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Some Relationships among Residual, Micro-Structure, and Micro-Hardness Ensued due to Vertical End Milling Operations.

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SOME RELATIONSHIPS AMONG RESIDUAL STRESSES, MICRO-STRUCTURE, AND MICRO-HARDNESS ENSUED DUE TO VERTICAL END MILLING OPERATIONS

بعض العلاقات بين الاجهادات المتخلفة والتركيب المجهرى
والصلادة الدقيقة بعد عمليات التفريز الطرفى الرأســــى

BY

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خلاصة :
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يعتبر دراسة الاجهادات المتخلفة نتجة تشغيل المعادن ذات أهمية كبرى فى التطبيقات الصناعـــة مثل صناعة الطائرات اذ أنها تؤثر على الخصائص الميكانيكية للمواد وعلى أمان وأستقرار الأجـــزاء المنتجة .

وفى هذا البحث أجريت اختبارات تفريز طرفى رأسى لألواح النحاس الأصفر سهل التشغيل فى ظروف قطع متباينة ، تم قدرت اجهادات الضغط المتخلفة بالأسطح المشغلة للعينات المختبرة وذلك بقياس مدى ترخيم الالواح بمدازالة طبقات سطحية منها .

كما تم فحص التركيب المجهرى للعينات وتقدير التغير فى منوسط حجم الحبيبات على أعماق متباينة من سطح القطعة المشغلة . ولقد تم تنمى الجوانب المشغلة للألواح باستخدام حامض النيتريـــك بتركيز ٣٢.٥٪ لاظهار حدود الحبيبات بها . تم أجريت اختبارات قياس الصلادة الدقيقة للعينات على أحرف الجوانب التى تم تفريزها وذلك باستخدام حمل قدره ١٠٠ جرام(١٠ نيوتن) بدءا من سطح العينة وحتى العمق الذى تثبت عنده قيمة رقم الصلاده الدقيقة .

وقد بينت نتائج التجارب أن قيم الاجهادات المتخلفة والصلادة الدقيقة القصوى تحدث آنيا عنـد القيم الدنيا لمتوسط حجم الحبيبات وذلك قرب أسطح الالواح . كما وجد أنه نزولا من تلك المواقــع ولاعماق أكبر فان قيم كل من الاجهادات المتخلفة والصلادة الدقيقة تتناقى بينما تتزايد أحجام الحبيبات وقد تم استنتاج العلاقات البينية التى تربط تلك المتغيرات الثلاثة مع بعضها حال اجراء التجـــارب المشار البها .

ABSTRACT-

The study of residual stresses due to machining is a very important facet in industrial applications such as in aircraft industry. They are known to affect the mechanical properties, stability and safety of the components.

End milling tests were performed on free machining brass plates. Compressive residual stresses were left within the machined surfaces. Assessments of the distribution of resisdual stresses underneath the machined surface have been given via a post removal technique. Microstructural examinations were made utilizing an optical microscope. Nitric acid of 32.5% concentration was used as etchant for the sides of the plates to reveal the proper grain boundaries. The change in the average grain size with the sub-surface depth, after milling, was determined.

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The milled sides of the free machining brass specimens were subjected, as well, to micro-hardness examinations via a 100 gram load starting from the specimen surface till no change in micro-hardness were noted. Relationships between the knoop micro-hardness values and the sub-surface depth were, then, obtained.

All the test results indicated that maxima for residual stresses and micro-hardness together with minima for average grain size occured near the surface of the plates. Moreover, It was found that starting off such locations values of residual stresses and micro-hardness decreased while grain size increased Inter-relations among these three variables under such conditions were, then, deduced.

NOMENCLATURE

C	A constant for the indentor given by manufacturer	
d_m	Average Grain Size	um
E	Young's modulus of Elasticity of workpiece material	GPa
h	Thickness of test specimen	m m
K	A constant measuring the extent to which dislocations are piled	
L_o	Length of test specimen	m m
L	The major diameter of micro-hardness indentor	m m
N	Speed of rotation of milling machine spindle	R.p.m
P_a	Applied load in Micro-Hardness Tester Indentors	N
S_m	Longitudinal feed rate of test specimen	m/s
t	Depth of cut	m m
a	Thickness of each removed layer while etching	m m
Δ_a	Thickness of etched layer	m m
Δ_f	Deflection of test specimen after etching	m m
S	Longitudinal residual stress	MPa
σ_{yp}	Yield stress of the material	HPa
σ_o	A stress representing a measure of the intrinsic resistance to dislocation motion.	HPa

1.INTRODUCTION

Many recent studies on residual stresses produced due to machining processes have been presened by Field [1], Barash and schoech [2], and Lui and Barash [3]. They employed high strength materials, as those utilized in air-craft industry, being machined by various processes such as milling, grinding, electrical discharge machining,...etc.

