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Hardness Variations as Affected by Bar Diameter of AISI 4140 Steel

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***Abstract*—**Hardness of the widely used structural steel is of vital importance since it may help in the determination of many mechanical properties of a material under loading situations. In order to obtain reliable information for design, properties homogeneity should be validated. In the current study the hardness variation over the different diameters of the same AISI 4140 bar is investigated. Measurements were taken on the two faces of the stock at equally spaced eight sectors and fifteen layers. Statistical and graphical analysis are performed to asses the distribution of hardness measurements over the specified area. Hardness measurements showed some degree of dispersion with about ± 10% of its nominal value provided by manufacturer. Hardness value is found to have a slight decrease trend as the diameter is reduced. However, an opposite behavior is noticed regarding the sequence of the sector indicating a nonuniform distribution over the same area either on the same face or considering the corresponding sector on the other face (cross section) of the same material bar.

***Keywords*—**Hardness; Hardness variation; AISI 4140 steel; Bar diameter; Statistical Analysis.

I. INTRODUCTION

HARDNESS may be defined as the resistance to plastic deformation and, for those who are concerned with the mechanics of materials; hardness is more likely to mean the resistance to indentation. Knowledge of hardness helps in the determination of some common mechanical properties of the material under loading.

A proper material selection to secure safety and economic task of a designed structural element requires the knowledge of the necessary minimum of the most important properties which meets performance demands. This requires the knowledge of work condition of structural element on the base of constructional calculations or experimental investigations. Usually the sufficient characteristics of constructional materials are their mechanical properties. Among the important properties, hardness (surface and homogeneity) represents one of the most important factors affecting product performance and its durability. Information about material properties should be available to consider the effects of undergoing loading conditions not only on the product outer surface but also in the zone on specified distance from the surface.

Homogeneity of material properties depend to great extents on its physiomechanical characteristics. Hardenability [1] of carbon steel usually defines the thickness of martensite layer after quenching. For instance, if the cast wall is not fully quenched on martensite and it contains products of diffusional decomposition of austenite the heterogeneity of the mechanical properties on the cross section of wall can occur and the mechanical properties of the external layers of quenched wall will be higher compare to the core. The content of alloying elements should not be higher than necessary for providing the hardenability adequate to size of element and way of quenching. If the distribution of stresses on the section is such that stress decreases towards the section centre it is possible to use the cast steel with lower, but sufficient hardenability to secure required mechanical properties, adequate to the loads on the cross section.

There is a clear distinction between the hardness and the hardenability of a material. The hardness measured on a porous P/M material is referred to as an apparent hardness. For a given microstructure, the apparent hardness of a ferrous P/M material is related to the density of the material; apparent hardness increases as density increases.

Hardenability refers to the relative ability of a ferrous alloy to form martensite when cooled from a temperature in the austenitic region of the phase diagram. Hardenability is commonly measured as the distance below a quenched surface where a metal exhibits a specific hardness (50 HRC for example) or a specific percentage of martensite in the microstructure.

To ensue that the produced products meet the customer's specifications, manufacturing organizations need to know the quality of the measurement data used in controlling and monitoring the relevant processes. One of the most common reasons for low quality products is the variability involved in the controlling data and measurements.

The overall variability may be related to one or more of the three main distinguished functional features: products interchangeability, appraisers or operators and equipment repeatability. The interaction between the variability in the measurement system and the environment usually deteriorates the ultimate product quality. Therefore, it is strongly to keep

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the variability of the measurement system as small as possible compared with the total variability of the manufacturing process.

Measurement system analysis (MSA) [2,3] is an experimental and mathematical method of determining how much the variation within the measurement process contributes to overall process variability. MSA involves GRR (gage repeatability and reproducibility – Gage R&R) studies to evaluate measurement systems. It is a system designed to help engineers and quality professionals assess, monitor, and reduce measurement system variation. It teaches how to conduct measurement system studies including linearity, stability, repeatability and reproducibility. MSA helps conform to ISO 9000 and ISO/TS 16 949:2002 requirements as well as AIAG standards. Measurement Systems Analysis teaches how to develop working standards that are traceable to the ISO.

