Bulent Aydemir[1)]
Baris Cal[2)]
Serdar Salman[3)]

1) TUBITAK, UME, Gebze, Kocaeli 41470, TURKEY, mail:bulent.aydemir@ume.tubitak.gov.tr

2) TUBITAK, UZAY, Ankara, TURKEY, mail:baris.cal@uzay.tubitak.gov.tr

3)MARMARA UNIVERSITY; Faculty of Technical Education,Goztepe- Istanbul, TURKEY mail:ssalman@marmara.edu.tr

THE ADVANTAGES OF NEW GENERATION HARDNESS MEASUREMENT METHODS

Abstract: *Traditionally hardness has been defined as resistance of a material to permanent penetration by another harder material. To determine hardness properties of material, static methods of measuring hardness Rockwell, Brinell, Vickers, Knoop are widely preferred. Hardness value in all these methods is; the value measured by various methods is based on intentation created by designed forces. These static methods have been used according to international standards which were defined with whole details. In recent years, a new instrumented indentation hardness method (Martens hardness) has developed. By this method, addition to similar results with traditional hardness methods also providing additional results related to mechanical properties of material.*
In this study, the basic structure of the hardness measuring methods and differences are highlighted by comparing each other. Also the reasons of prefering the Martens hardness method are discussed.
Keywords: *Hardness, Hardness measurements, Instrumented indentation hardness, Martens hardness*

1. INTRODUCTION

Hardness is defined as the resistance of a material to various kinds of permanent shape change and penetration by another harder material. Determining the material property analysis and hardness measurement, the methods of measuring hardness Rockwell, Brinell, Vickers, Knoop and instrumented indentation (martens) are well known.

The event of hardness should be discussed after categorizing hardness methods according to such factors as test force, indenter shape and test cycle. Test force is the most important factor, hardness methods can be classified as fixed-load tests, such as Brinell and Rockwell and variable-load tests, such as Vickers and Microvickers to which the similarity rule of hardness applies. There are three indenter shapes: ball (Brinell, Rockwell Scale B), pyramid (Vickers, Knoop, Berkovich), and conical (Rockwell diamond indenter, which has a spherical tip). Testing cycles depends on two factors which are velocity and duration of penetration. There are two main types of hardness measuring: based on measuring the area of indentation and based on measuring the depth of indentation (Table 1 and Table 2).

In all hardness methods the measured hardness value depends on test load and dwell time. However, anyone who has done these measurements would appreciate the difficulties involved in recording accurate measurements. A specific limitation of some hardness methods (Vickers, Knoop) is the microscopic measurement of hardness indentations after the indenter is removed from tested material. Hardness values of obtained from these measurements can vary primarily by limitations from resolution of the optical system, also from the perception of the operator and finally from elastic recovery of the material.

Martens Hardness test has an increasing popularity in last couple of years especially in the fields of applied engineering. Formerly it is known as Universal Hardness Test or Instrumented Indentation, nowadays it is named as Martens Hardness Test and is suitable for hardness testing of most materials. In this method hardness value calculated from indentation depth under working load and variation in hardness value is much less than variation in traditional methods caused by material's visco-elastic and optical properties. During elastic and plastic deformation user can be able to get load and displacement values to determine hardness of material. Also effects of both elastic and plastic deformation, visco-elastic effects during loading can be used for defining other properties of material.

Table 1. Hardness tests based on measuring the area of an indentation

Hardness Method	Sym-bol	Method of Measuring the Dimensions of an Indentation		Definition of Hardness, Hardness = Test Force／Area of Indentation			Indenter			Category			Year of Inven-tion
		Depth measurement	Micros-copic	Surface Area	Projec-ted Area	Unit System	Material	Indenter Shape	Indentation Shape	Macro	Micro	Nano	
Brinell	HB			●			Carbide (Hard Steel)	Ball	Not similar	●			1900
Meyer					●								1908
Vickers	HV			●				Regular square pyramid angle between opposite faces: 136°		●	●		1925
Knoop	HK		● After load is removed		●	CGS		Quadrangular pyramid angle between opposite faces: 172.5° and 130°			●		1939
Berkovich				●	*		Diamond	Berkovich triangular pyramid angle between indenter axis and face: 63.03°	Analogous		●		1951
Instrumented Indentation (Martens)	HM	● When load is applied		●		SI		Berkovich and Vickers are used for nanoindentation; Ball indenters are also used for other applications		●	●	●	ISO 14577 - 2002
(Nanoindentation included)	HIT				●								

* Berkovich defines hardness H, which is determined from the surface area of an indentation and the hardness H', which is determined from the projected area of an indentation.