It has been generally observed that, for a given workpiece material, the nature and magnitude of the residual stresses in machined surfaces depend on the cutting conditions such as the cutting speed, feed rate, depth of cut, tool geometry, and whether or not a lubricant is used [4].

It has been found that absolute values of the residual stress near the surface are high and then decrease continuously with an increase in the depth beneath the machined surface [4,5].

It has also been found that the depth of the stressed layer and the magnitude of the maximum residual stress tended to increase for higher depths of cut and greater feed rates and with the decrease in the cutting speed [5].

It is obvious that the residual stresses cause alterations in workpiece grain sizes. Machining processes result, mostly, in workpiece hardening depending on the severity of machining. It is expected, therefore, that the machining conditions will control all three inter-related phenomena viz; residual stresses, micro-structure and micro-hardness. Milling operations are often used to even flat workpieces. However, little published data exist about the ensued residual stresses, micro-hardness, and grain size variations for the milled workpieces. These phenomena inter-relationships are not available in the literature. Such variables are closely related to workpiece surface integrities, mechanical properties and performance.

The objective of the present research is to assess the role of the change in vertical end-milling conditions upon the afore-mentioned variables. Possible inter-relationships among them will be forwarded.

2.EXPERIMENTAL PROCEDURE AND ANALYSIS

2-1 PREPARATION OF TEST SPECIMENS

An experimental program has been designed to assess the residual stresses ensued in free machining brass plates due to vertical milling operations. The available brass was selected as a test material since it is free machining non-ferrous alloy which introduces little tool wear. Wear is known to cause additional superimposed residual stresses.

Workpieces made of free-machining brass plates having dimensions of 100x18x16 mm and of a chemical composition of 62.5% Cu, 33.9% Zn, 3.1% Pb, and 0.5% Sn were employed in the as-recieved condition. The specimens were ground from the as-recieved condition to take off any irregularities in specimen surfaces. The grinding operations were performed employing a surface grinding machine at a speed of 40m/s, depth of 0.01mm and longitudinal feed of 0.05m/s. Ample cooling were ensured to avoid superimposing additional residual stresses.

Table (1) The employed Milling Conditions

Spindle Speed, N,R.P.m.	Depth of Cut, $t, \times 10^{-3}$ m	Feed Rates, S_m, $\times 10^{-3}$ m/s
80, 160	0.1	0.4,0.5,0.75, 1.08,1.58
400,800	0.1	0.4,0.75,1.58
160,400,800	0.4,0.8,1.2	0.75

The specimens were, then, face-milled using a 12-teeth H.S.S helical cutter of 50mm diameter and a helix angle of 15°. The plates were machined under the unlubricated face-milling conditions according to the details given in Table (1). Fig. (1) gives the vertical end-milling employed set-up.

2-2. DEFLECTION MEASUREMENTS

After milling utilizing the predetermined conditions as given in Table (1), the specimens were removed from the clamping device and then etched via the following procedure:
(1) Specimen sides were masked utilizing suitable wax to protect the specimen from acid attacks. This keeps the width of the specimen unchanged during the etching process.

(2) The initial weight of the specimen was recorded utilizing an electric balance of ± 0.0001 Grams sensitivity.

(3) The etching process was performed using nitric acid (HNO₃)of 15% concentration. The etching time required to remove a depth of 50 um from the specimen surface was estimated by calculating the volume of the material to be removed, v, via the following relationship:

$$V = A \times a \qquad\qquad ...(1)$$

where A is the surface area of the specimen, a is the thickness of the material to be removed. The surface area of the specimen was taken to be 0.0018 m² and the thickness of the layer to be removed was considered to be 0.05×10^{-3} m. In order to calculate the corresponding weight, the density of brass was taken to be 8.3 gr./cm³.

The necessary etching time was determined by trial and error process by emmersing the specimen in the etchant for different times. The time which gave a removed weight equal to 0.747×10^{-3} Kg was taken as the time required to remove a 0.05×10^{-3} m depth. This time was considered constant throughout the experimental work.