II. Experimental Setup and Instrumentation

A 200 mm length and 150 mm diameter round hot rolled and annealed AISI 4140 steel bar is used in the current analysis. Mechanical properties and chemical composition, as provided by manufacturer, are listed in Tables I. To prepare the workpiece for testing, several preliminary operations were performed. The stock was prepared by mounting it on a manual lathe with a 4-jaw chuck. In order to support the size and weight of the stock material a center drill was used to create a location for a live spindle to seat. The end of the stock material was faced to create a flat surface on the end of the workpiece. This procedure was done on the opposite side (face) and then repeated for all the stock material bars.

A section (disk) about 20 mm thickness was taken off of each of the three materials stocks for possible further offline chemical and/or mechanical examination testing.

Hardness testing was taken from the same billet as the stock material being tested using a portable Rockwell testing apparatus. Device calibration using its reference block was performed for measuring credibility. Calibration procedures were performed so that to resemble the real stratifying distribution as shown by Fig. 1.

The current study represents a partial investigation of a general research including two different stages. The first (current) stage was the hardness measurement on both sections of each material bar as described by Fig. 1. This included eight sectors of 45deg angular space and nine radial layers which led to a total of 160 readings for both faces of each of the three material types.

The second stage, however, will consider the study of hardness variability on the longitudinal surface, as affected by cutting conditions: speed, feed and depth of cut; of each of the three material bars as described in Fig. 1. Data will be published in the near.

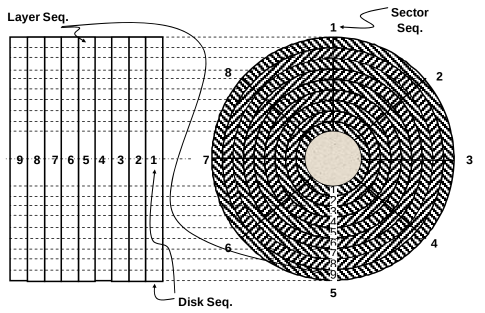


Fig. 1 Stratifying design on cross-section for hardness measurement

III. Instrumentation Mathematical Modeling of Hardness Variation

A. *Measurement and analysis for Side A*

Table II gives simple descriptive of the whole data representing hardness of Side A of the material. Although the mean value, HRB= 101.851, is close to the nominal one provided by the manufacture, 99, Table I, a wide dispersion can be observed over all sectors and layers, Table II.

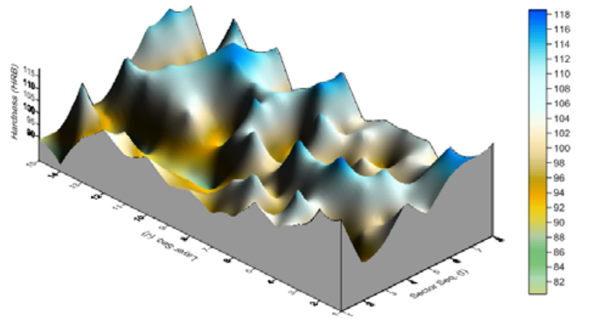
Hardness distribution over the entire cross sectional area is shown in Fig. 2 as three dimensional and contour graphs.

TABLE I
Mechanical properties and chemical composition of the employed materials

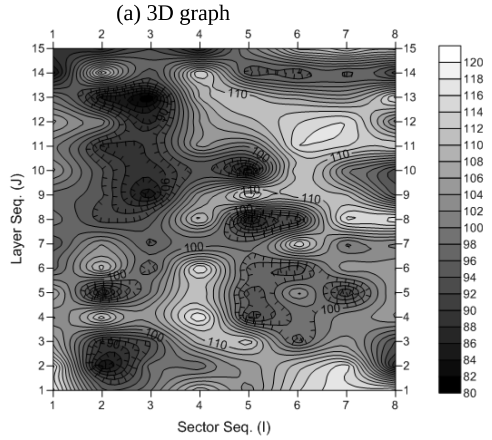
Material	Mechanical Physical Properties				Chemical Composition (%)							
	Tensile Stren. (Mpa)	Yield Stren. (Mpa)	Hardn. (HRB)	Elo. (%)	C	Mn	Si	P	S	Cr	Mo	Ni
AISI 4140	1093	945	99	14	.41	.88	.28	.018	.009	1.01	.18	.10

TABLE II
DESCRIPTIVE STATISTICS OF SIDE A OF AISI4140

	N	Minimum	Maximum	Mean	Std. Deviation
Hardness	119	79.7	118.9	101.851	10.2564
Valid N (listwise)	119				



