the tensile test can be a cumbersome method concerning its bulky equipment, detailed sample preparation protocols and considerably high cost. Since there is a strong relation between hardness and tensile strength of the materials, there are some research studies aimed to establish a correlation between the tensile properties and hardness values of a material. In fact, hardness measurement is mostly a trivial process which can be performed without complicated protocols to get information about a material in an apparently cheap and fast way by using small-scale benchtop instruments. In this research work, we adopted similar approach to attain an analytical relationship between mechanical properties like tensile strength, yield strength, strain hardening exponent and strength coefficient of a low melting point alloy system, tin-bismuth (Sn-Bi) and their Vickers hardness numbers. This thesis covers a comparative analysis of data from hardness and tensile tests to develop a mathematical relationship that will predict the stress-strain behavior of these alloys, particularly eutectic. Hence four different compositions of the Sn-Bi alloys are used with Bi percentages such as 30%, 40%, 50% and 57% in this work. Tensile tests were performed at room temperature and their plastic regions up to UTS were analyzed to determine the aforementioned mechanical properties of the given alloy compositions. Concurrently hardness measurements were performed to obtain their Vickers hardness numbers. As a result, we determine a strong relationship between the tensile mechanical properties and the hardness of the Sn-Bi alloy and the established numeric model predicted most of the mechanical properties with a high statistical significance.

Keywords: Vickers hardness, tensile strength, strain hardening exponent, Tin, Bismuth, SnBi alloy

ÖZ

VICKERS SERTLİK ÖLÇÜMÜ İLE KALAY-BİZMUT ALAŞIMLARININ ÇEKME TİPİ MEKANİK ÖZELLİKLERİNİN TAHMİN EDİLMESİ

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Gerilim yüklemesi altındaki mekanik özellikler, malzemelerin mekanik davranışını tahmin etmek için en temel olarak kullanılanlardır. Bununla birlikte, çekme testi, yüksek teknoloji tabanlı ekipman, ayrıntılı numune hazırlama protokolleri ve oldukça yüksek maliyet gereksinimleri ile kompleks bir yöntemdir. Malzemelerin sertliği ve gerilme mukavemeti arasında güçlü bir ilişki olduğu için, literatürde bir malzemenin gerilme özellikleri ile sertlik değerleri arasında bir korelasyon kurmayı amaçlayan bazı araştırma çalışmaları vardır. Aslında, sertlik ölçümü çoğunlukla küçük ölçekli enstrümanlar kullanarak bir malzeme hakkında bilgiyi ucuz ve hızlı bir şekilde almak için karmaşık protokoller olmadan gerçekleştirilebilecek kolay bir süreçtir. Bu çalışmada, düşük erime noktalı alaşım bileşimi, kalay-bizmut (Sn-Bi) ve Vickers sertliklerinin gerilme mukavemeti, akma dayanımı, gerinim sertleşmesi katsayısı ve mukavemet sabiti gibi mekanik özellikler arasındaki analitik bir ilişkiyi elde etmek için benzer bir yaklaşım benimsenmiştir. Bu tez çalışması, bu alaşımların, özellikle ötektik bileşim için, mekanik davranışını tahmin edecek bir matematiksel ilişkiyi geliştirmek için, sertlik ve çekme deneylerinden elde edilen verilerin karşılaştırmalı bir analizini kapsamaktadır. Değişen Bi içeriğine sahip alaşımlar, bu çalışmada %30,%40,%50 ve%57 gibi Bi oranları ile kullanılmıştır. Çekme testleri oda sıcaklığında ve nihai gerilme mukavemetine kadar deforme edilerek gerçekleştirilmiş ve verilen alaşım bileşimlerinin yukarıda belirtilen mekanik özelliklerini belirlemek için analiz edilmiştir. Aynı zamanda Vickers sertlik sayılarını elde etmek için sertlik ölçümleri yapılmıştır. Sonuç olarak, gerilme mekanik özellikleri ile Sn-Bi alaşımının sertliği ve mekanik özelliklerin çoğunun istatistiksel olarak anlamlı olduğu yerleşik sayısal model arasında güçlü bir ilişki olduğunu tespit edilmiştir.

Anahtar Kelimeler: Vickers sertliği, çekme mukavemeti, gerinim sertleşmesi kaysayısı, kalay, bizmut, Kalay-Bizmut alaşımı

To My Family

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LIST OF ABBREVIATIONS

UTS	Ultimate Tensile strength
ΔL%	Percent Elongation
RA%	Reduction In Area
F	Load
F_y	load at yielding
$\boldsymbol{l_o}$	Gauge Length of the Specimen
w_0	Width of the Specimen
t_0	Thickness of the Specimen
σ_t	True Stress
σ_y	Yield Strength or Yield Point
σ_{uts}	Ultimate Tensile Strength
$\sigma_{fracture}$	Fracture Strength
A	Instantaneous Cross-Sectional Area of The Specimen.
A_o	Original Cross-Sectional Area of The Specimen.
σ_E	Engineering stress.
ϵ_E	Engineering strain.
E	Elastic Modulus
$\boldsymbol{l}$	Instantaneous Length
$\boldsymbol{\epsilon_T}$	True Strain
$\boldsymbol{\sigma}$	Flow Stress
K	Strength Index
n	Strain Hardening Exponent
HV	Hardness in Vickers Scale
R^2	Coefficient of Correlation

CHAPTER 1

1. OVERVIEW

The mechanical properties of the materials such as yield strength, ultimate tensile strength and elastic modulus are the important material parameters to understand the plastic deformation of materials during manufacturing and determine elastic loads that can handle under service conditions. Thus, there is a need to know these properties beforehand. Hence numerous mechanical characterization tests are used to determine their conformance to desired specifications. Today, in almost all metal manufacturing companies, engineers and designers use these characterization tests to prove, examine or develop the mechanical properties of the materials. The appropriate characterization test should imitate the stress conditions which the material is going to be subjected to. Uniaxial tensile test is the frequently used mechanical characterization test since most structural elements usually impose tensile loads on components. Additionally, hardness test can also be encountered in many manufacturing facilities especially to predict the wear resistance of the materials. Alternatively, it is also used to make a ballpark assumption about the strength of the materials since it is easy to use and simple to collect data.

1.1.Tensile Test

The investigation of the fundamental properties of the engineering materials, especially mechanical ones is necessary and important for the assembly, manufacturing, design and quality purposes. Such properties of the materials can be investigated by subjecting them to tests which simulate the conditions enforced on the material during manufacturing or mechanical challenges during its service lifespan [1]. Materials are being tested under loads which represent the service loading conditions like tension, compression, bending, and torsion and these tests are generally destructive in nature since they generally result with a fracture.

Elastic modulus, yield and ultimate strength of the materials determined by the tensile test are mainly used to help to classify the materials according to their mechanical properties. The ultimate tensile strength (UTS), yield strength or yield point (σ_y), modulus of elasticity (E), percent elongation ($\Delta L\%$) and reduction in area (RA%) are the most important data which are obtained from the stress-strain curve recorded during a uniaxial tensile test. Uniaxial tensile test data can also be used to find toughness, Poisson's ratio and resilience of the material as well.

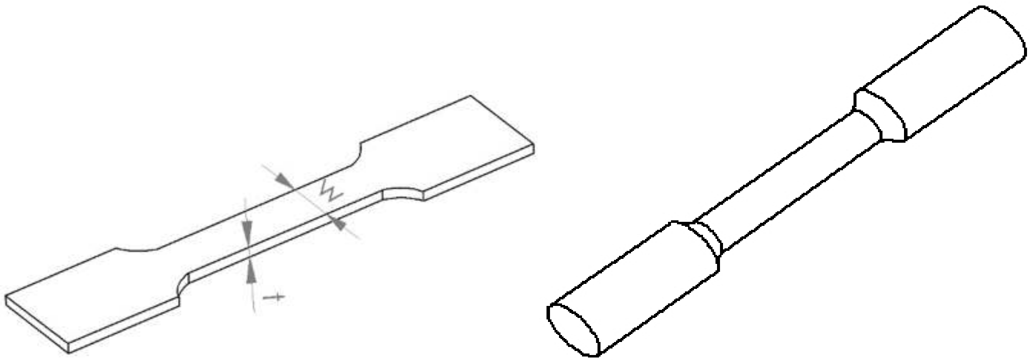


Figure 1. A Standard Tensile Test Specimen.

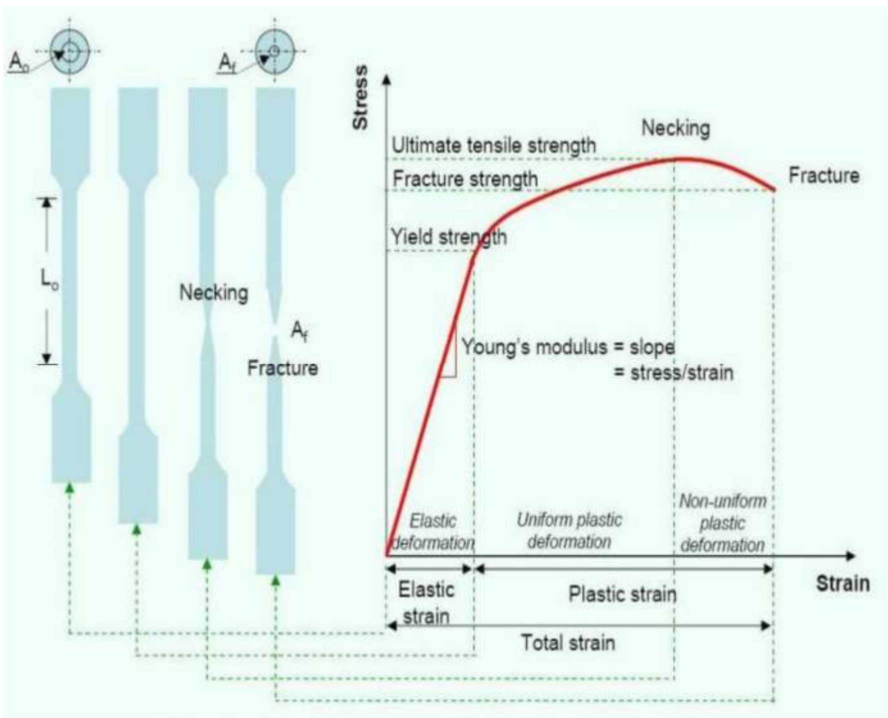


Figure 2. Deformation Pattern of a Ductile Specimen at Proceeding Stages of Loading as given by the Stress-Strain Curve on the Right. [2]

1.1.1. Types of tensile testing machines

Uniaxial test devices can be operated either by a mechanical screw or a hydraulic system (Figure 3) [2]. For the mechanical screw equipped systems, upward motion of the upper crosshead of the machine is provided by the motion of the two screws which in turn generates the load necessary to deform the specimen. On the other hand, hydraulic systems use an incompressible fluid such as oil which is pressurized by the motion of a piston. The pre-defined amounts of strains, loads or stroke rates can be determined by the combined action of actuator rod and piston which is controlled by a modern closed loop servo-hydraulic machine. The main parts of these two systems are shown in Figure 3. Both machines can be reconfigured to apply various loads like tension, compression, bending, and torsion to the specimen by rearranging the test apparatus according to the specific load. In addition, the modern uniaxial testing machines involve computer-controlled systems. Therefore, it is now possible to investigate the strain, stress, extension or other deformation parameters and work on them concurrently by using a software. Thus, these strength properties can now be easily determined by such commercially available software based on the force versus extension charts with the initially measured geometrical dimensions of the specimen compared to tedious analytical works used to be done traditionally. Hence, extension amount of the sample has to be measured strictly during the test which necessitates the use of an extensometer. The extensometer is a special device that measures the amount of elongation or contraction of the specimen length which is used for the calculation of strain. There are different types of extensometers. The most common type of the extensometer is called contact-type extensometer that touches the specimen during the deformation and the change in the arms of the extensometers is recorded. Nowadays, it is also possible to find extensometers which use optical means like laser to determine the amount of change in the longest dimension of the sample via digital image correlation technique

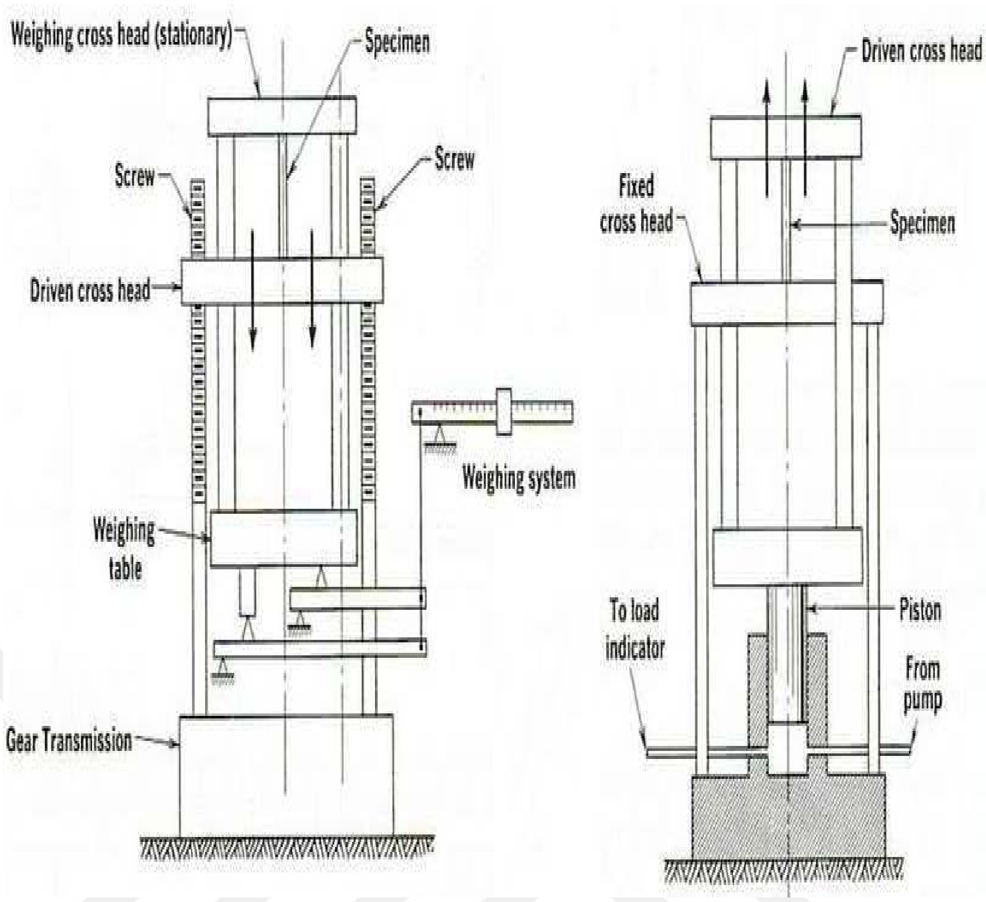


Figure 3. Schematics Showing of a Screw Driven Machine and a Hydraulic Testing Machine.

1.1.2. Engineering and True stress-strain curve

1.1.2.1. Engineering stress-strain curve

Uniaxial tensile test is broadly used to verify the strength of the materials and check their compliance with the given specifications. In the uniaxial tensile test, the specimen is being subjected to increasing tensile force along its longitudinal dimension while attached elongation recorders such as extensometers are taking the incremental extension value during the test [3].

Both elastic and plastic deformation behavior can be observed depending on the material during the tensile testing. At first, an elastic deformation where bonds between the atoms are stretched will occur until the yield stress of the material. Elastic deformation manifests as a linear relationship between the load and extension. After the yield stress of the material, deformation has plastic nature as well. Plastic deformation where the form of the material is changed permanently has a nonlinear character. Engineering strain and engineering stress can be readily calculated by the given equations 1.1 and 1.2 below:

$$\sigma_E = \frac{P}{A_0} \qquad \text{Eq.1.1}$$

$$\epsilon_E = \frac{l - l_0}{l_0} \qquad \text{Eq.1.2}$$

l_o is the original length of the specimen.

l is the final length of the specimen

P is the axial tensile load.