(4) After the removal of the specified layer (0.05×10^{-3} m), the specimen was cleaned using running water in the specially designed set up. The deflection of the plates was measured via a sensitive dial gauge ($\pm$ 1um) placed at the plate central position. Downward deflection means that the surface after machining is left with residual compressive stresses. After the removal of the specified layer, and measuring the deflection, the dial indicator was readjusted in order to be of the same initial position for the height. New deflection measurements were then recorded. The procedure was repeated until no further deflection was noted which signified the end of the stressed layer.

The longitudinal (axial) residual stresses were determined via Davidenkov's approximate formula [6] which states that:

$$S = [4 \ E \ (h - a)^2/3 \ L^2]. \ (\Delta f/\Delta a) \qquad ...(2)$$

It has been found [7] that all residual stresses ensued due to vertical milling were of compressive nature with maxima some distance below the machined surface in all cases. The distance was found to be about 0.05×10^{-3} m Moreover, the residual stress distributions were found to be of similar exponential trends (see Figs.2,3).

2-3. MICRO-STRUCTURAL ANALYSIS

The importance of grain size in governing the strength and fracture toughness of plates focuses a special attention on the role of processing in creating fine grains [8]. In order to determine the average grain size of specimens micro-structural examinations were performed. A mechanical saw was employed to shear the specimens transversely. The specimens were prepared for microscopic examination by wet prepolishing utilizing nylon polishing powder (1 um to 7 um). The metallographic structure was revealed by etching the polished specimens using a solution of HNO₃ of 32.5% concentration. The etching time ranged between 5 to 30 seconds.

Grain size measurements were taken out of enlarged photos for workpieces via the camera of a special metallurgical microscope. Different photos were taken in two perpendicular directions in order to arrive at the average grain size in the feed direction for any given depth under-neath workpiece surface.

In order to determine the average grain size, straight lines were drawn on the photographic pictures parallel to the specimen surface. The distance between the lines were taken as 5 mm which is equivalent to an actual distance of 100 μm in practice).

2-4. MICRO-HARDNESS TESTING

The knoop hardness number (KHN) is defined as follows :

$$KHN = P_a / L_o^2 \text{ q} \qquad \qquad ...(3)$$

The load P_a applied during micro-hardness testing must be small and, hence, requires excercising extreme care in all stages of testing [8]. The projection of the knoop indentation in this study is a flat rhomb, knowing that the applied load Pa = 50 grams (0.5 N) acted upon for a period of 12 seconds.

All readings were taken on the machined surface in the direction of the measured residual stress. The recorded values of knoop micro-hardness were the mean of three readings on the surface. Such readings were taken 50 μm apart beneath the specimen surface.

3. TEST RESULTS AND DISCUSSION

3-1. RELATIONSHIPS BETWEEN RESIDUAL STRESSES AND MICRO-STRUCTURE

It has been emperically established by Hall [9] and Petch [10] that the material's yield stress is related to the grain size by the relationship :

$$\sigma_{yp} = \sigma_o + k.d_m^{-0.5} \qquad \qquad ...(4)$$

The Hall-Petch equation, Equation (4), has been found to express the grain size role in governing the flow, fracture and fatigue strength at any plastic strain up to fracture [2].

Fig. (4) gives relationships among the longitudinal residual stresses, S, and the average grain size, d_m, at various depths of cut viz; 0.4, 0.8 and 1.2 x 10^{-3} m at a cutter speed of 160 R.p.m. It can be seen that as the compressive residual stress, S, decreases, the average grain size, dm, increases. For the same residual stress, the average grain size increases as the depth of cut decreases. For the same grain size, the residual stress increases as the depth of cut decreases.

Fig. (5) illustrates a similar situation for a spindle speed of 400 R.p.m. Fig. (6) illustrates the case of spindle speed of 800 R.p.m. It can be seen that the material becomes less stressed for higher spindle speeds.

3-2. RELATIONSHIPS BETWEEN THE MICRO-HARDNESS AND MICRO-STRUCTURE:

Figs.(7 - a & b) give values of the knoop hardness number, KHN, for specimens at depth of cut of 0.8 and 1.2 x 10^{-3} m at cutting speeds of 160, 400 and 800 R.p.m. It can be deduced from this figure that as the spindle speed increases, the surface and sub-surface micro-hardness decreases. However, the depth of the stressed layer appears to be un-affected by the change in speed.