(a) 3D graph

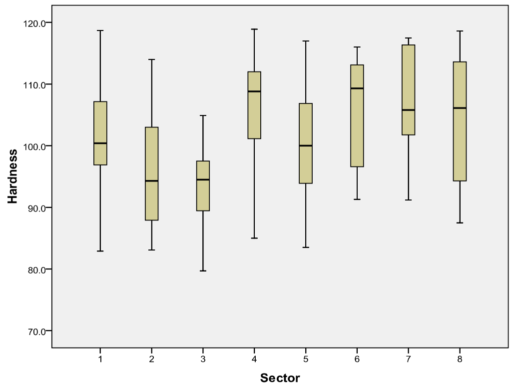


(b) Contour graph

Fig. 2 Three dimensions and contour graphs for Side A of AISI 4140

As show by Fig. 3, data are randomly distributed without any significant paten. This is significantly observed although what is shown in Fig. 3.a where a very slight increase in hardness is noticed as at advanced sector sequences. Trend weakness is evident from the trend statistical criteria that are listed in Table III.

A reversed trend is observed regarding the effect of layer sequence on the hardness distribution, Fig. 3. Data indicates, Fig. 3.a, that hardness is slightly increased toward the center of the bar.



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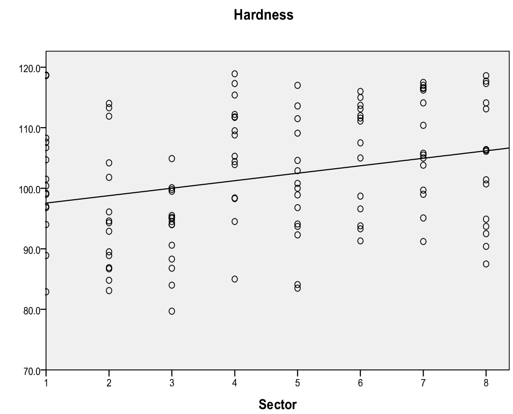

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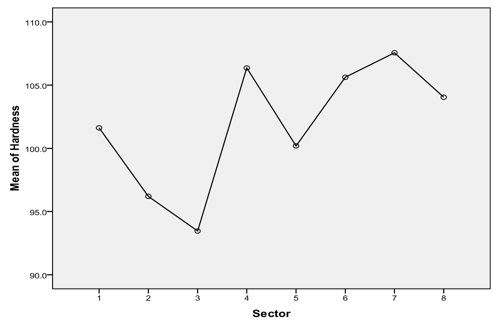
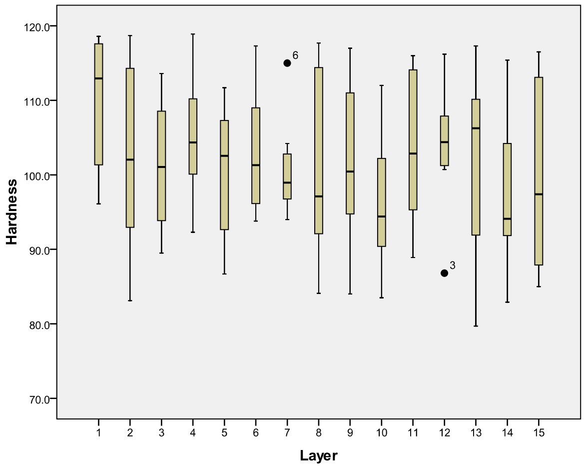


(c)

Fig. 3 Hardness distribution trend over sectors sequence

However, as explained by Fig. 5, hardness normal probability indicates an acceptable distribution.



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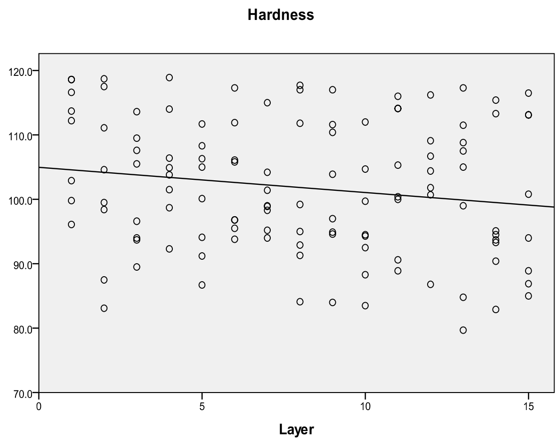