A_o is the original cross-sectional area of the specimen.

σ_E is the engineering stress.

ϵ_E is the engineering strain.

The applied force divided by the original cross-sectional area provides the engineering stress in units of Newton/m^2 or Pascal (Pa). An estimation is made on the strain component, as the ratio of the change in longitudinal axis length to the initial length which is the reference dimension for strain calculation. Though it seems quite simple, selection of reference area and length needs some care. Fixed reference quantities are employed to differentiate between the engineering stress and strain, primarily the initial cross-sectional area or initial length. Because of set values of the cross-sectional area and length of the specimen, while the loads are applied, these definitions hold true for the majority of the engineering applications. The engineering stress calculated using the above definition (as the ratio of the applied load to the unchanged cross-sectional area) seems to be an incorrect measure in such scenarios. As a result, substitute strain and stress measurement methods are accessible to conquer this problem. The lines that follow are devoted to the true stress and true strain discussion:

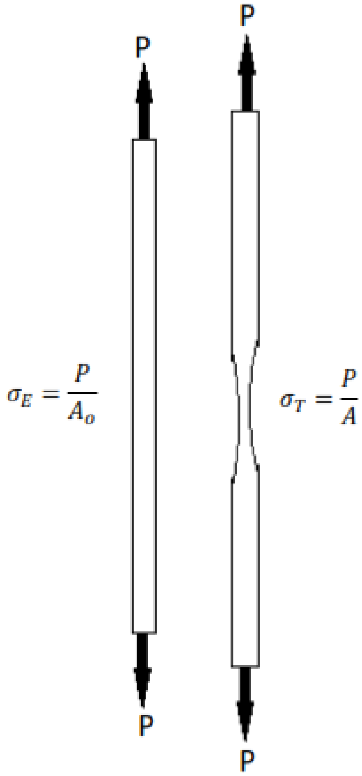


Figure 4. Engineering Stress vs. True Stress Measurement.

1.1.2.2. True stress-strain curve

True stress is defined as the ratio of the applied load to the instantaneous cross-sectional area. Since no volume change occurs for the specimen, there is a relationship between the true stress and the engineering stress [3]. Under such an assumption:

$$\sigma_T = \frac{P}{A} \quad \text{Eq.1.3}$$

where σ_T is True Stress, A is the reduced cross-sectional area of the specimen.

1.1.2.3. The relation between engineering and true stress

$$A.l = A_0.l_0 \quad \text{Eq.1.4}$$

$$\sigma_T = \frac{F}{A} = \frac{F}{A_0}.\frac{l}{l_0} = \sigma_E.(1 + \epsilon_E) \quad \text{Eq.1.5}$$

The increase rate in the instantaneous gauge length is defined as the true strain of the material.

$$True\ Strain\ \ \epsilon_T = \int_{l_0}^{l} \frac{dl}{l} = ln\left(\frac{l}{l_0}\right) \qquad \text{Eq.1.6}$$

The relation between engineering and true strain is:

$$\epsilon_T = ln\left(\frac{l+\Delta l}{l_0}\right) = ln\left(\frac{l}{l_0} + \frac{\Delta l}{l_0}\right) = ln(1+\epsilon_E) \qquad \text{Eq.1.7}$$

True stress and strain curve is same with the engineering stress and strain curve at small deformations in the elastic range as shown in Figure 5. However, the true stress will differentiate itself with values gradually higher than the engineering stress for large deformations in the plastic range due to the reduction in the instantaneous cross-section of the specimen.

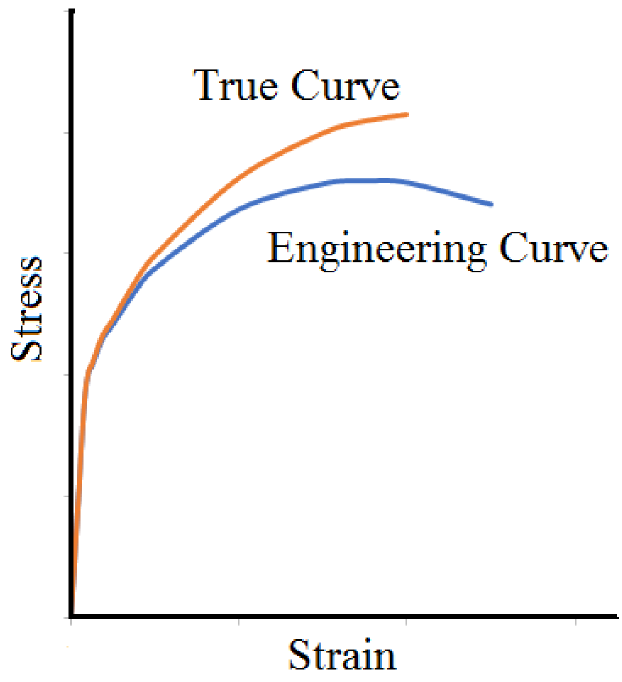


Figure 5. Engineering Stress-Strain Curve vs a True Stress-Strain Curve.

1.2. Tensile properties

1.2.1. Linear-elastic region

The linear-elastic region is observed until the stress value reaches to yield point of the material and the elastic deformation is recoverable after the unloading of the specimen.

In this region, the engineering stress-strain relationship can be defined by the Hooke's Law. In addition, the slope of this linear curve is denoted as the modulus of elasticity.

$$\text{Hooke's Law: } \sigma = Ee \qquad \text{Eq.1.8}$$

The slope of the stress-strain curve in the elastic region is denoted with E and it is specific for each type of the material.

1.2.2. Yield Strength

During the application of the force, yielding occurs when the elastic stress-strain relationship starts to become nonlinear. The yield point or the yield strength can be defined as the end of the elastic deformation and the beginning of the plastic deformation. The yield stress is found by dividing the force at yield by the original cross-sectional area of the tensile test specimen, which is shown in Equation 1.9.

$$\sigma_y = \frac{F_y}{A_0} \qquad \text{Eq.1.9}$$

The location of the yield point can be found directly from the stress-strain curve for almost all metallic materials. The yield point determination can be performed by sketching a linear line whose slope is equal to the elastic modulus of the material with an offset value of 0.2% strain from the original curve. The intersection point of the sketched linear offset line and stress-strain curve of the material is accepted as the yield strength of the material.

The yield strength is a very critical parameter to consider for both static and dynamic components when they are designed. Since plastic deformation is not desired for engineering structural designs during their service, there is a need to determine the yield strength of the materials correctly [4].

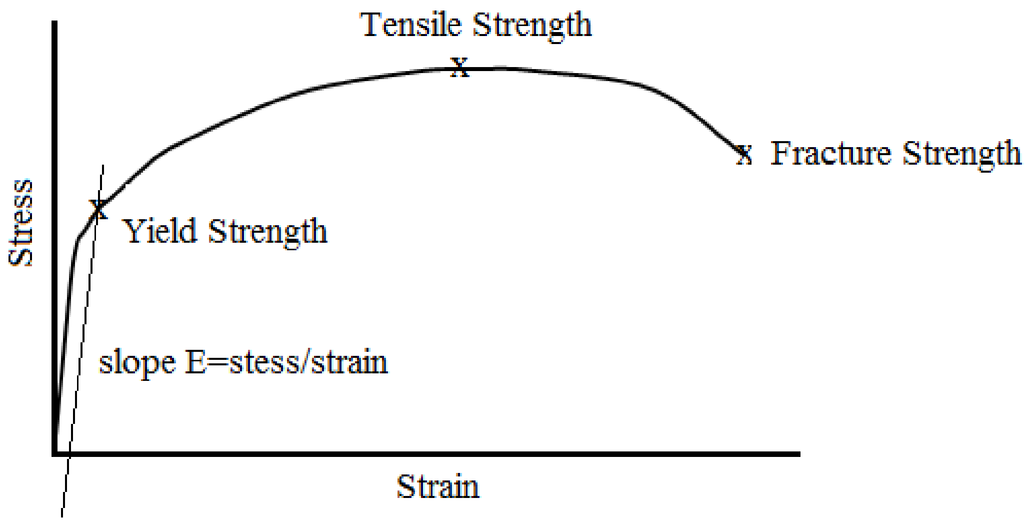


Figure 6. Engineering Stress-Strain Curve.

1.2.3. Ultimate tensile strength

After the yield point, the increase in the stress causes a permanent deformation on the specimen through continuous loading. For the materials that show the strain hardening or work hardening behavior, the stress value increases until a neck occurs in the specimen. When the maximum load is observed in the stress-strain curve, the specimen reaches the ultimate tensile strength (σ_{uts}) (equation 1.10). The increase in the stress is a result of the reduction in the cross-sectional area of the specimen, usually observed in the gauge length of the material.

$$\sigma_{uts} = \frac{F_{max}}{A_0} \qquad \text{Eq.1.10}$$

1.2.4. Breaking Strength

When the necking is observed on the tensile test specimen, the uniaxial stress starts declining until the specimen breaks. The load at the breakage should be divided to original cross-sectional area A_0 as shown in the equation 1.11 to evaluate the fracture strength ($\sigma_{fracture}$). The corresponding strain at fracture strength is regarded as the fracture strain; ε. The fracture strain can be calculated by plotting a straight line at the beginning of the fracture point which is parallel to the linear region of the stress-strain curve.

$$\sigma_{fracture} = \frac{F_{fracture}}{A_0} \qquad \text{Eq.1.11}$$

1.2.5. Plastic Region with uniform deformation

The non-linear behavior following the yield stress in true stress-strain curve designates the plastic deformation region where the elastoplastic material goes through permanent shape change. Deformation up to UTS is uniform and needs to be characterized frequently since it is particularly important for manufacturing purposes. Strain hardening or work hardening describes the increase of stress necessary to continue deformation at any stage of plastic strain. Intensity of strain hardening which is symbolized as n and called strain hardening exponent in the simple power law relationship, called Holloman Equation is determined by the slope of the flow curve which is described by this equation [3].

$$\sigma = K\varepsilon^n \qquad \text{Eq.1.12}$$

Hardening parameters for metals (K and n) are usually determined using a log-log plot of true stress-strain curve which is developed by taking natural logarithm on both sides of the power-law equation as shown below:

$$\ln\sigma = \ln K + \text{n} \ln\varepsilon \qquad \text{Eq.1.13}$$

where K is the strength coefficient when strain equal to 1.0, and strain hardening exponent (n) is the slope of log-log curve.

This equation can be valid only from the beginning of plastic flow to the maximum load at which the specimen begins to neck down.

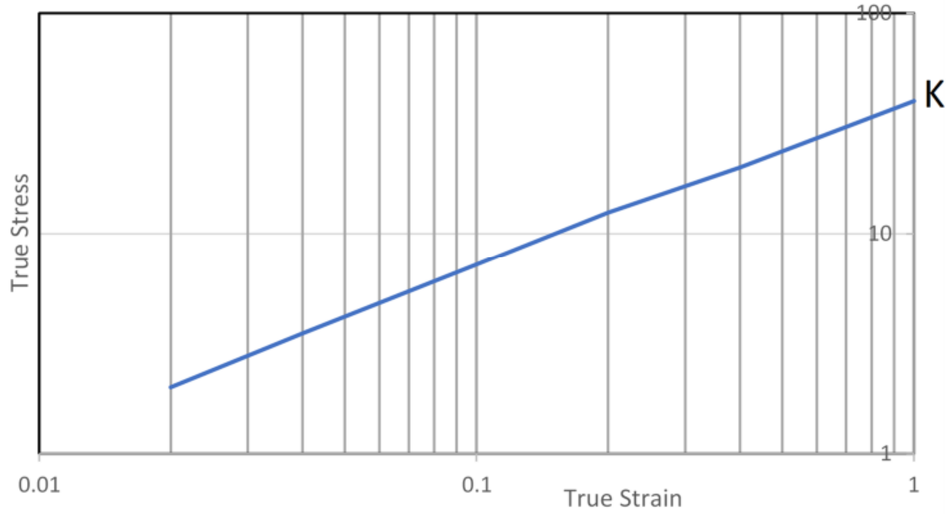


Figure 7. Log-log Plot of the Uniform Plastic Deformation Portion of a True Stress-Strain Curve.

1.3. The Hardness Test

1.3.1. Introduction

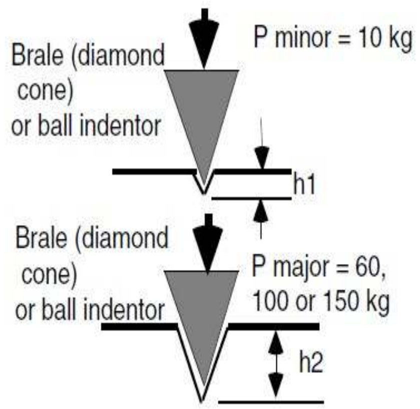
Materials' resistance to indentation is named as Hardness. In other words, it is the resistance to localized plastic deformation caused by a penetrator which is harder than the tested material. The resistance to indentation is also an indicator for scratch, abrasion or wear resistance. Though hardness is not a fundamental property of a material, it can relate to these properties since both uniaxial tensile test and hardness test give information about the strength of the material. Advantages of hardness test would be its ease to perform, simple instrumentation to use and its non-destructive nature.

Due to the ease of operation, hardness test is commonly used to have a ballpark idea about the strength of the most metallic materials. If suitable equipment and hardness scale are used, the given hardness number can be converted to other hardness scale numbers or to some of the mechanical properties of the material if an appropriate analytical relationship is established between each other.

All of the hardness scales cover the huge range of hardness from soft rubber to hard ceramic materials. There exists two main categories, macro and micro-hardness measurements depending on the amount of loading. In macro-hardness, the applied loads during the test is more than 1 kilogram. If the applied loads are 1 kilogram or below, it is called micro-hardness testing and the specimens for the micro-hardness test is very thin (down to 0.00125 mm). Micro-hardness measurements are mainly used for coated surfaces and surface hardened very thin parts [5].

1.3.2. Rockwell Hardness Test

The Rockwell hardness is a differential depth method measured from the permanent depth of the plastic deformation caused by the indenter tip. The specimen is being subjected to an intender force which is shown in Figure 8. The typical load for the intender is around 10 kg. The position of the indenter can be controlled with a sensor and when the equilibrium is reached, the indenter goes back to its original position.



Rockwell Scale (X =)	Indentor	Pmajor (kg)
A	Brale (diamond)	60
B	1/16" ball	100
C	Brale (diamond)	150
D	Brale (diamond)	100
E	1/8" ball	100
F	1/8" ball	60
M	1/4" ball	100
R	1/2" ball	60

$$HRX = R_X = M - \frac{(h_2 - h_1)}{0.002}$$

M = 100 for A, C, and D scales

M = 130 for B, E, M, R, etc. scales

Figure 8. Rockwell Principles

There are some important facts which should be taken into account during a Rockwell hardness test:

- The specimen thickness should be at least ten times greater than the depth of the indented area.
- For the curved surfaces, the hardness values can drop down.
- The distance between each indentation region for each repetition should be 3 to 5 times longer than the indentation diameter.
- The indenter and the anvil should be positioned perfectly and they should be cleaned before the test.
- The surface should be perfectly flat and perpendicular to the indenter.
- The speed of the indenter should be constant during the test.
- The specimen should not contain corroded surface and if there is any corrosion, it should be cleaned and surface should be smoothed.