Fig. (8) illustrates some relationships between the average grain size and the micro-hardness for depth of cut, t, of 0.8 and 1.2 x 10^{-3} m at spindle speeds

of 160, 400, and 800 R.p.m. For the same depth of cut and spindle speed; the grain size is seen to increase as the micro-hardness number decreases. It can, also, be shown that the micro-hardness for the same grain size increases for higher cutting speeds. Whereas, the mean grain size increases due to higher cutting speeds for the same micro-hardness number.

3-3. RELATIONSHIPS BETWEEN MICRO-HARDNESS, MICRO-STRUCTURE, AND RESIDUAL STRESSES:

Fig. (9) shows some plots for the relationships among the axial compressive residual stresses, average grain size, and knoop micro-hardness number throughout the sub-surface depth of the vertically milled free machining brass specimens. It can be seen from Fig. (9) that both the micro-hardness and the compressive residual stresses decrease at greater sub-surface depths and for shallower depths of cut. On the other hand, the mean grain size was found to increase for lower micro-hardness and smaller axial compressive residual stress under the employed test conditions.

4. CONCLUSIONS

From the above-mentioned experimental study of the residual stresses, micro-structure, and micro-hardness of vertically milled free machining brass plates, it is concluded that:

(1) The level of the ensued axial compressive stresses rises for greater depths of cut and for slower spindle speeds.

(2) Similar axial compressive residual stress patterns as ensued in workpieces due to vertical end milling were obtained with maxima at an identical sub-surface depth regardless of variations in cutting conditions.

(3) Definite negative correlations exist among the values of mean grain size and both of axial residual stresses and micro-hardness for vertically end-milled workpieces.

(4) Approximate linear relationships exist between the ensued axial residual stresses and the reciprocal of the square root of the mean grain size of free machining brass plates depending upon the depth of cut and the spindle speed for a fixed feed rate.

(5) The slopes of such relationships increase for smaller depths of cut and for higher spindle speeds.

(6) Hyperbolic form relationships hold between the mean grain size and the micro-hardness of the work piece. The level of micro-hardness is found to rise for greater depths of cut and for higher spindle speeds. Such values level-off upon approaching the level of workpieces original mean grain size before machining at sub-surface depths greater than 250 um.

5. ACKNOWLEDGEMENT

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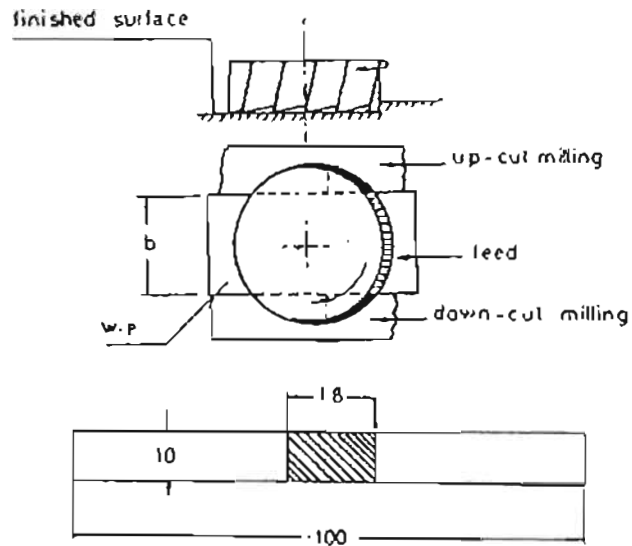[11] Armstrong, R.W., Metall. Trans. Vol. 1, 1970, pp. 1169-1176.

finished surface

up-cul milling

b

leed

w.p

down-cul milling

|—18—|

| 10 | ///// | |

|—— 100 ——|

Fig.(1): A Schematic Diagram for the
Vertical End-Milling Set-up.