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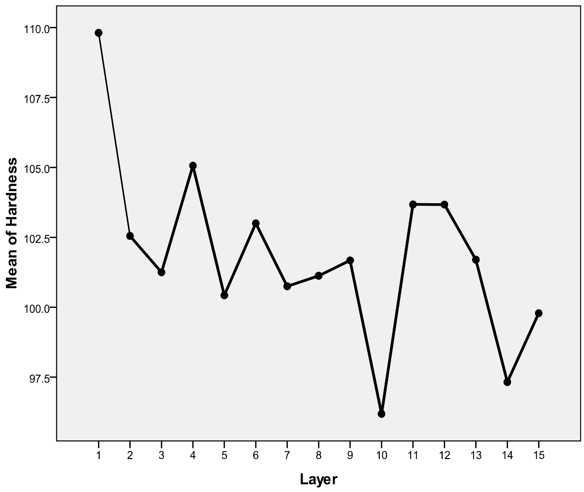
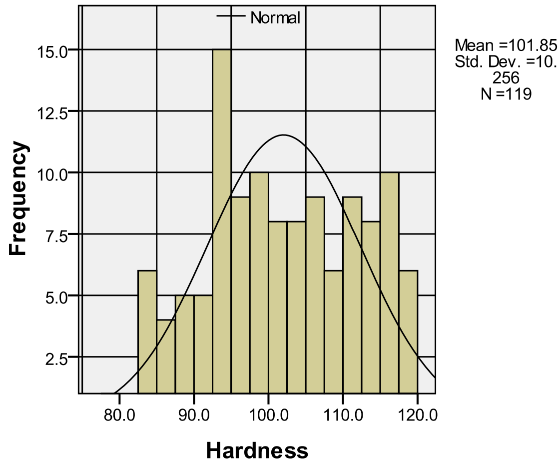
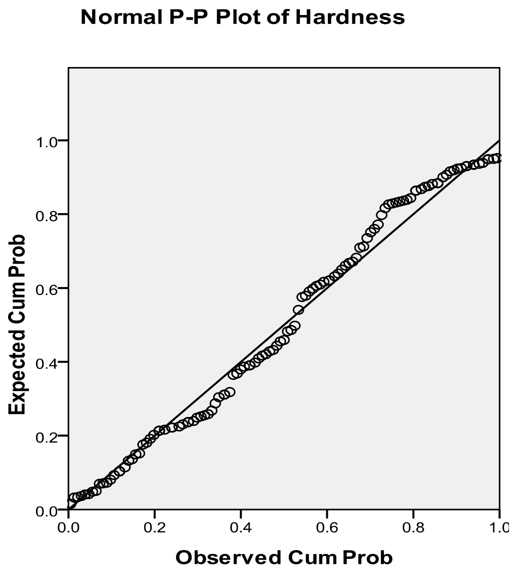


(c)

Fig. 4 Hardness distribution trend over layers sequence



(a)



(b)

Fig. 5 Statistical Criteria for hardness variation of side A of AISI 4140

B. Measurement and analysis for Side B

Hardness measurement distribution on the other side of the bar, Side B, is represented by Fig. 6 as three dimensional and contour graphs. Basic statistical information of the entire set of data on side B is listed in Table IV.

As shown by Fig. 7, the data are randomly distributed with no specific pattern but with relatively wide validation domain. However, a very slight increase in hardness is noticed as at advanced sector sequences. Regarding the effect of layer sequence on the hardness distribution, Fig. 7.b, data indicates that hardness is slightly increased toward the center of the bar.

TABLE III
MODEL SUMMARY AND PARAMETER ESTIMATES OF THE EFFECT OF SECTOR SEQUENCE ON HARDNESS

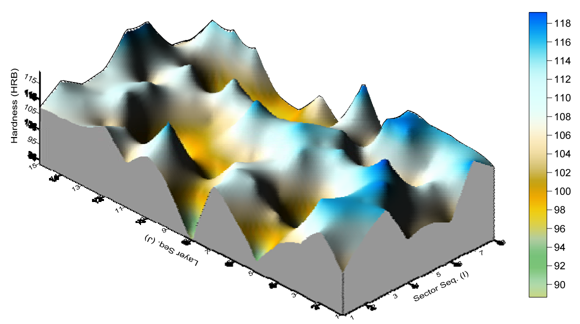
Dependent Variable:Hardness

Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Linear	.077	9.775	1	117	.002	96.310	1.235

The independent variable is Sector.