1.3.3. The Brinell Hardness Test

In the Brinell hardness test method, the specimen is being subjected to an indenter load applied by a 10 mm hardened steel or carbide ball. The load applied by the indenter can be up to 3000 kg for hard metals and the load can be reduced down to 500 kg for softer materials. For the iron and steel, the minimum indentation time is around 10-15 seconds. However, if other materials are being tested, the minimum indentation time can be up to 30 seconds. The diameter of the impressed area is determined by an optical microscope. The diameter of the indentation is measured from at least two perpendicular directions d_1, and d_2 as shown in Figure 9 and averaged with a calibrated device. Then Brinell hardness number is determined by dividing the applied load by the impressed surface area according to the equation given below.

$$BH = \frac{P}{\frac{\pi D}{2}\left[D - \sqrt{D^2 - d^2}\right]} \qquad \text{Eq.1.14}$$

Where:

BH is the Brinell Hardness

D is the diameter of the ball [mm]

d is the average impression diameter of indentation [mm]

P is the test load (kg)

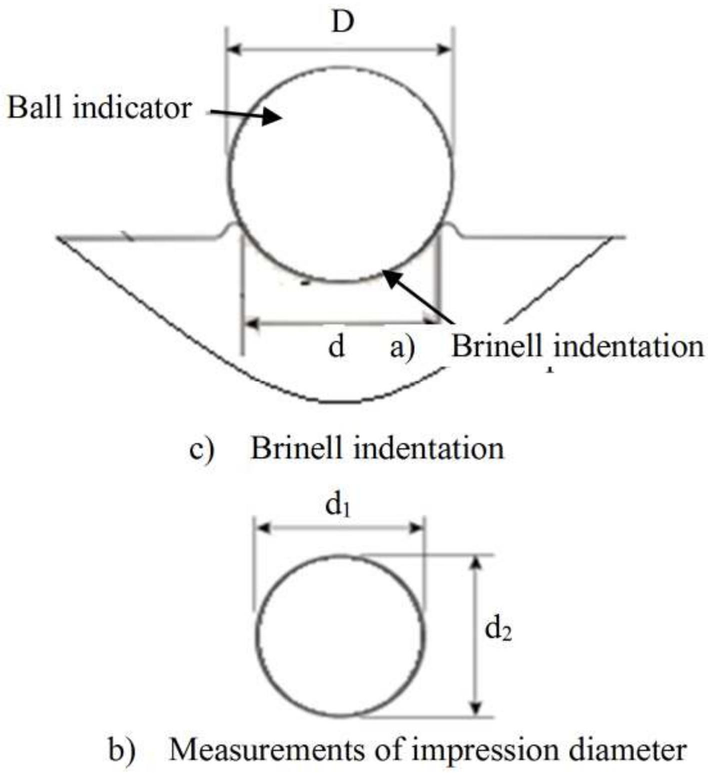


Figure 9. Brinell Principle

The hardness number table is an easy way to determine the Brinell Hardness. The Brinell hardness number should be structured well to give all necessary information for the measured hardness experiment. For instance, “75 HB 10/500/30” expresses that the hardness result is found to be 75 in Brinell Hardness scale by using an indenter which has a diameter of 10 mm hardened steel. In addition, “500/30” denotes the indentation load of 500 kilograms for a test time of 30 seconds.

When the specimen is considered as a hard metal, the indenter can be changed to tungsten-carbide option. The Brinell hardness indenter will be a good choice if the widest and deepest indentation amount is required. Since Brinell indenter imposes on multiple grains with deviations, results with higher precision can be obtained. If the macro hardness measurement is required, Brinell scale is the best option for heterogeneous microstructures.

1.3.4. Vickers Hardness Test

The main difference of the Vickers Hardness method from the other hardness measurement techniques is the square-based pyramid shape of its indenter with an angle of 136° among its opposing faces as shown in Figure 10. The typical load for this type of hardness is between 1 kg to 100 kg. 10 to 15 seconds is the usual indentation time during loading for Vickers hardness. When the indentation is finished, the indenter goes back to its original position. To get the Vickers hardness value, two diagonals of the indented area should be measured via microscope. Vickers hardness number can be calculated by dividing the load (kilogram) by the total area of the indentation (millimeter square) as given by the equations below.

$$HV = \frac{2F\sin\left(\frac{136^{o}}{2}\right)}{L^2} \qquad \text{Eq.1.15}$$

$$HV \approx 1.854\frac{F}{L^2} \qquad \text{Eq.1.16}$$

where

L = arithmetic mean of the two diagonals, L1 and L2, mm

F = applied load, kg

HV = Vickers hardness

θ = angle between opposite faces of diamond is 136°

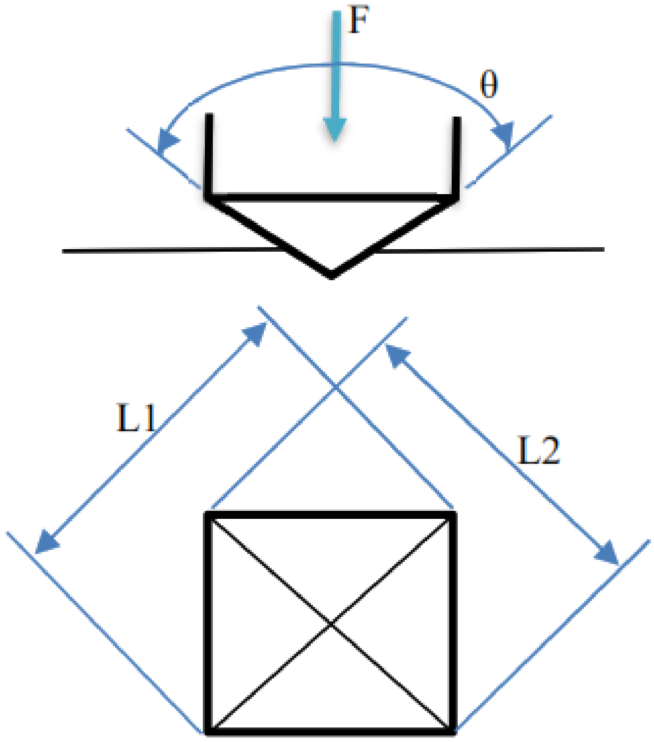


Figure 10. Vickers Principle

When the two diagonals of the indentation area is measured, the Vickers hardness can be readily evaluated with the given formula above. However, it is more convenient to use conversion tables. The Vickers measurement should be stated as “800GV/10”, which means that the hardness number in Vickers scale is 800 and this measurement is performed with 10 kilograms of force. The different loading settings might give the similar hardness results if the specimen has a uniform microstructure and thus it is more advantageous than changing the hardness scale. The main advantage of using the Vickers hardness method is its low standard deviation throughout measurements. In addition, there is no need to change the indenter tip for different types of metals or surfaces. The hardness of all metals can be measured with only one indenter in Vickers system. Yet this system is disadvantageous due to its high cost compared to the Rockwell and Brinell systems.

1.4. Relation between flow strength and hardness

The estimation of the yield strength and ultimate tensile strength of the materials with the simple test methods such as hardness test instead of uniaxial tensile testing is not new for researchers. Both tests can be used simultaneously to establish a valid correlation between hardness and strength values for particular metal and alloys so that hardness testing can be used as an eventual method to determine yield and ultimate tensile strength as well as strain hardening exponent and strength coefficient of the materials by a mathematical transformation. The general relationship between hardness and flow stress can be expressed by the following equation:

$$H = C.\sigma \qquad \text{Eq.1.17}$$

where H is the hardness value and σ is the uniaxial flow stress of the material. The "C" term is named the elastic constraint factor. Since deformation is local, plastic zone formed during indentation is enveloped with an elastic material which avoids the plastic flow of impressed region any further like in a closed die forging. Because of this elastic constraint, mean compressive stress to cause plastic flow during hardness measurement should be higher than the one needed for simple compression. According to slip-line field theory applied by Prandtl for plane-strain compression C was found to be 2.57. On the other hand the geometry of the Brinell test is not symmetric like plane strain condition. Shaw and DeSalvo [6] showed that plastic region under the indenter ball does not look like slip-line field. In fact it resembles an elastic-plastic boundary under a sphere that is pressed against a flat surface with a constant maximum shear stress. According to this model, the material carried away by the indenter cause a decrease in the elastic material without causing any pile-up of the material around the spherical ball. Hence elastic constraint factor based on elastic-plastic model is very close to 3.0 for the materials which do not strain harden under a spherical ball indentation[5]. The units of the σ is in mega pascals (MPa) and H is measured as kg/mm^2. Flow stress value in the Equation 1.15 is related to the plastic strain caused by the geometry of the indenter tip, in other words it is exclusive to the hardness measurement type.

In the literature, there are several academic works to estimate the mechanical properties such as ultimate tensile strength and yield strength from hardness test measurement. [6-11] For the last 50 years, researchers worked intensely for the estimation of the strength of the materials from its hardness values since such an approach will decrease the required amount of tedious mechanical tests.

Tabor [7] has proposed that there is a direct relationship between the ultimate tensile strength and the Vickers hardness of metals and it is also related with the strain hardening coefficient according to the given relationship below:

$$TS = \left(\frac{H}{C}\right)(1-n)\left(\frac{12.5n}{1-n}\right)^{n} \qquad \text{Eq.1.18}$$

where C is a constant with a value of 2.9 for steels and 3.0 for the copper alloys. The "n" term represents the strain hardening coefficient, UTS is the ultimate tensile strength of the material and H is represented as Vickers hardness.

The relation was extended with the work of the Cahoon [8] in the form of:

$$TS = \left(\frac{H}{2.9}\right)\left(\frac{n}{0.217}\right)^{n} \qquad \text{Eq.1.19}$$

where n is the strain hardening coefficient and H is the Vickers Hardness.

After that, Cahoon et al [9] proposed a new relation to estimate the yield strength of the material by using regular hardness measurements for copper, steel, and aluminium in the form of:

$$YS = \left(\frac{H}{3}\right)(0.1)^{n} \qquad \text{Eq.1.20}$$

Every relationship given above requires the knowledge of the strain hardening coefficient, which can be estimated with Meyer's hardness measurements where projected area of the indentation is used instead of surface area of the indent and from the empirical relationships of the uniaxial tensile or compression tests.

Pavlina and Van Tyne [10] reported a simple linear behavior which can be used to estimate the ultimate tensile strength and yield strength of steel by utilizing the Vickers hardness value within the following equations:

$$YS = -90.7 + 2.876 * Hv \qquad \text{Eq.1.21}$$

$$UTS = -99.8 + 3.734*Hv \qquad \text{Eq.1.22}$$

where Hv has units of kg/mm^2 and strength has units of mega pascals (MPa).

No other parameter other than hardness value is required to approximate the strength of the material by the above relationships. However, the relationship between the hardness and mechanical properties of non- ferrous alloys is rarely studied while most of the correlations were made for steel alloys [11]. Therefore, in this research work, we established an analytical relationship between Vickers Hardness and tensile mechanical properties of low melting point non-ferrous alloy system of Tin- Bismuth (Sn-Bi).

1.5. Pure Bismuth and Tin-Bismuth Alloys

Bismuth is a brittle, crystalline material. The bismuth has one of the smallest thermal conductivity values and it is also known as the most naturally diamagnetic material. Bismuth is considered as a stable element with its heavy atomic mass. Pure Bismuth is easily available at high purity and as a commercial grade.

There are lots of application areas for the Bismuth compositions such as fishing sinkers, carbide stabilizer in the production of the malleable iron and it is being used to improve the machinability and toughness of some aluminum, brass and low carbon steel. Since it is safer than lead, it is gradually replacing it in the areas like solder alloys. For the alloying element, it can be used for the manufacturing of the low melting point alloys like Sn-Bi eutectic which is frequently used as the raw material for rapid prototyping sheet metal forming dies. The bismuth can also be alloyed with many non-ferrous metals like copper, antimony, lead, indium, and cadmium.

Bismuth-Tin alloys can be used in different shapes or sizes as bar, foil, wire, sheet, ribbon and ingot. The bismuth with ultra-high purity and high purity forms can be also used in the form of powder, submicron powder as targets for thin film deposition, pellets for the chemical vapor (CVD) and physical vapor deposition (PVD) applications. Bismuth and its alloys are commercially available in different standards of grades including military, reagent, technical, food, agricultural, pharmacy and optical grades which strictly follows corresponding ASTM testing guidelines for each. The basic applications of the alloys involve radiation shielding, soldering, casting, bearing and assembly [12].

Table 1 Tin-Bismuth Alloy(Eutectic) Properties. [12]

Appearance	Metallic solid in various forms (wire, bar, sheet, powder, paste)
Melting Point	139 °C
Density	8.12-8.56 g/cm^3
Tensile Strength	55-70 MPa
Thermal Conductivity	19-30 W/m.K
Electrical Resistivity	0.383 µ & Ohm; middot; cm

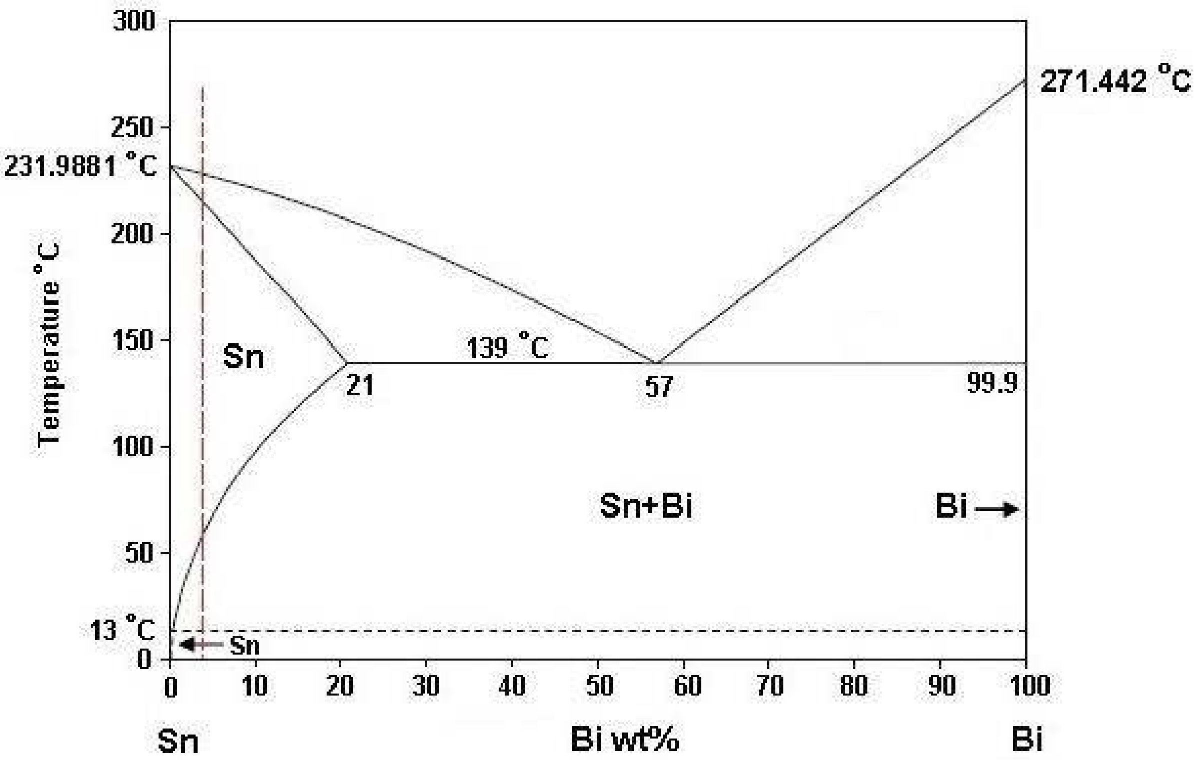


Figure 11. Tin-Bismuth Phase Diagram. [13]

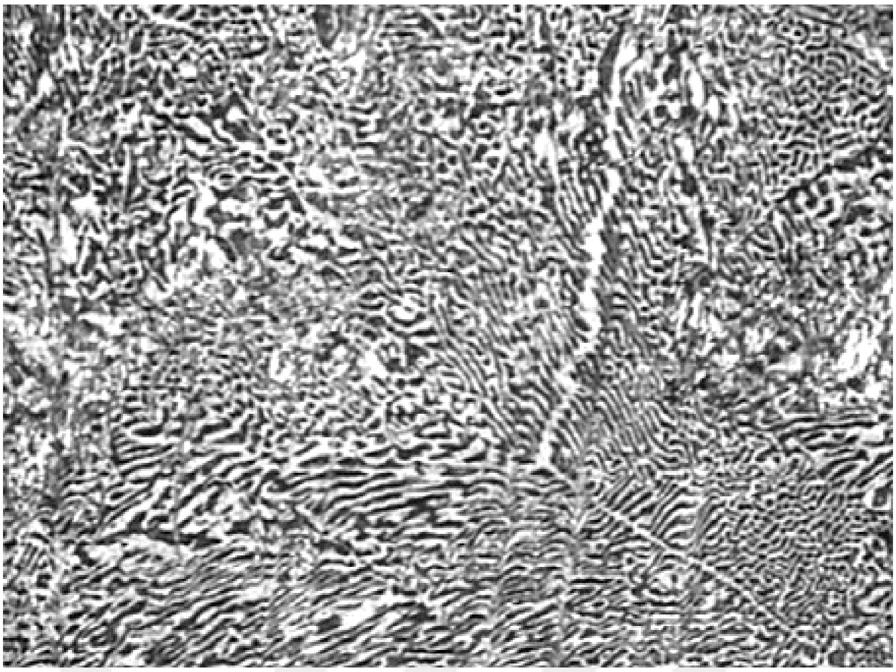


Figure 12. Sn-Bi Eutectic Alloy Microstructure, 200x, etchant 2% Nital.[14]

1.7. Aim and Scope of the Thesis Study

The aim of this work is to correlate the hardness values with the strength values of the proeutectic and eutectic Sn-Bi alloys by using the method of least squares regression analysis to obtain a mathematical expression as a function of hardness which will eventually predict with accuracy mechanical material properties of other Sn-Bi alloy compositions. To investigate the relationship, three proeutectic and eutectic compositions of the Sn-Bi alloy were chosen for experiments. Proeutectic compositions of the Bismuth were respectively 30%, 40%, 50% and eutectic composition with of 57% Bi by weight. The compositions were prepared by mixing pure Sn and Bi according to their weight percent compositions.