Table 2. Hardness tests based on measuring the depth of an indentation (Rockwell and Rockwell Superficial)

Hardness Method	Sym-bol	Method of Measuring the Dimensions of an Indentation	Definition of hardness		Indenter: Material	Indenter: Indenter Shape	Indenter: Indentation Shape	Category: Macro	Category: Micro	Category: Nano	Year of Inven-tion
Rockwell	HRC	Measure the depth of indenter penetration. (1) Apply the initial test force todetermine the origin of depth measurement. (2) Increase the load until the full test force is reached. (3) Remove the test force until the initial test force is reached. Then obtain the difference h (mm) in depth between (2) and (1).	Hardness = 100 - 500 h (10/150)	Unit CGS	Diamond	Spherical tip R 0.2 mm Cone angle 120°	Not analogous	•			1919
Rockwell Superficial	HR30N		Hardness = 100 - 1000 h (3/30)					• (Light test load)			
Rockwell	HRB		Hardness = 130 - 500 h (10/100)		Hard steel Carbide	Ball		•			
Rockwell Superficial	HR30T		Hardness = 100 - 1000 h (3/30)					• (Light test load)			

In Vickers hardness; geometry of the indenter, which is identical to the Vickers pyramidal diamond, makes the result theoretically independent from the chosen test force.

Measurement parameters of traditional depth sensing hardness methods (Rockwell and Rockwell superficial) sketched schematically in Figure 1. The left side of the scheme shows the parameter in the traditional hardness test (vickers, brinell etc.). The parameter in the length measurement performed by human observer has been considered to be particularly important in the traditional technique. The right side shows group of the parameters in the Martens hardness test.

Aims of this study are to determine the Martens hardness and traditional Vickers hardness on two tin-based bearing materials. The Vickers hardness was calculated independently from the force-indentation depth curves that were recorded during Martens hardness using EN ISO 14577-1 standard method. Martens hardness were carried out to evaluate the indentation of materials by considering both the force and displacement during plastic and elastic deformation. By monitoring the complete cycle of increasing and removal of the test force, hardness values were determined. The reasons for preference of the Martens hardness methods are discussed

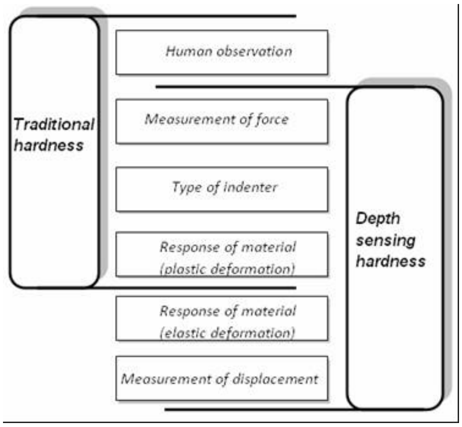

Figure 1. Schematic presentation of the measurement parameters of traditional and depth sensing hardness test methods

2. MATERIALS AND METHODS

Two commercially available tin-based bearing materials were investigated. Chemical compositions of the materials were shown in Table 3. The chemical composition of the materials are determined by optical emission spectroscopy (OES).

Table 3. Chemical compositions of two different tin-based bearing materials.

Material name	Sn	Sb	Pb	Cu	Fe
WM-2	89.264	7.2305	0.4024	3.0320	0.0162
WM-5	60.309	20.251	16.622	2.6670	0.0189

2.1. Hardness tests

Martens hardness of two different bearing materials was examined by Zwick model Z05 testing machine and Vickers indenter shown in Figure 2. Operating test forces were; first of all 250N and 500N, then 9.807N, 49.03N and 98.07N were selected to compare 2 different bearing materials. Maximum test force was applied on the material for 10s and application and removal period of test force was 8s.