Subsurface Depth, µm

$N = 160$ R.P.M

$l = 0.1$ mm

feed rate$(S_m x10^{-3} m/s)$

• 0.4
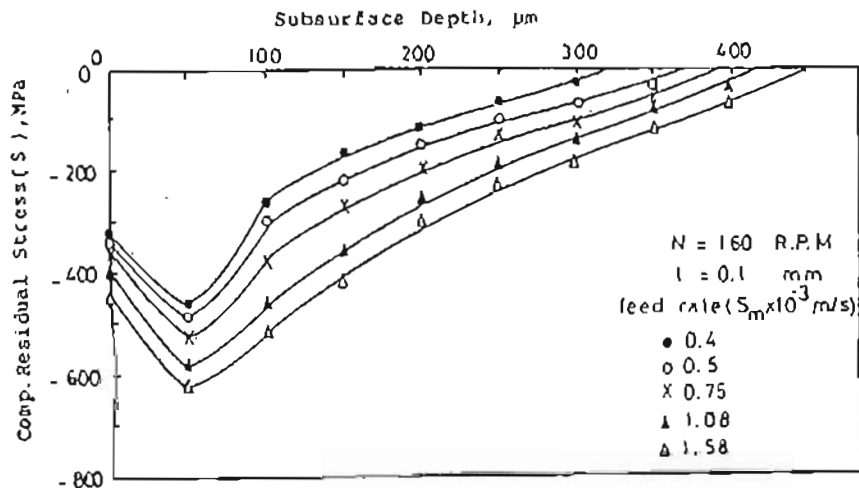o 0.5
X 0.75
▲ 1.08
△ 1.58

Comp. Residual Stress(S), MPa

Fig. (2) : The relationships between the sub-surface depth and the axial compressive
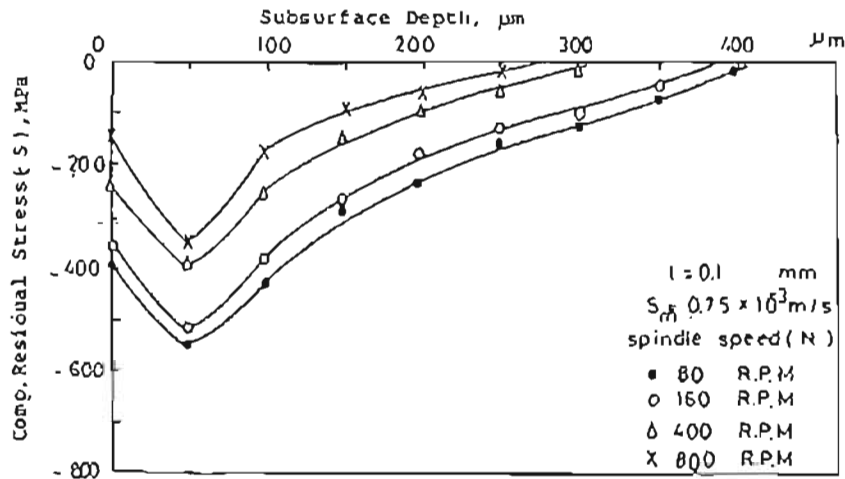residual stresses for different feed rates (S_m) at $N = 160$ R.P.M. and
$t = 0.1 \times 10^{-3}$ m