CHAPTER 2

PREDICTION OF TENSILE MECHANICAL PROPERTIES OF TIN-BISMUTH ALLOYS BY VICKERS HARDNESS TEST

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Abstract

Determination of static mechanical properties of alloys; such as yield strength and UTS, by simple hardness test is a popular research field because of ease of application, its non-destructive nature and lower cost of equipment. In this study, empirical correlations between mechanical properties of Sn-Bi alloys and their Vickers hardness values are derived by applying linear regression analysis on hardness and strain rate controlled tensile test results. For this, the amount of soft pro-eutectic phase is varied by casting alloys with 30%, 40%, 50% Bi with eutectic composition (57%Bi). The results indicate very good linear correlations between the Vickers hardness and yield strength, UTS and strength coefficient. However, statistically strong correlation could not be established between the hardness and the strain hardening exponent.

Keywords: Vickers hardness, tensile strength, yield strength, strain hardening exponent, Tin, Bismuth, Sn-Bi alloy.

2.1. INTRODUCTION

The Sn-Bi alloys are commonly preferred in the manufacturing industry because of their low melting point and good machinability. Sn-Bi alloys recently are being promoted as an alternative to lead-based solders to minimize the lead consumption. [15]. In addition to this, because of its low melting point (~139 ºC) eutectic SnBi composition (57 % Bi by weight) is used as a die material for sheet metal forming processes in automobile prototyping industry. Such low melting point makes the casting process quite easy and manageable. Furthermore, eutectic composition of this alloy demonstrates almost no shrinkage upon solidification. This behavior is particularly an advantage to assume the details of the mold and enable a perfect cast piece upon solidification [16]. The phase diagram of the Sn-Bi alloy shown in Figure 13 is taken as reference for sample preparation throughout this research [13].

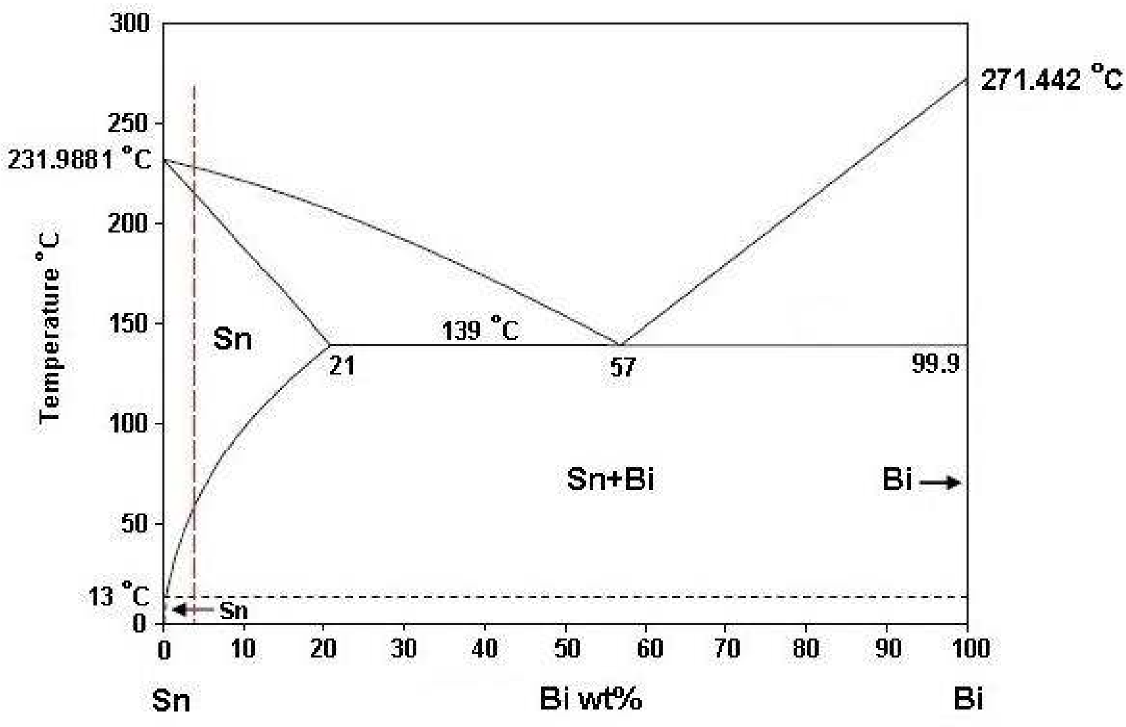

Figure 13. Phase Diagram of Sn-Bi Alloy

Since Bi has higher strength than tin and tin has a higher ductility than bismuth, the mechanical behavior of the overall Sn-Bi alloy will be a compromise between the properties of tin and bismuth composition percentages. Tension tests are generally used to gather information about mechanical properties of the materials under uniaxial tensile stress and the data obtained can be used for comparison purposes or for verification of the mechanical requirements of the material. The specimen is generally prepared in dimensions strictly following the standard protocols. During the test, force and elongation of the material are measured with sensors like load-cells and extensometers respectively. From the force and elongation history, engineering or true stress-strain diagrams can be obtained.

However, there are some requirements which need to be fulfilled to obtain a valuable data from the uniaxial tensile testing. For example, according to the ASTM standards, extensometers must conform some specifications like output, linearity and temperature range based on the requisites of the experiment. In addition, the setup cost of an average tensile testing machine requires a significant investment together with their yearly calibration services [17].

On the other hand, the hardness machine measures the resistance of the material to indentation which is a local permanent deformation. The main application of the hardness machine is to determine a ballpark estimate about the mechanical quality of the test specimen [7].

The hardness determination procedure is generally quite simple. The test material is penetrated with a constant compression load by an object harder than the sample itself. The hardness test is based on the measuring the critical dimensions of the indented surface. Common hardness scales can be classified as Rockwell, Vickers, and Brinell for the indentation hardness [5].

Nowadays most manufacturing companies have a hardness machine for quality control purposes, which makes this technique attractive in order to determine or confirm the mechanical properties like yield and tensile strength for routinely manufactured materials instead of using a tensile test with tiresome protocols. In fact, hardness test has advantages compared to tensile test since it is almost non-destructive method, its comparatively small frame structure is easy to fit on a benchtop and the specimen preparation protocols and test procedures are quite simple [5].

It is a known fact that hardness and strength values of materials have a direct correlation. In several research studies it is shown that average mechanical strength can be predicted with a high accuracy just by performing a hardness test. Krishna and his colleagues claimed that strength can be determined with a good approximation for low and medium strain hardening materials. Indeed, their work on the copper alloys demonstrates a linear relationship between the hardness and the ultimate tensile strength [11]. Furthermore, composition of the alloy is a key factor which determines distribution of the phases and thus the microstructure which will affect the hardness and strength values [18]. Another research which relates strength and hardness investigated the effect of morphology of the material during the hardness testing [19]. Datsko also investigated the hardness and ultimate tensile strength of different materials such as Inconel 718 nickel-based super-alloy, Type 304 stainless steel and a grade of brass [20]. It has been concluded that the hardness test is a reasonably easy method to obtain yield and tensile strength of the materials. Datsko's work was based on finding the hardness coefficient of the material from at least two hardness measurements and estimating the tensile strength of the material approximately. The prediction of the tensile properties with Vickers micro-hardness data was also reported by Milot [21]. In 1953, the correlation between hardness, elastic modulus and tensile strength of the materials is investigated by Murphy [22] and he concluded that the Vickers hardness value is dependent on the test load and indentation speed. The linear relationship between the ultimate tensile strength and the Vickers hardness is also reported in this research. However, a noticeable relationship between hardness and yield strength is not observed for the same material.

Hardness versus tensile strength correlations were particularly studied for steel alloys. In 1991, Lai and Lim [23] predicted the tensile strength of the steels by hardness test with good accuracy. However, Pavlina and Van Tyne [10] noted that when steels show high strain hardening behavior, their correlation equation gives lower strength value for a given hardness value.

In the Shen *et al.*'s work, it was reported that nanoindentation technique can be used to investigate the creep behavior of the Sn-Bi alloys [24]. Shen *et al.* showed that compositions which have bismuth up to 10 % by weight exhibit the highest elastic moduli and hardness values while the compositions that have bismuth amount above 10% by weight, demonstrated easily detectable creep behavior.

In 2015, Mokhtari and Nishikawa [25] pointed out that mechanical properties of the Sn-Bi alloys can be manipulated by controlling its microstructure via addition of other elements such as nickel and indium.

The aim of this work is to determine the correlation between the hardness and tensile strength values of the Sn-Bi alloy and establish a mathematical relationship by least square regression analysis to predict the yield and tensile strength of any alloy composition with a known Vickers hardness value. To investigate the relationship, three pro-eutectic and eutectic compositions of the Sn-Bi alloy were chosen for experiments. Pro-eutectic compositions of the Bismuth were respectively 30%, 40 %, 50 % and eutectic composition with of 57 % Bi by weight. The compositions were prepared by mixing pure Sn and Bi according to their weight percent amounts.

2.2. EXPERIMENTAL PROCEDURE

Firstly, we prepared three pro-eutectic compositions and the eutectic composition of Sn-Bi alloy system by mixing them in appropriate ratios in the melt state.

Following melt mixing, the molten metal with varying compositions was poured into the permanent molds made out of steel to get the near shape suitable for machining to get the appropriate tensile testing sample final dimensions. Molten alloys were poured into the steel molds shown in the below figure at a temperature slightly above $T_{liquidus}$ in order to shorten the total solidification time to avoid macro-segregation due to density difference between components during the molten state.

Figure 14. Permanent Steel Mold for Casting Sn-Bi Alloy

After casting stage, the sample rods were machined at a universal lathe to get the final shape and dimensions as given by the technical drawing in Figure 15. The thermo-mechanical simulator system, Gleeble 3500 tensile test setup is shown in Figure 16 [26].

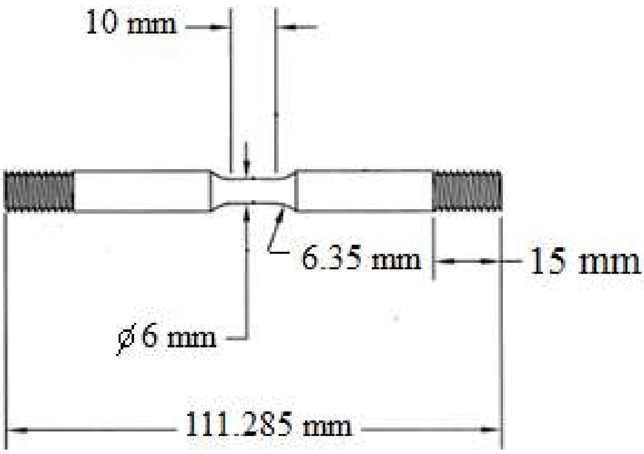

Figure 15. Technical Drawing for the Tensile Testing Specimen

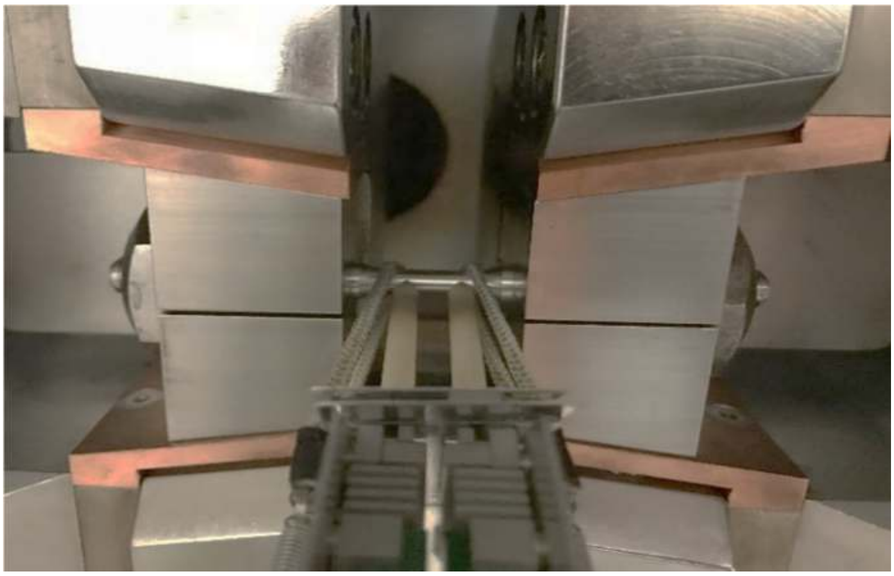

Figure 16. Room Temperature Tensile Test Setup

All tensile tests were performed at room temperature by Gleeble 3500 at a strain rate of 10^{-3} per second and contact-type extensometer HZT071 was used to get true stress-strain curves of each composition. UTS values are used to express the mechanical strength of the material. Figure 17 shows the initial tensile test specimen and the ruptured one at the end of the experiment.

Figure 17. Initial and Ruptured Tensile Test Specimen

The hardness measurements were performed by Zwick-Roell hardness machine. Vickers scale was used to determine the hardness of each composition. Hardness measurements were taken randomly to take account all areas of the specimen which were cast from the same composition batch with the tensile samples in plate shape. Five measurements were taken for each composition. The hardness test results are completed with the test load of 1961 N and 25 mm/min indentation speed. Figure 18 shows the hardness measurement device used for our work.

Figure 18. Hardness Measurement Test Device

2.3. RESULTS AND DISCUSSIONS

The room temperature true stress-strain curves for each composition are presented in Figures 19-22 respectively. All of the tensile tests were performed with five repetitions to obtain a statistically significant data.