Figure 2. Martens hardness testing device

Test force “F” and indenter displacement “h” are measured automatically during the test process, during increasing as well as decreasing test force.
As using a stiff test frame, the indenter displacement represents the sum of the elastic displacement of the sample surface and the plastic depth of the impression. Tests are carried out in the range of ambient temperatures between 23^{o}C and 25^{o}C. Each sample was tested twice and values shown are the averages of ten measurements. During the tests, mechanical behavior of two different tin-based bearing materials are inspected as a function of Martens hardness by load–displacement curves. The hardness values were measured automatically by testing machine software TestXpert.

Martens hardness is determined from the values given by the force/indentation depth curve during the increasing of the test force, preferably after reaching the specified test force. Martens hardness is defined as the test force F divided by As(h) the surface area of the indenter penetrating beyond the zero-point of the contact and is expressed in N/mm^2. Adding, it was shown indentation hardness (H_{IT}), elastic reverse deformation work of indentation (W_{elast}) and total mechanical work of indentation (W_{total}).

Vickers hardness test was used HV1, HV5 and HV10 scales by Zwick testing machine. Test forces 9.807 N, 49.03 N and 98.07 N were selected according to EN ISO 6507-1 to compare with Martens hardness results. Maximum test force was applied for 10s and application and removal period of test force was 8s, too. Vickers hardness values were determined by microscopic measurement of hardness indentations after indenter was removed by operator.

3. RESULTS

Typical Martens hardness force–displacement curves for the two different tin-based bearing materials tested are shown in Figure 3. Martens hardness is measured from the values given by the force-indentation depth curve during the increasing test force, preferably after reaching the specified test force. It includes the plastic and elastic deformation. Test procedure is performed under load or displacement (indentation depth) control. Test force F and the indenter displacement h are measured automatically during test process both increasing as well as decreasing test forces.

Martens hardness tests which were made on two different tin-based bearing materials (WM2 and WM5) were carried out at 250N and 500N test forces. It is clear in Figure 6a and b that WM2 material shows the lowest penetration. Also increase in test force increases the indenter displacement.

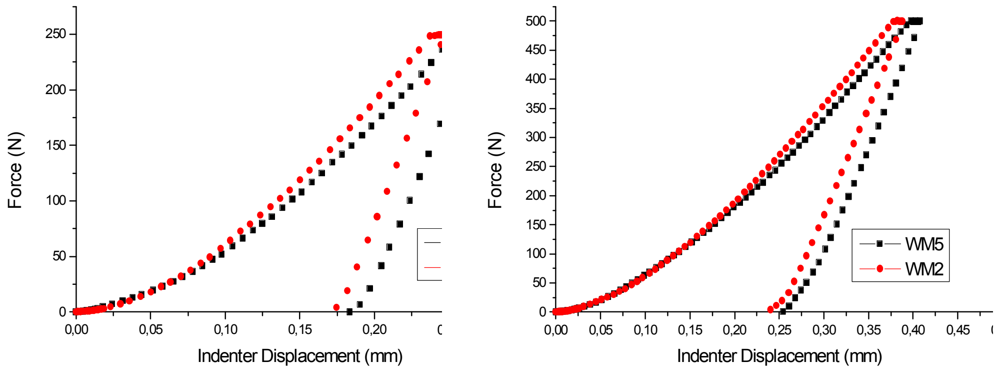

Figure 3. Force–indenter displacement curves showing the loading and unloading curves for two different tin-based bearing materials under 250 and 500 N force

Table 4. Martens hardness results of tin-based materials (WM2 and WM5)

Material	**Martens Hardness**	**Force**	**indentation hardness**	**Total mechanical work of indentation**	**Elastic reverse deformation work of indentation**
Symbol	***HM***	***F***	***H_{IT}***	***W_{total}***	***W_{elast}***
Unit	***N/mm²***	***N***	***N/mm²***	***N.mm***	***N.mm***
WM2	284	249.64	309	16.171	0.387
	295	499.79	320	45.771	0.970
WM5	227	249.51	257	19.183	1.224
	239	499.85	263	52.403	2.351

When the results given in Table 4 were evaluated, rate of increase in force is changing Martens hardness value of about 4-5% for different sample materials. It is found that the Martens hardness values of the WM2 materials are higher than WM5 in all forces. Similarly, there are changing in rates of calculated work values. It was shown elastic reverse deformation work of indentation (W_{elast}) and total mechanical work of indentation (W_{total}) values, gives information about visco-elastic behavior of the specimen materials.