Fig. (3) : The relationships between the sub-surface depth and compressive residual stresses for different spindle speeds of revolution (N) at $s_m = 0.75 \times 10^{-3}$ m/s & t = 0.1 ×10^{-3} m
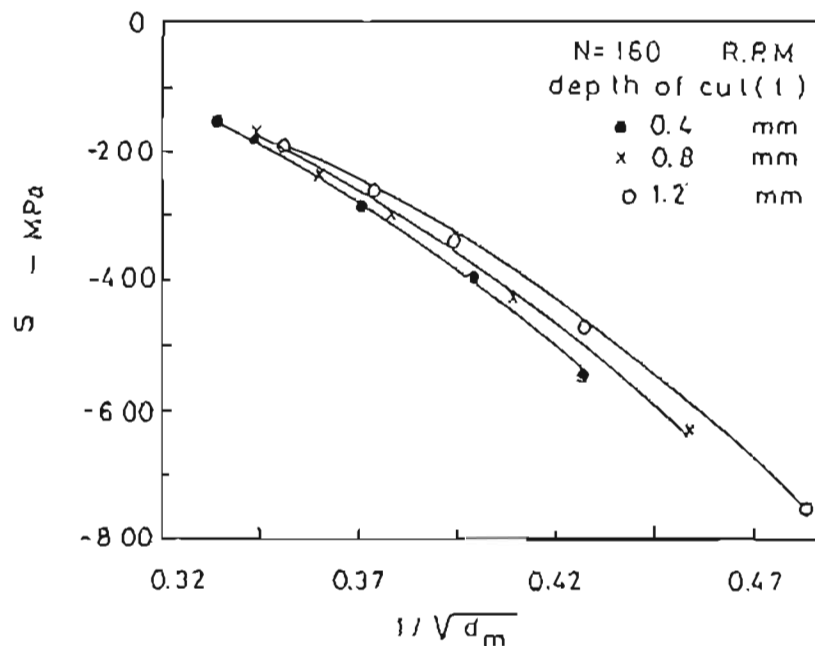
Fig. (4) : The relationships between the compressive residual stress (S) and the mean grain size (d$_m$) and (1/$\sqrt{d_m}$) at various depths of cut (t) viz; 0.4, 0.8 and 1.2 × 10^{-3} m at a spindle speed of revolution of 160 R.P.M.
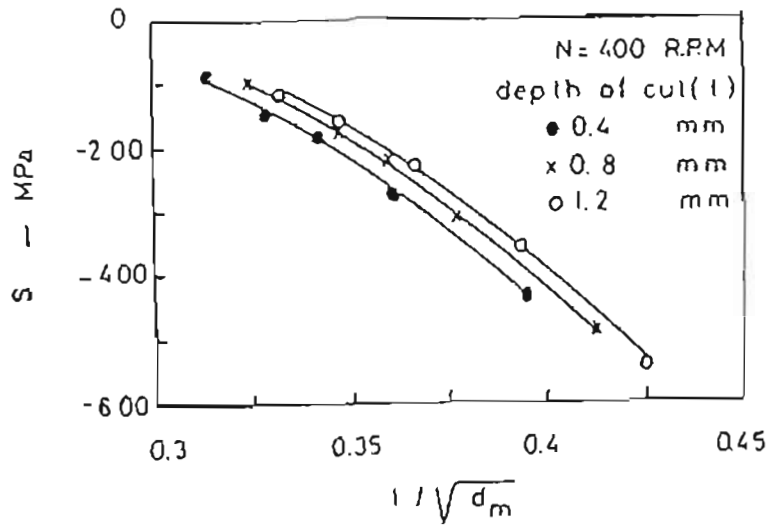
Fig. (5) : The relationships between the compressive residual stress (S) and the mean grain size (d_m) and (1/ $\sqrt{d_m}$) at depths of cut viz; 0.4, 0.8 and 1.2 x 10^{-3} m at spindle speeds of revolution of 400 R.P.M.
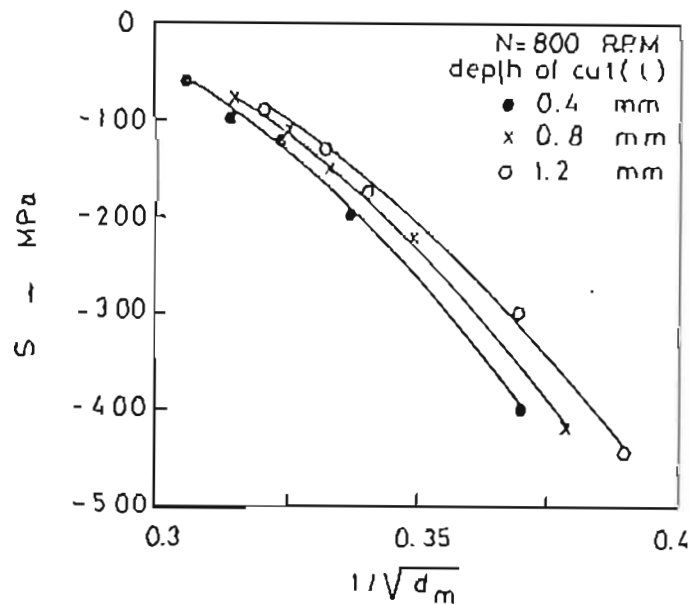