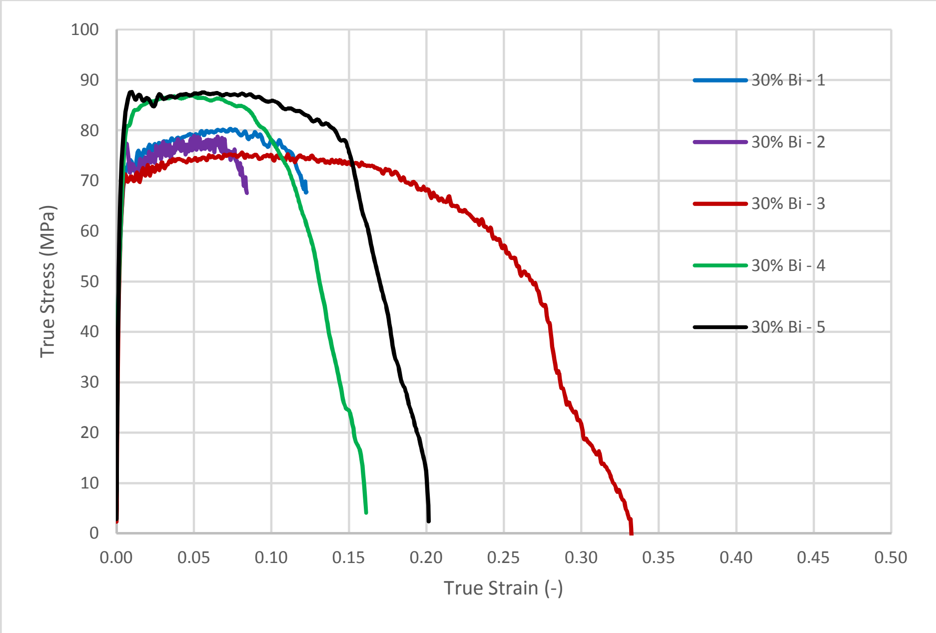

Figure 19. True Stress-Strain Curves for 30% Bi Composition

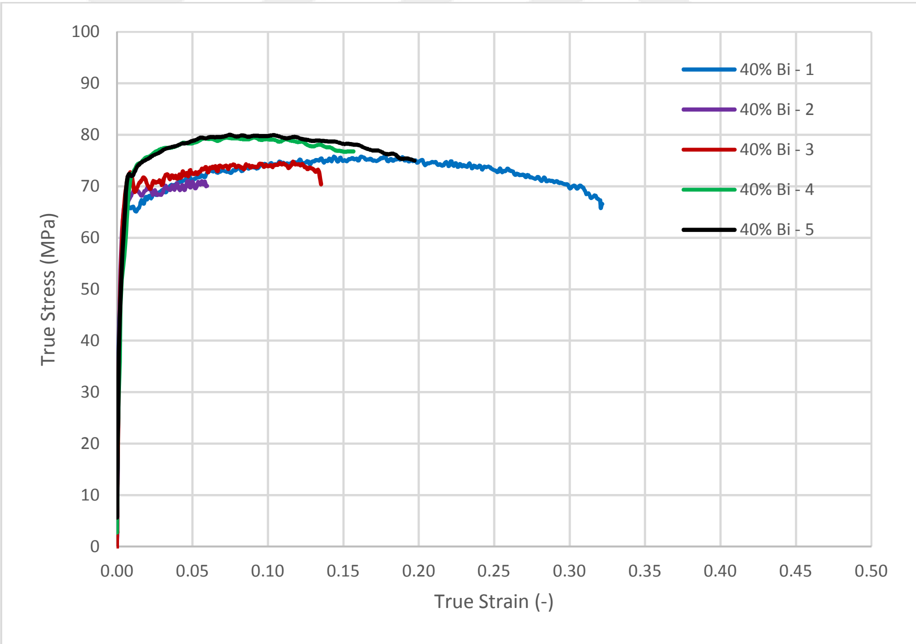

Figure 20. True Stress-Strain Curves for 40% Bi Composition

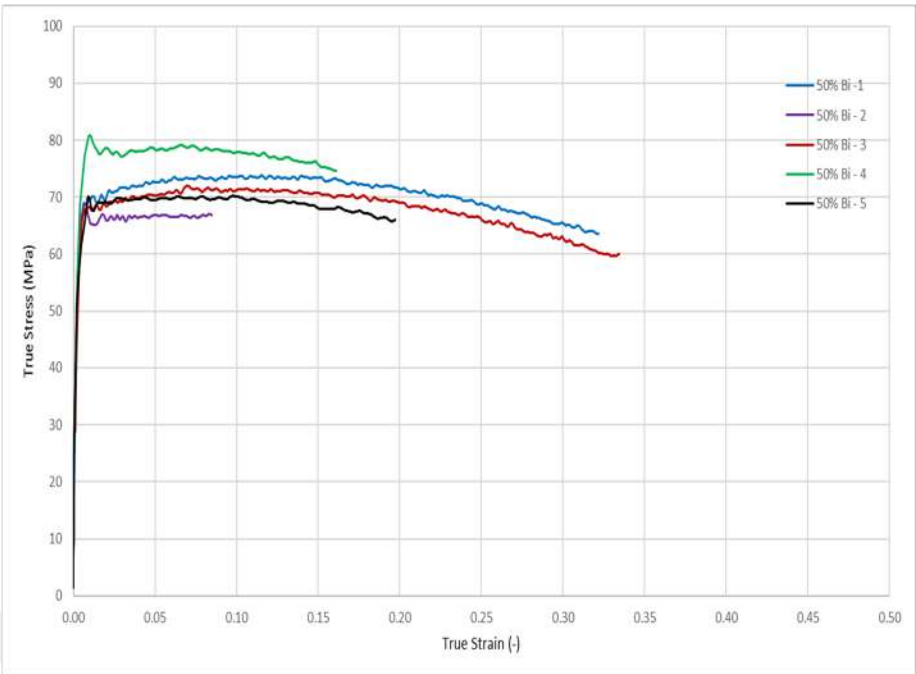

Figure 21. True Stress-Strain Curves for 50% Bi Composition

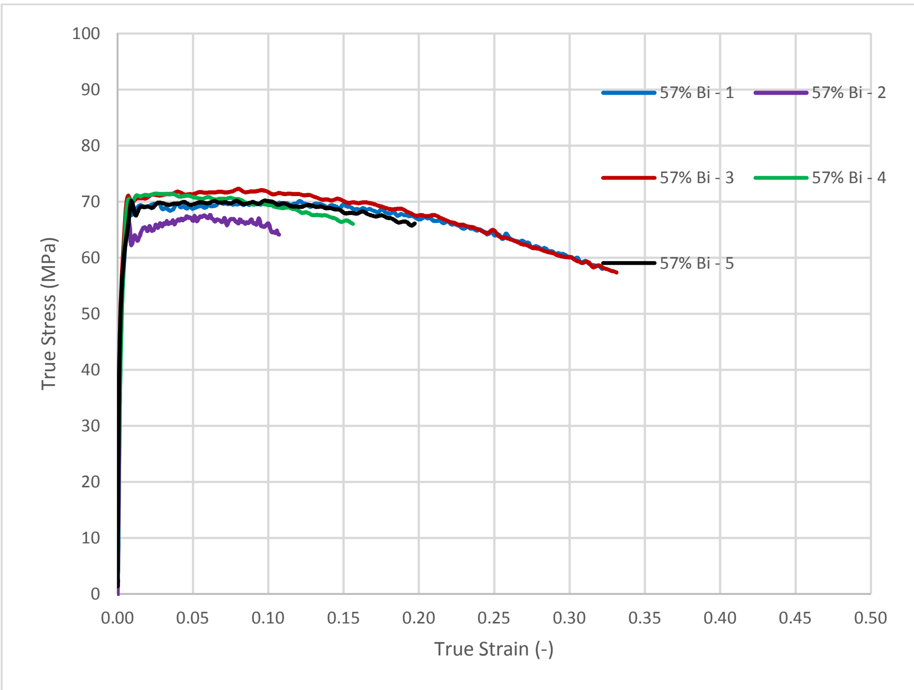

Figure 22. True Stress-Strain Curves for 57% Bi Composition

When the true stress-strain graphs were investigated, we observed some doubtful differences in the elongation patterns for some samples. Since they were prepared by casting method we suspect that there could exist macro-segregations and porosities in some samples which might have caused premature fractures during the tensile test. However, we assume the sample whose elongation to failure is the highest as the expected value and treated the average curves accordingly.

The first material property we have studied was ultimate tensile strength as a function of hardness. Thus, the average values of UTS for each composition with its error bars were as presented in Figure 23.

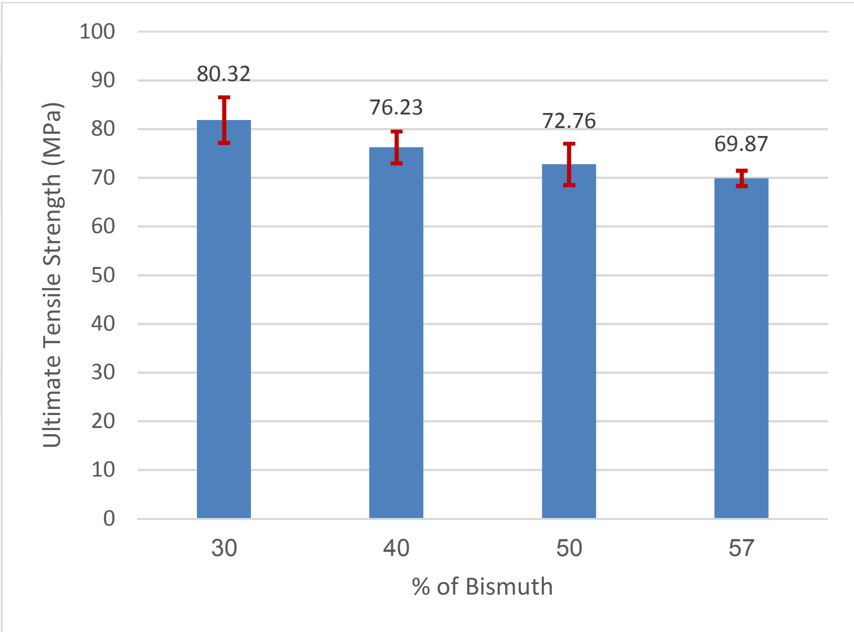

Figure 23. Average Ultimate Tensile Strength for each Alloy Composition

The hardness test results were completed with the test load of 1961 N, 25 mm/min indentation speed and Vickers probe. The results of the hardness test with their error bars are reported in Figure 24.

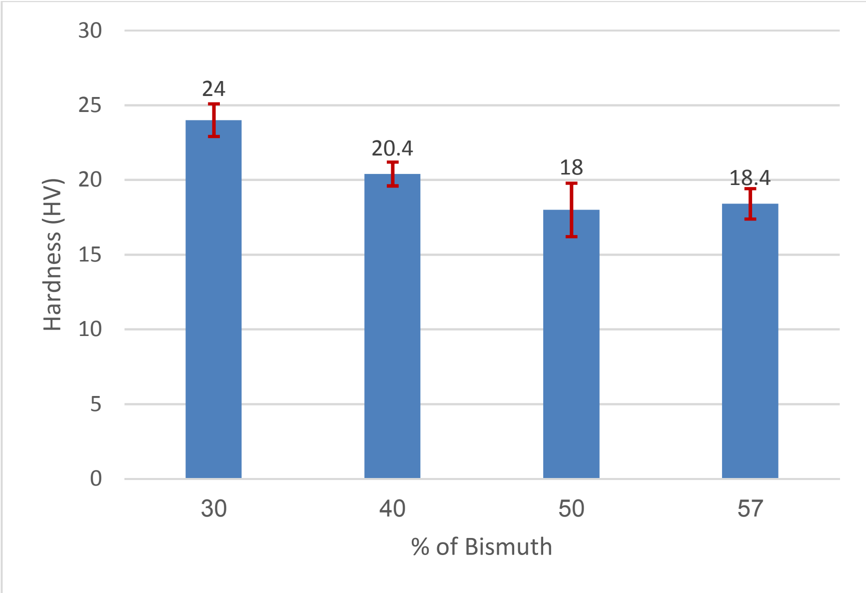

Figure 24. Average Vickers Hardness Numbers for Each Alloy Composition

The overall results for the ultimate tensile strength and Vickers Hardness Numbers of the pro-eutectic and eutectic compositions of Sn-Bi alloys are presented in Table 2 and Table 3 respectively.

Table 2 Ultimate Tensile Strength for All Compositions

UTS (MPa) vs. % of Bi				
# of Rep.	**30**	**40**	**50**	**57**
1	80.10	75.84	73.86	69.41
2	78.91	71.09	67.03	67.18
3	75.62	74.77	71.34	71.64
4	86.92	79.45	78.80	71.31
5	87.64	79.99	72.77	69.83
Average	80.32	76.23	72.76	69.87
St. Dev.	3.48	3.26	4.26	1.59

The average of the ultimate tensile strength of each composition and their standard deviation were calculated and is reported in Table 2. We observe that as the % Bi increases average UTS decreases. Though standard deviations in proeutectic compositions are slightly high compared to eutectic one, we suspect that there is an inverse relationship between the Bi amount and the UTS of these alloys which needs further investigation which should include hypereutectic region as well.

The hardness readings were taken from five different areas of the plate samples prepared for hardness measurements to randomize the overall behavior of the composition.

Table 3 lists the Vickers hardness numbers for all compositions with their averages and standard deviations.

Table 3 Hardness Results for All Compositions

Hardness (HV) vs % of Bi				
# of rep	**30**	**40**	**50**	**57**
1	24	20	16	18
2	25	21	16	18
3	24	21	18	17
4	25	21	20	19
5	22	19	20	20
Average	24.00	20.40	18.00	18.40
St.Dev	1.10	0.80	1.79	1.02

Since we suspect that there are some doubtful data resulted from casting defects, the possible outliers for the stress-strain curves for all compositions was eliminated according to Chauvenet Criterion. The main idea of the Chauvenet Criterion is to create an acceptable band of data around the mean values of the all data points and eliminate the ones that are outside of the created band. All data points that fall within this band around the mean have a probability of 1-1/(2N) where N is sample size. Data points can be rejected if the probability of their deviation from the mean is less than 1/(2N). We need the mean and the standard deviation of the data set to apply Chauvenet Criterion. After that each data point is being subjected to following formula.

$$T = \frac{|X_i - \bar{X}|}{s} \qquad \text{Eq.2.1}$$

Where X_i is the data point, $\bar{X}$ is the mean of all data points and s is the standard deviation.

The Chauvenet's Criterion is applied to the five repetitions for all compositions to eliminate the outliers for the ultimate tensile test results. The following tables given below show the change in the standard deviation and mean for ultimate tensile strength before and after Chauvenet Criterion.

Table 4 UTS Values for 30% Bismuth Alloy

	Before Chauvenet	1st Chauvenet Calc.
average	80,32	78,21
sum of (data-mean)^2	109,726388	71,08745845
st. dev.	4,684578699	4,21566894

Table 5 UTS Values for 40% Bismuth Alloy

	Before Chauvenet	1st Chauvenet Calc.	2nd Chauvenet Calc.
average	76,23	77,51	73,90
sum of (data-mean)^2	53,20059261	26,78718081	12,66873528
st. dev.	3,261919454	2,587816687	2,054972448

Table 6 UTS Values for 50% Bismuth Alloy

	Before Chauvenet	1st Chauvenet Calc.	2nd Chauvenet Calc.
average	72,76	70,74	72,60
sum of (data-mean)^2	72,55655405	36,03810075	3,214482691
st. dev.	4,259006752	3,465934253	1,267770226

Table 7 UTS Values for 57% Bismuth Alloy

	Before Chauvenet	1st Chauvenet Calc.
average	69,87	70,55
sum of (data-mean)^2	12,65572	5,398084
st. dev.	1,590956945	1,161688857

Once the outliers were eliminated from the tensile test data, the average stress-strain curves were calculated. The main procedure to calculate the average stress-strain curves is based on determining the five stress values at most for each corresponding strain value and averaging the stress values for that particular strain. The excel function VLOOKUP is used to find the average stress-strain curves. The repetitions have different maximum strain values, thus the average curves are calculated up to the common strain with minimum difference between all repetitions. When stress-strain curves of common strain are obtained, the stress value of each strain values are taken to their averages. Following graphs show the average true stress-strain curves up to UTS values and cleaned of doubtful data by Chauvenet's Criterion.