TABLE IV
ONE-SAMPLE STATISTICS (T-TEST)

	N	Mean	Std. Deviation	Std. Error Mean
Hardness	119	101.851	10.2564	.9402



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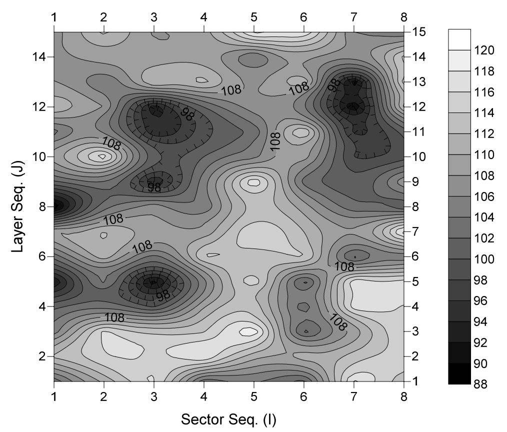

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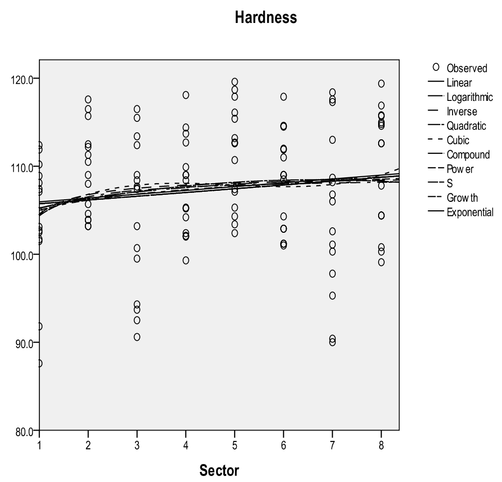
Fig. 6 Three dimensions and contour graphs for Side B of AISI 4140



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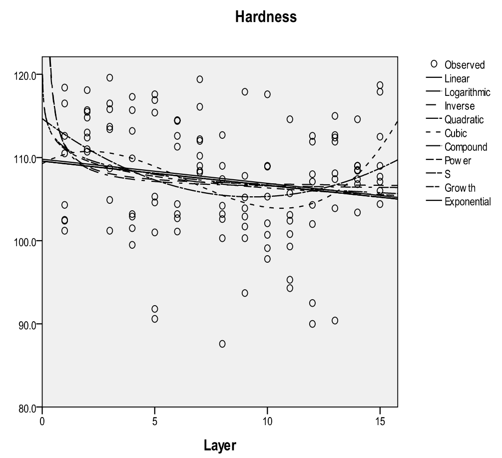

(b)

Fig. 7 Hardness distribution trend over layers sequence for Side B

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C. Measurement and analysis for both Sides A and B

In this section data for both sides are merged together and the analysis is repeated considering the entire data (240 data points). Basic statistical information of the entire set of data is listed in Table V. Mean hardness value is found around HRB=103 comparing to the nominal value of HRB=99 provided by the manufacturer, Table I. Standard deviation of the data based on 99% confidence interval is found 6.33 to yield a HRB range of (89 to 111.3). However, probability distribution of the data in Fig. 8 suggests some deficiency in the frequency of the data extremes, especially the high value measurements. Accordingly, the data with mean values are of less frequency.

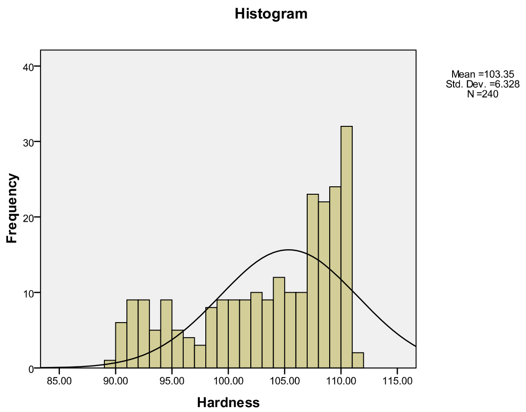
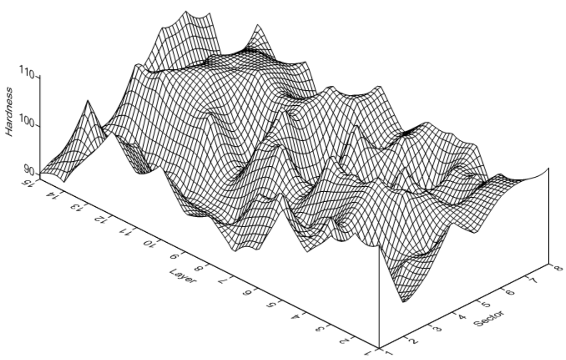