Table 5. Martens and vickers hardness results of tin-based material

Material	**Force**	**Martens Hardness**	**Vickers Hardness calculated**		**Vickers method**	**Force**	**Vickers Hardness**
Symbol	***F***	***HM***	HV_{cal}		***H***	***F***	***HV***
Unit	***N***	***N/mm²***	**-**		**-**	***N***	**-**
WM2	9.807	260.8	24.6		HV 1	9.807	26.9
	49.03	276.1	26.1		HV 5	49.03	23.5
	98.07	275.4	26.0		HV 10	98.07	23.4

As seen in Table 5, Martens and Vickers hardness measurements done for same material (WM2). By using Martens hardness results, Vickers hardness values (HV_{cal}) was calculated with the following formula.

$HV_{cal} = 0{,}0945\ H_{IT}$ (according to EN ISO 14577-1 F3 formula)

Martens hardness values were vary up to 3.68% from the average for the same material and different forces. However, the Vickers hardness values were vary up to 9.34% from the average. Also converted Martens hardness results have standard deviation of 0.82HV and Vickers hardness results have standard deviation of 1.99HV.

4. CONCLUSION

This study demonstrated that the Martens and Vickers hardness are dependent on force between 9,807 N and 98,07 N. The Vickers hardness calculated from the force-indentation depth curve (HV_{cal}) vary up to 3.68% from the average hardness and standard deviation 0.82HV. On the contrary, HV values measured using the traditional Vickers method, were vary up to 9,35% from the average hardness and standard deviation 1.99HV. Martens hardness tests were carried out to evaluate the indentation of materials by considering both the force and displacement during plastic and elastic deformation. Observer eliminated in this test method so errors and deviations caused by observer is eliminated as well. Vickers hardness are test methods that determination among majority of the human observation.

Standard deviation shows repeatability, reliability and quality of test process. How much standard deviation is small this much reliable, repeatable and high quality measurements done. According to results in Table 5, Martens test results are more reliable, repeatable and higher quality than Vickers test results.

Additionally, Martens hardness is new method and able to provide additional information about the mechanical properties of material such as elastic and plastic deformation limits etc. Especially, Martens hardness method has advantages such as determination of hardness for changeable forces and no need to human observation.

Therefore, Martens hardness method will become preferred method as it is not only time saving method but also can give more information about material properties compare to traditional hardness testing methods.

REFERENCES:

[1] Aydemir B., Sertlik Olcum Yontemlerinin Bugunu ve Yarini, Metal Dunyasi, Sayi 189, Sayfa 84-87, 2009

[2] Bora M.O., Coban O., Sinmazcelik T., Gunay V., Zeren M., Materials and Design 31 2707–2715, 2010

[3] EN ISO 14577-1,2002, Metallic materials -- Instrumented indentation test for hardness and materials parameters -- Part 1: Test method

[4] EN ISO 6507-1,2005, Metallic materials -- Vickers hardness test -- Part 1: Test method

[5] Hardness testing with Zwick, Zwick/Roell, Dokuman no FP 303, 2009

[6] Shakeel A.S., McCabe J.F., Bull S., Rusby S., Wassell R.W., Dental Materials 23 1079–1085, 2007

[7] Ullner C., Beckmann J., Morrell R., Journal of the European Ceramic Society22 1183–1189, 2002

[8] Ullner C., Reimann E., Kohlhoff H., Subaric-Leitis A., Measurement 43 216–222, 2010

[9] Yamamoto T., The Present and Future of Hardness Standard Blocks Solid State Phenomena Vol. 118 pp 457-462, Trans Tech Publications, Switzerland, 2006