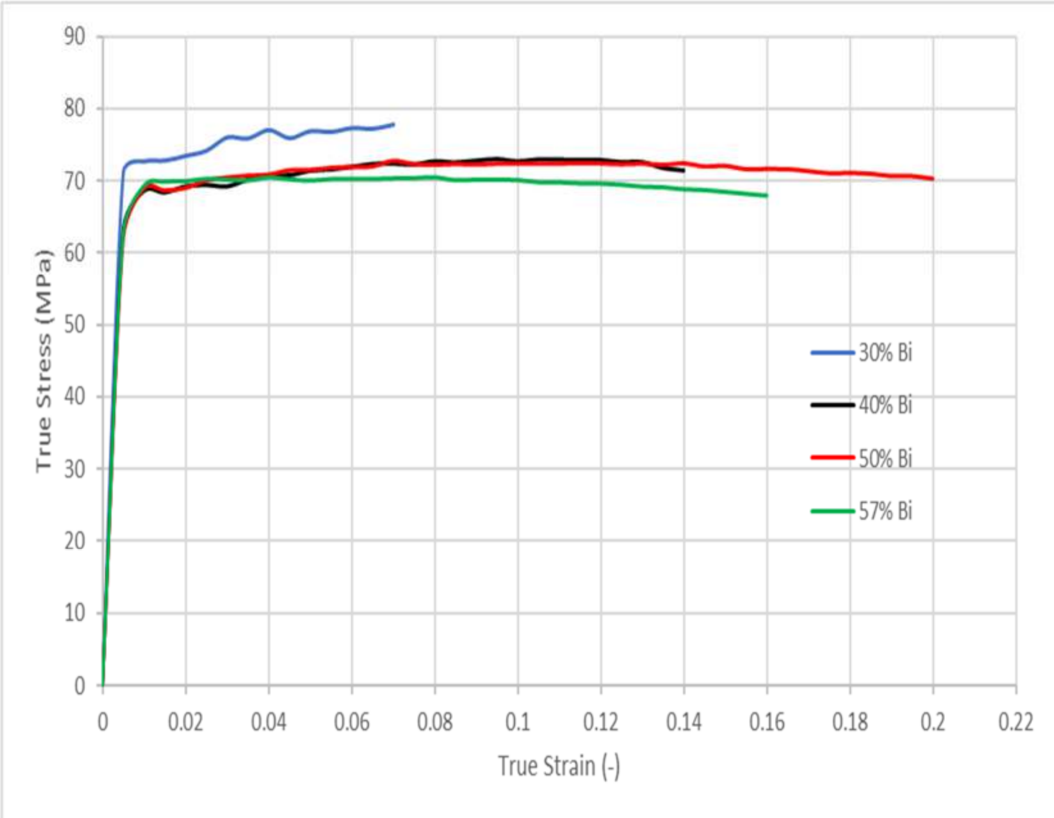

Figure 25. Averaged Stress-Strain Curves up to UTS with all Alloy Samples

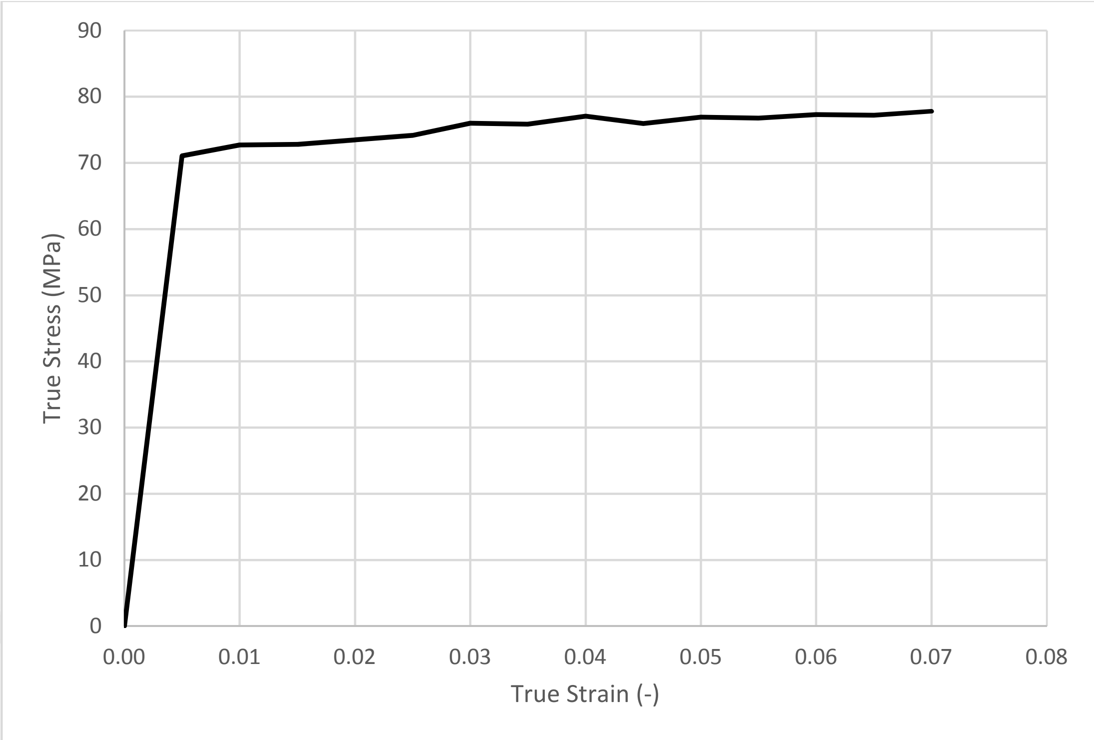

Figure 26. Averaged True Stress-Strain Curve up to UTS for 30% Bi Alloy

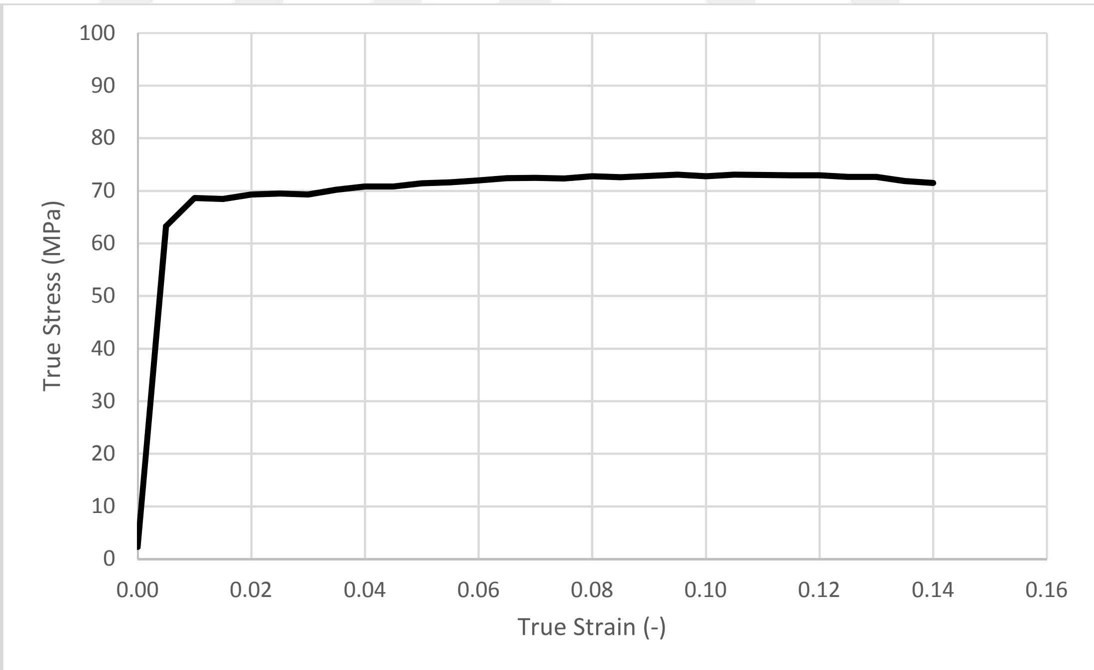

Figure 27. Averaged True Stress-Strain Curve up to UTS for 40% Bi Alloy

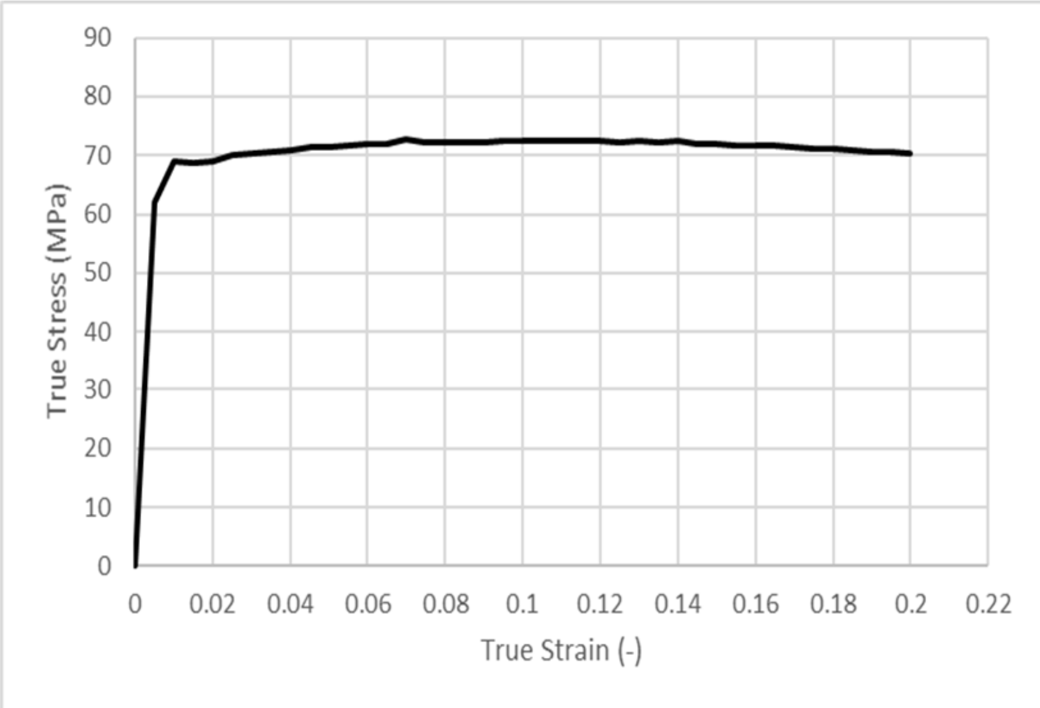

Figure 28. Averaged True Stress-Strain Curve up to UTS for 50% Bi Alloy

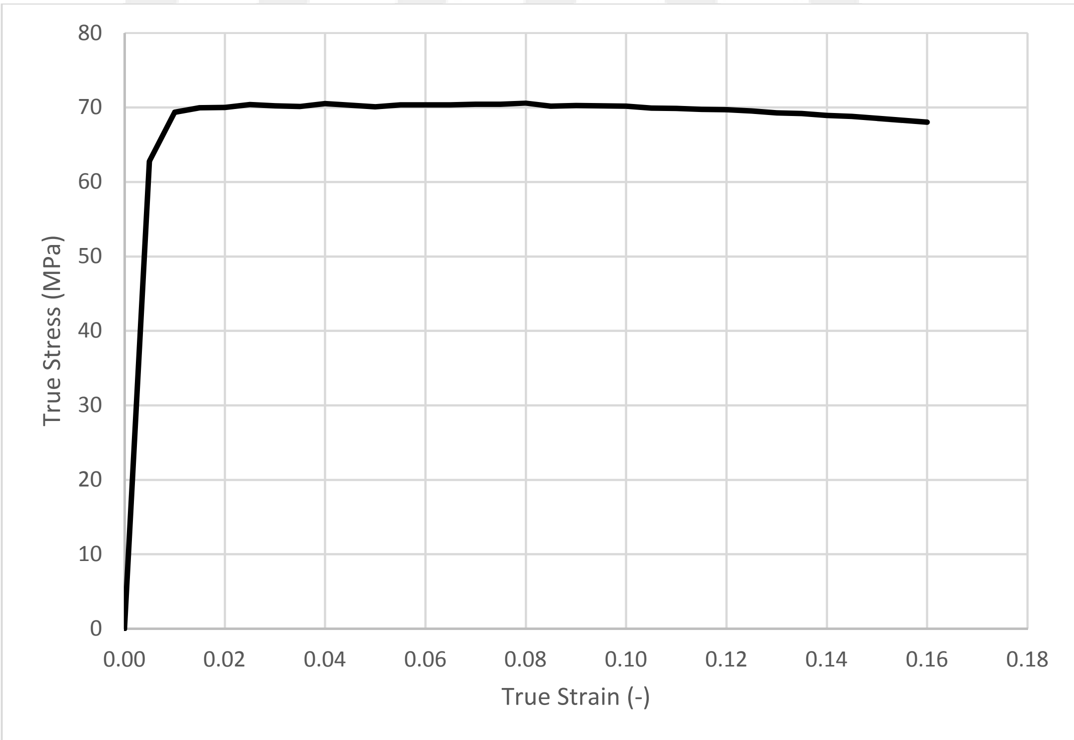

Figure 29. Averaged True Stress-Strain Curve up to UTS for 57 % Bi (Eutectic) Alloy

After studying UTS we also tried to establish a relationship between yield strength (Y.S.), strength coefficient (K) and strain hardening exponent (n) for all compositions. The n and K values were found by using the Power Law function and can also be easily processed with log-log transformation. The average stress-strain curve of all compositions were used for n and K value calculations.

Power Law function tries to minimize the least squares of an error between the stress-strain curve obtained from the experimental study and the theoretical one. Following figures below show the difference in stress-strain values between the experimental and the fitted data.

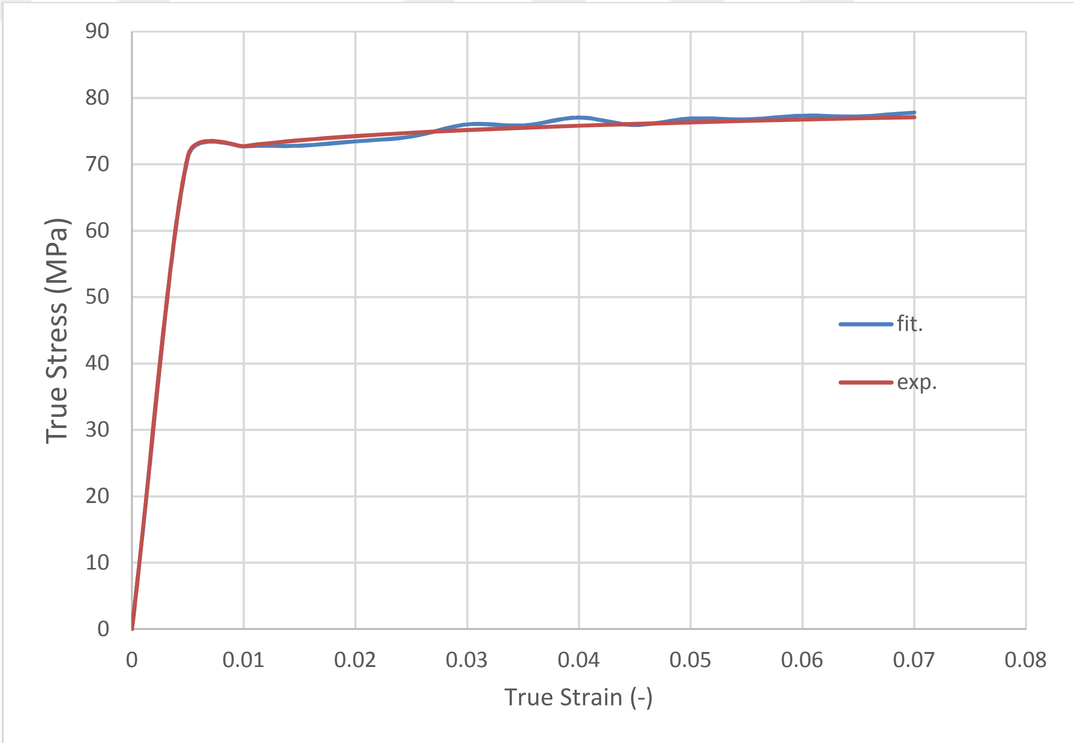

Figure 30. Stress-strain curves based on the experimental and fitted data for 30% Bi alloy