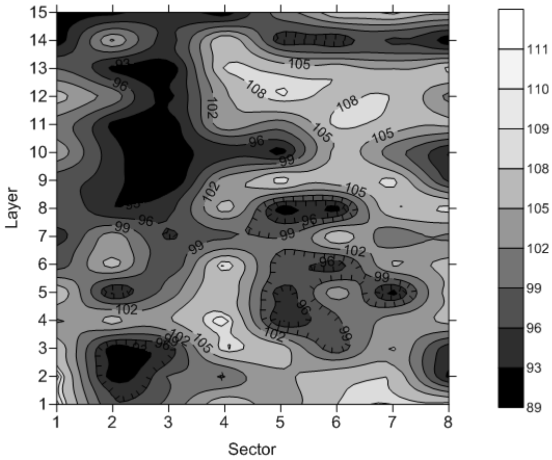
Fig. 8 Frequency distribution for both sides

These observations are reflected in the measurement actual distribution of the data either on three dimensions or contour graphs, Fig.9.

Further evidence of data distribution may be explained using data distribution regarding either layer or sector as shown in Fig. 10. Regarding data distribution on different bar diameter or, layer, Fig. 10.a, the previous drawn conclusion is supported that hardness increases as diameter decreases. This trend is reversed regarding the sequence of sector.

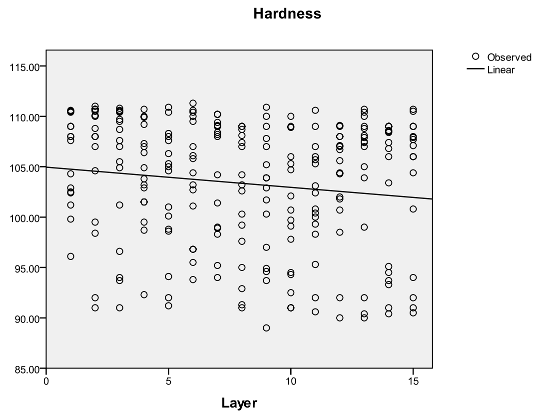


(a) 3 Dimensional graph



(b) contour graph

Fig. 9 Three dimensions and contour graphs for both sides of AISI 4140



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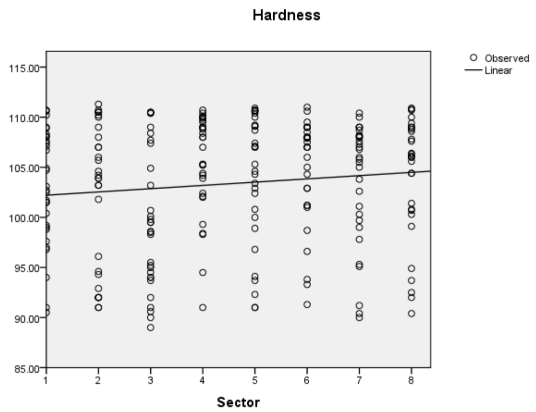

(b)

Fig. 10 Hardness distribution for both sides

TABLE V
STATISTICS FOR SIDES

Hardness

N	Valid	240
	Missing	0
Mean		103.3529
Std. Error of Mean		.40845
Std. Deviation		6.32760
Range		22.30
Minimum		89.00
Maximum		111.30

IV. CONCLUSION

A prior information about hardness variation should be accounted for in advance to ensure better design of steel constructions and products. It is very common that the material is not of homogenous mechanical properties hence, it is desired to consider within the material selection and design stages. In the current study the hardness variation over the different diameters of the same AISI 4140 bar is investigated. Measurements were taken on the two faces of the stock at equally spaced eight sectors and fifteen layers. Statistical and graphical analysis are performed to asses the distribution of hardness measurements over the specified area. Hardness measurements showed some degree of dispersion with about ± 10% of its nominal value provided by manufacturer. Hardness value is found to have a slight decrease trend as the diameter is reduced. However, an opposite behavior is noticed regarding the sequence of the sector indicating a nonuniform distribution over the same area either on the same face or considering the corresponding sector on the other face (cross section) of the same material bar.

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