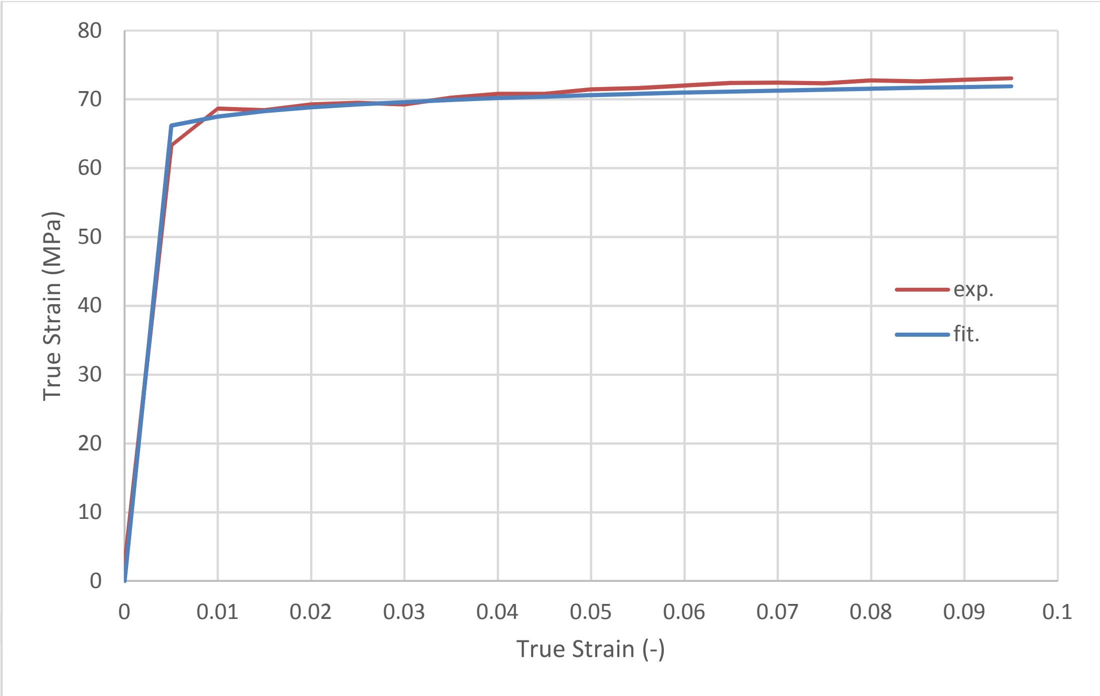

Figure 31. Stress-strain curves based on the experimental and fitted data for 40% Bi Alloy

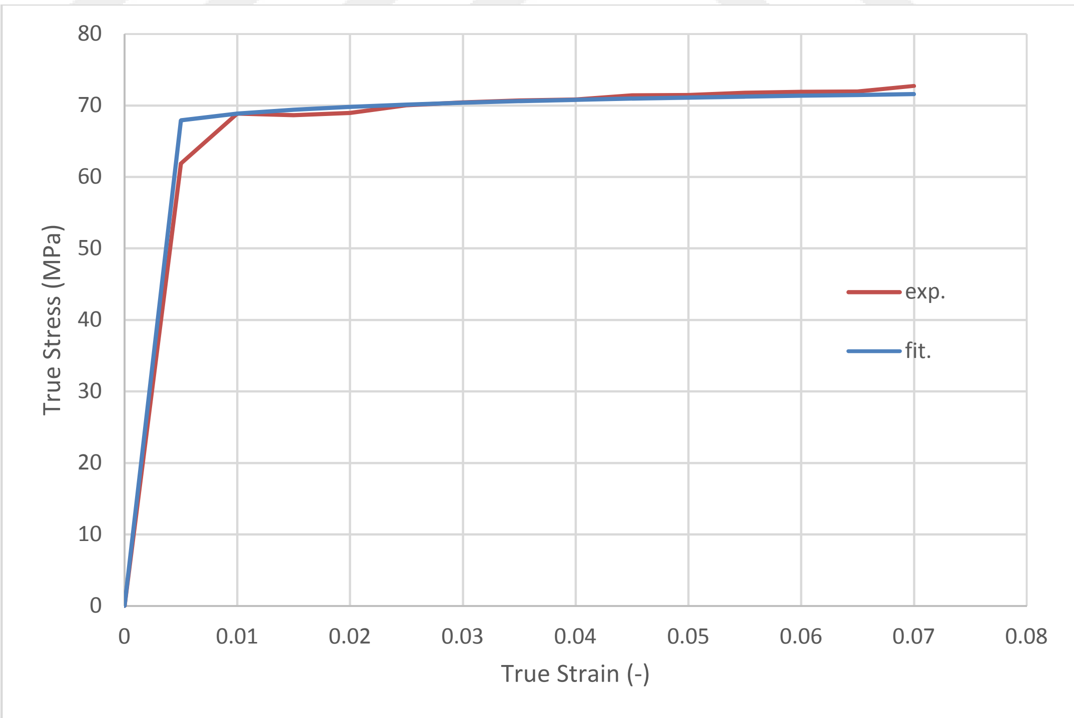

Figure 32. Stress-strain curves based on the experimental and fitted data for 50% Bi alloy

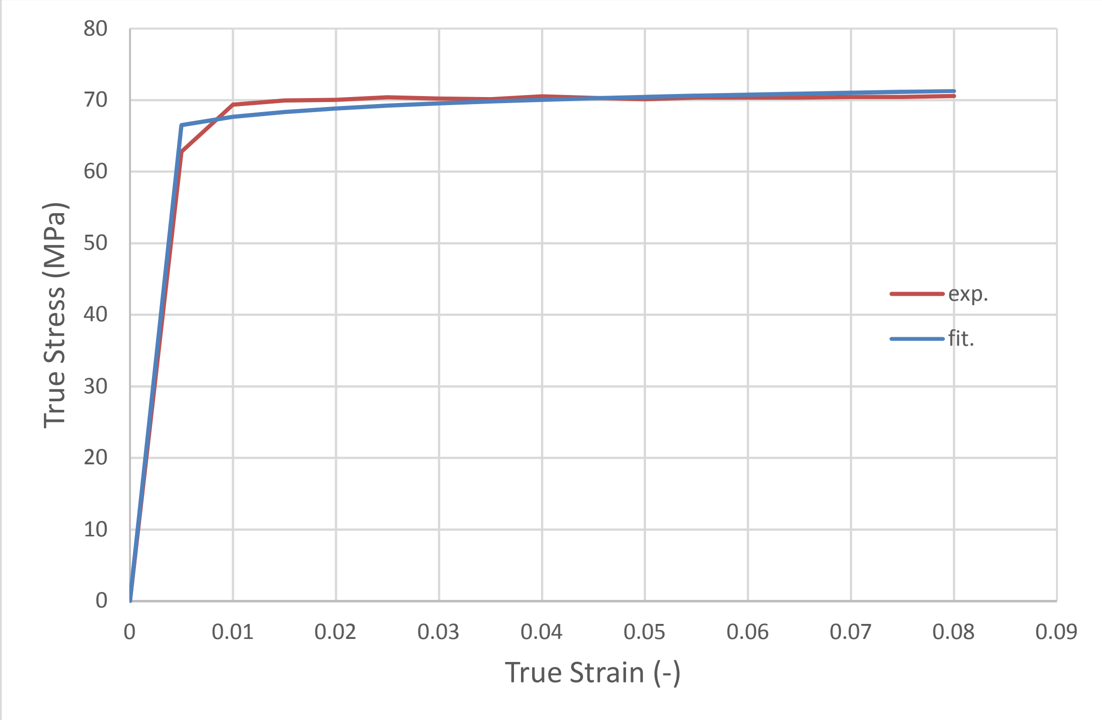

Figure 33. Stress-strain curves based on the experimental and fitted data for Eutectic (57 % Bi) alloy

When all the stress-strain curves are analyzed, a good consistency between the experimental and fitted data can be easily noticed. The related consistency is obtained with the parameters of strain hardening exponent and strength coefficient obtained by aforementioned Power Law function. So, the n and K parameters of the Sn-Bi alloys are reported in the table 8.

Table 8 Strain hardening exponent (n) and Strength coefficient (K)

K (MPa) & n				
% of Bi	**30**	**40**	**50**	**57**
strength coefficient(K)	83.5	76.8	75.5	75.9
strain hardening exponent(n)	0.03	0.028	0.02	0.025

In order to determine the yield stress of all compositions, 0.2% offset method is used. The yield stresses for all compositions are reported in Table 9

Table 9 Yield Stress for Sn-Bi alloys with respect to % Bismuth

YS (MPa)				
% of Bi	**30**	**40**	**50**	**57**
Average	70.25	63.29	61.89	63.08
St.Dev.	1.835	1.303	0.790	1.65

The ultimate tensile strength (UTS) results with respect to different Bismuth compositions are given in Table 10

Table 10 UTS Results for % Bismuth

UTS (MPa)				
% of Bi	**30**	**40**	**50**	**57**
Average	78.21	73.90	72.60	70.55
St.Dev.	4.12	2.05	1.27	1.16

All the regression analysis based on method of least squares were performed after data outlier based on Chauvenet's Criterion was applied.

The relation between the hardness and the ultimate tensile strength is given in Figure 34.

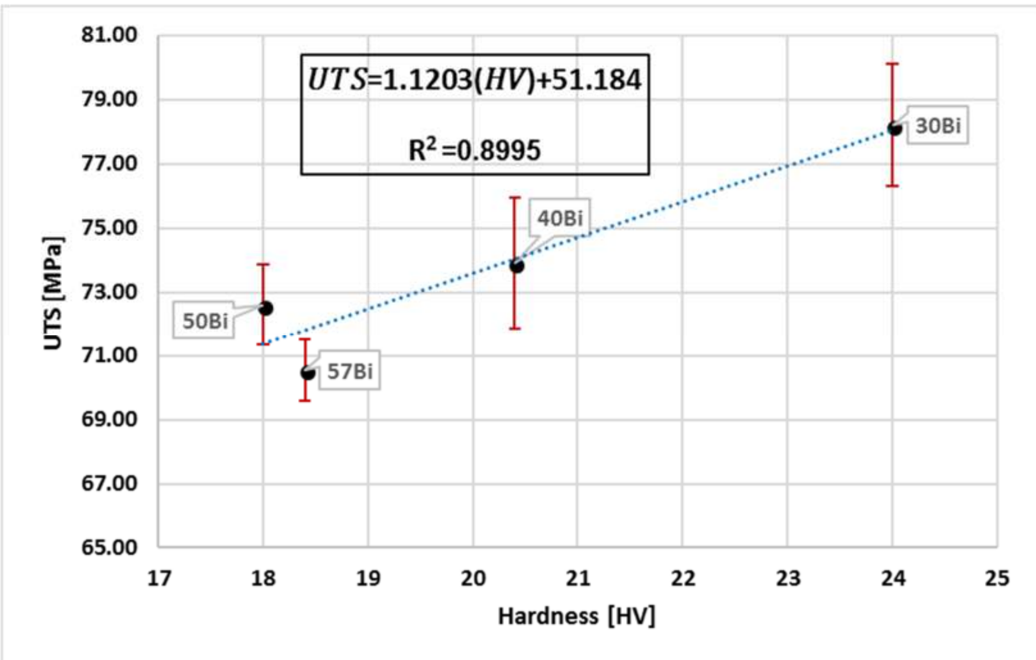

Figure 34. The averaged ultimate tensile strength vs Vickers Hardness Number

According to applied regression analysis, the UTS versus hardness behavior can be reported as almost linear with a strong correlation coefficient R^2 value as 0.8995.

From this regression analysis, the ultimate tensile strength of the proeutectic and eutectic Sn-Bi alloys can be calculated with the following equation:

$$UTS = 1.1203(HV) + 51.184 \qquad \text{Eq.2.2}$$

where:

UTS = Ultimate Tensile Strength (MPa)

HV= Hardness in Vickers Scale

The relationship between the Vickers hardness number and the yield strength is given likewise in Figure 35.

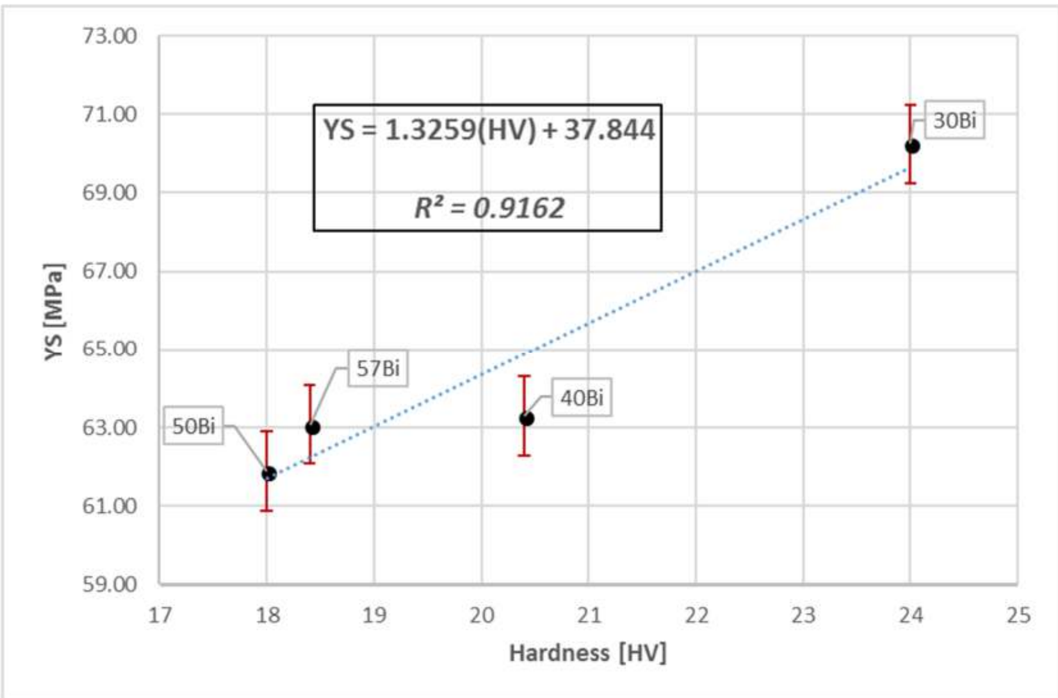

Figure 35 The averaged yield strength vs Vickers Hardness Number

The relationship between the yield strength and Vickers hardness number is almost linear with a strong correlation coefficient R^2 value calculated as 0.9162.

From this regression analysis, the Yield strength of the proeutectic and eutectic Sn-Bi alloys can be calculated with the following equation:

$$US = 1.3259(HV) + 37.844 \qquad \text{Eq.2.3}$$

where:

YS = Yield strength (MPa)

HV= Hardness number in Vickers Scale

The relationship between the Vickers hardness and the strength coefficient (K) is given in Figure 36.

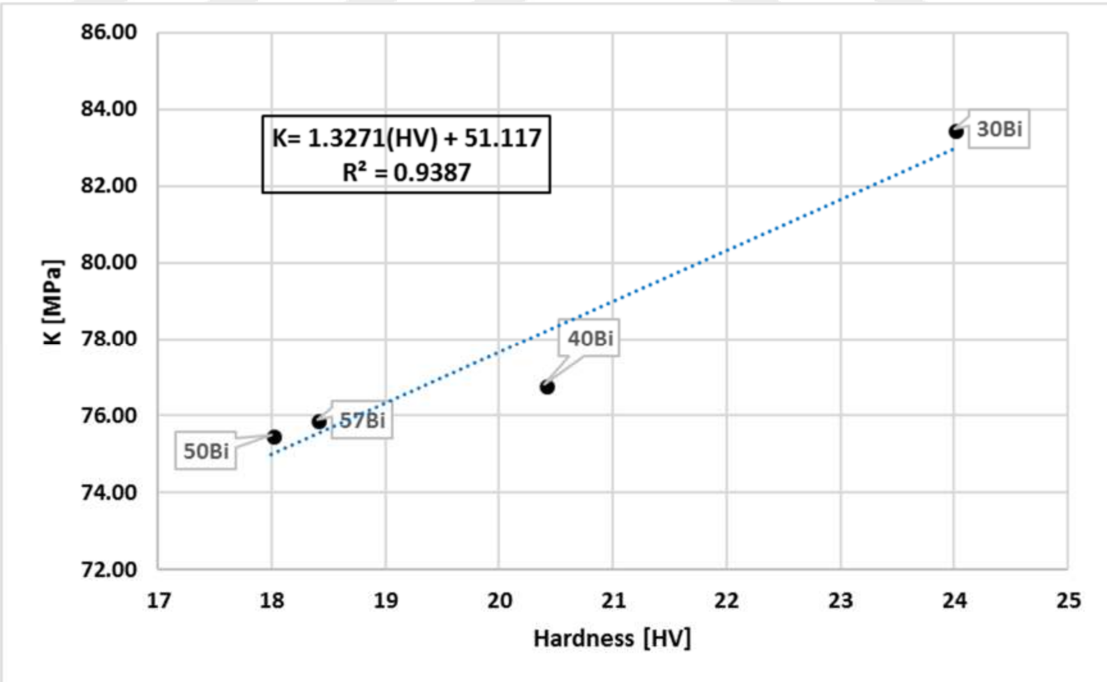

Figure 36. The Strength Coefficient (K) vs Vickers Hardness Number

The relationship between strength coefficient (K) and Vickers hardness number is almost linear with a very strong correlation coefficient R^2 value calculated as 0.9387.

From this regression analysis, we attained the following equation which can be used to determine the strength coefficient (K) of the proeutectic and eutectic Sn-Bi alloys readily:

$$K = 1.3271(HV) + 51.117 \qquad \text{Eq.2.4}$$

where:

K = Strength Coefficient (MPa)

HV= Hardness number in Vickers Scale

Lastly, we analyzed the relationship between the Vickers hardness and the strain hardening exponent (n) which is demonstrated in Figure 37.

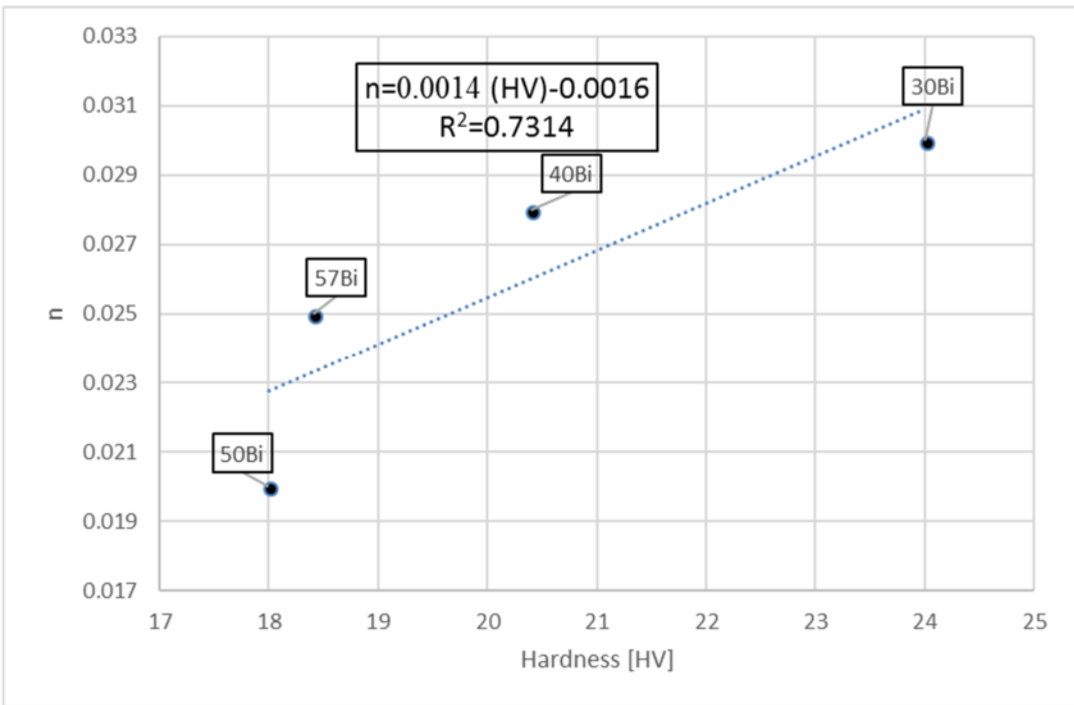

Figure 37. The Strain Hardening Exponent (n) versus Vickers Hardness Number

From this regression analysis, we conclude that the correlation between the strain hardening exponent (n) and Vickers hardness is not as strong as other properties with R^2 =0.7314 slightly lower than the previous ones. We might need further data to reach a final decision with respect to this relationship. However it is statistically significant and the strain hardening exponent of the proeutectic and eutectic Sn-Bi alloys can still be calculated with the following equation:

$$n = 0.0014(HV) - 0.0016 \qquad \text{Eq.2.5}$$

where:

n = Strain Hardening Exponent

HV= Hardness number in Vickers Scale

2.4. CONCLUSION

The results of this study show that tensile mechanical properties of the proeutectic and eutectic Sn-Bi alloys can be determined with a good estimation by only performing hardness measurements of Vickers scale.

The Vickers hardness and ultimate tensile strength, yield strength and strength coefficient values are in a good consistency with a linear behavior and a strong correlation coefficient.

When the true stress-strain curves were examined, a certain variation in the ductility of the specimens within the same alloy system is observed. We think that this issue is probably due to some casting defects like macrosegregation and interval voids. Therefore, stress-strain data points were averaged and filtered up by data outlier method based on Chauvenet Criteria for each sample to randomize the effect of such defects.

We also noticed that the yield strength and the ultimate tensile strength values of the proeutectic and eutectic Sn-Bi alloys are very close to each other which is an indication of a perfectly plastic behavior at room temperature.

Since the homologous temperature which is the ratio of test temperature to the melting point of the alloy in Kelvin scale is around 0.72, there is a strong possibility of creep behavior at room temperature for all the worked compositions. It means that following the yield stress, the material goes through almost no work hardening behavior under uniaxial tensile test.

For the future work, increasing the data points in the regression analysis might improve particularly strain hardening exponent prediction.

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APPENDIX

Hardness measurement report for the 30% bismuth composition

Zwick Roell **HARDNESS REPORT** **12.01.2018**

Parameter table:

Müşteri	: Sn-Bi	Testi yapan :	MSMM
Malzeme	: steel	Sarj No	: 1

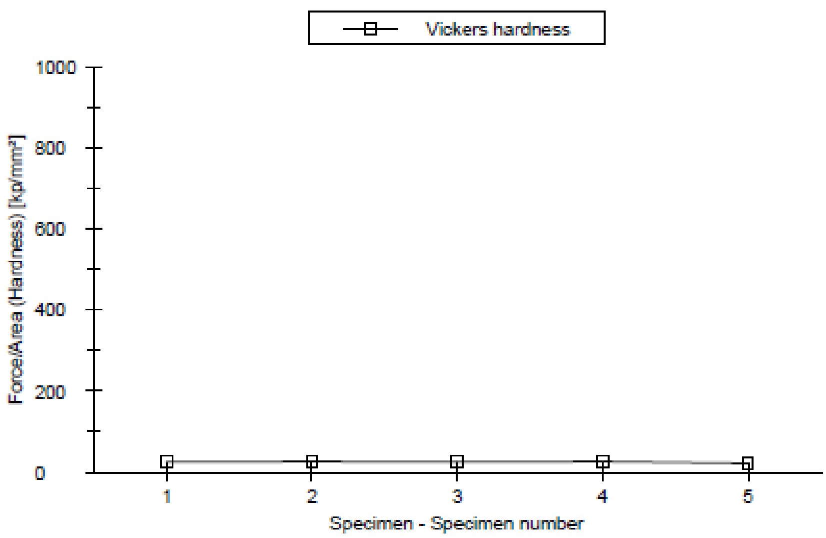
Testing method:

Sertlik metodu :	Vickers hardness	Objective lens :	20 : 1
Test yükü	: 1,961 N	Test speed	: 25 mm/min

Results:

Nr	d_h µm	d_v µm	d µm	HV 0.2
1	124,88	123,52	124,20	24
2	123,12	120,01	121,56	25
3	124,00	124,84	124,42	24
4	122,68	122,20	122,44	25
5	131,04	130,55	130,80	22

Series graph:



Statistics:

Series n = 5	d_h µm	d_v µm	d µm	HV 0.2
x	125,15	124,23	124,69	24
s	3,40	3,96	3,62	1
v	2,72	3,19	2,90	5,57

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Hardness measurement report for the 40% bismuth composition

Zwick / Roell HARDNESS REPORT 12.01.2018

Parameter table:

Müşteri : Sn-Bi   Testi yapan : MSMM
Malzeme : steel   Sarj No : 1

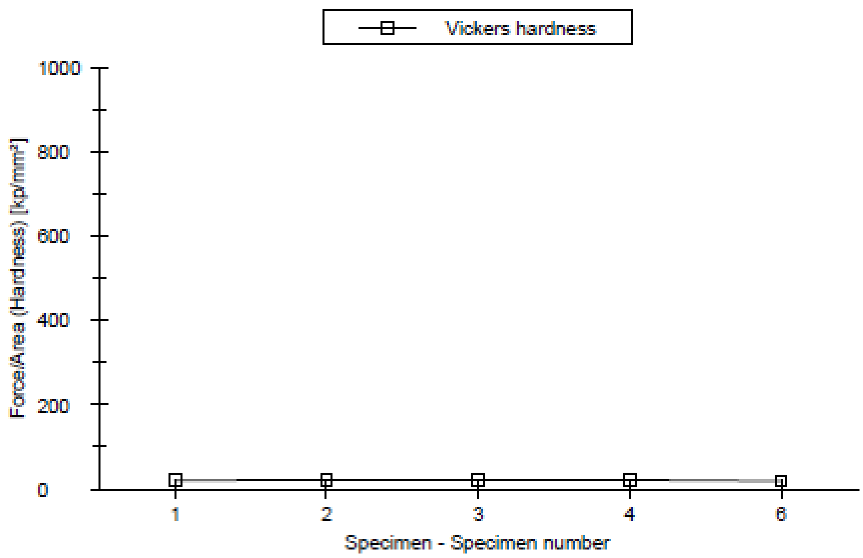
Testing method:

Sertlik metodu : Vickers hardness   Objective lens : 20 : 1
Test yükü : 1,961 N   Test speed : 25 mm/min

Results:

Nr	d_h µm	d_v µm	d µm	HV 0.2
1	134,12	134,95	134,53	20
2	134,12	132,75	133,43	21
3	134,56	133,19	133,87	21
4	133,68	133,19	133,43	21
6	141,59	139,35	140,47	19

Series graph:



Statistics:

Series n = 5	d_h µm	d_v µm	d µm	HV 0.2
$\bar{x}$	135,61	134,69	135,15	20
s	3,36	2,74	3,01	1
ν	2,48	2,03	2,23	4,27

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Hardness measurement report for the 50% bismuth composition

Zwick / Roell HARDNESS REPORT 12.01.2018

Parameter table:

Müşteri : Sn-Bi Testi yapan : MSMM
Malzeme : steel Sarj No : 1

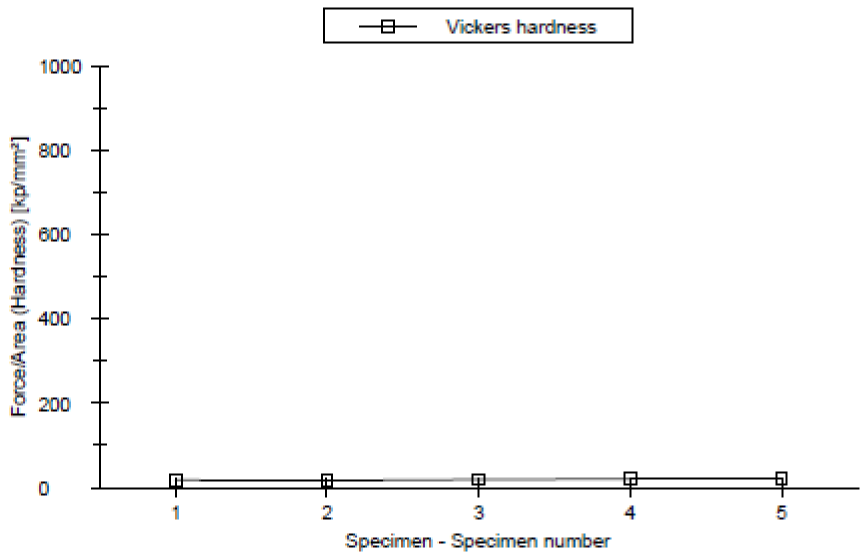
Testing method:

Sertlik metodu : Vickers hardness Objective lens : 20 : 1
Test yükü : 1,961 N Test speed : 25 mm/min

Results:

Nr	d_h µm	d_v µm	d µm	HV 0.2
1	148,19	151,65	149,92	16
2	155,22	153,85	154,54	16
3	144,23	144,18	144,21	18
4	138,07	135,39	136,73	20
5	138,07	137,59	137,83	20

Series graph:



Statistics:

Series n = 5	d_h µm	d_v µm	d µm	HV 0.2
$\bar{x}$	144,76	144,53	144,65	18
s	7,26	8,21	7,66	2
v	5,02	5,68	5,30	10,47

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Hardness measurement report for the eutectic composition

Zwick Roell HARDNESS REPORT 12.01.2018

Parameter table:

Müşteri : Sn-Bi   Testi yapan : MSMM
Malzeme : steel   Sarj No : 1

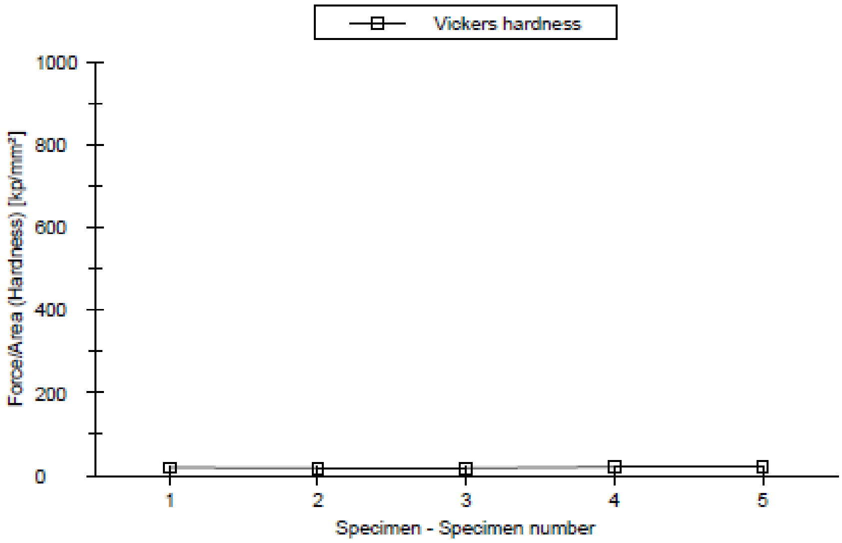
Testing method:

Sertlik metodu : Vickers hardness   Objective lens : 20 : 1
Test yükü : 1,961 N   Test speed : 25 mm/min

Results:

Nr	d_h µm	d_v µm	d µm	HV 0.2
1	143,79	140,67	142,23	18
2	145,55	144,18	144,87	18
3	148,63	147,70	148,16	17
4	138,95	138,47	138,71	19
5	136,75	138,03	137,39	20

Series graph:



Statistics:

Series n = 5	d_h µm	d_v µm	d µm	HV 0.2
$\bar{x}$	142,73	141,81	142,27	18
s	4,84	4,10	4,41	1
ν	3,39	2,89	3,10	6,16

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Specimen technical drawing that is used for the tensile tests