Fig. (6): The relationships between the compressive residual stress (S) and mean grain size (d_m) and (1/ $\sqrt{d_m}$) at various depths of cut viz; 0.4, 0.8 and 1.2x10^{-3} m at a spindle speed of 800 R.P.M.
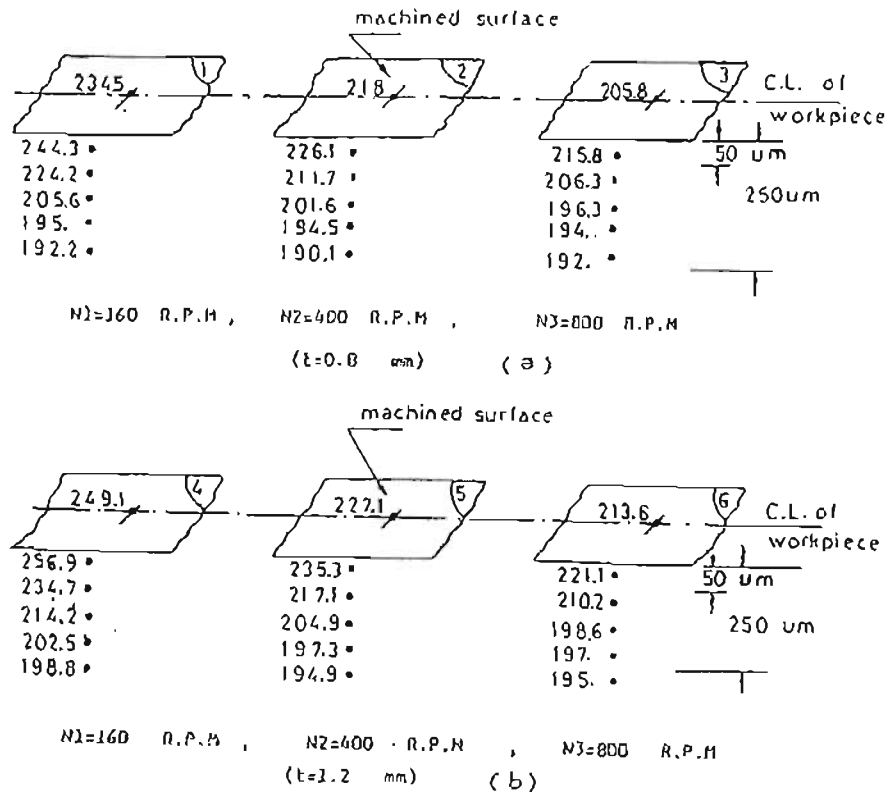
Fig. (7) : The values of surface and sub-surface microhardness for depths cut of
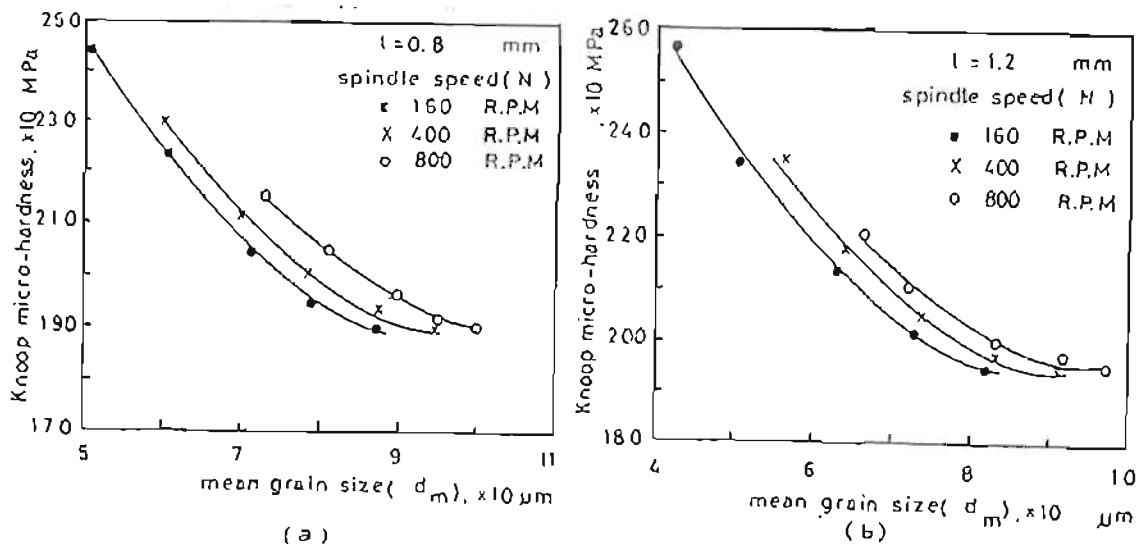(a&b)   t = 0.8 and 1.2x10⁻³ m at spindle speeds of revolution of 160,400 and 800
R.P.M.

Fig. (8) : The relationships between the mean grain size and the micro-hardness
(a&b) at various spindle speeds of revolution viz; 160,400 and 800 R.P.M. for
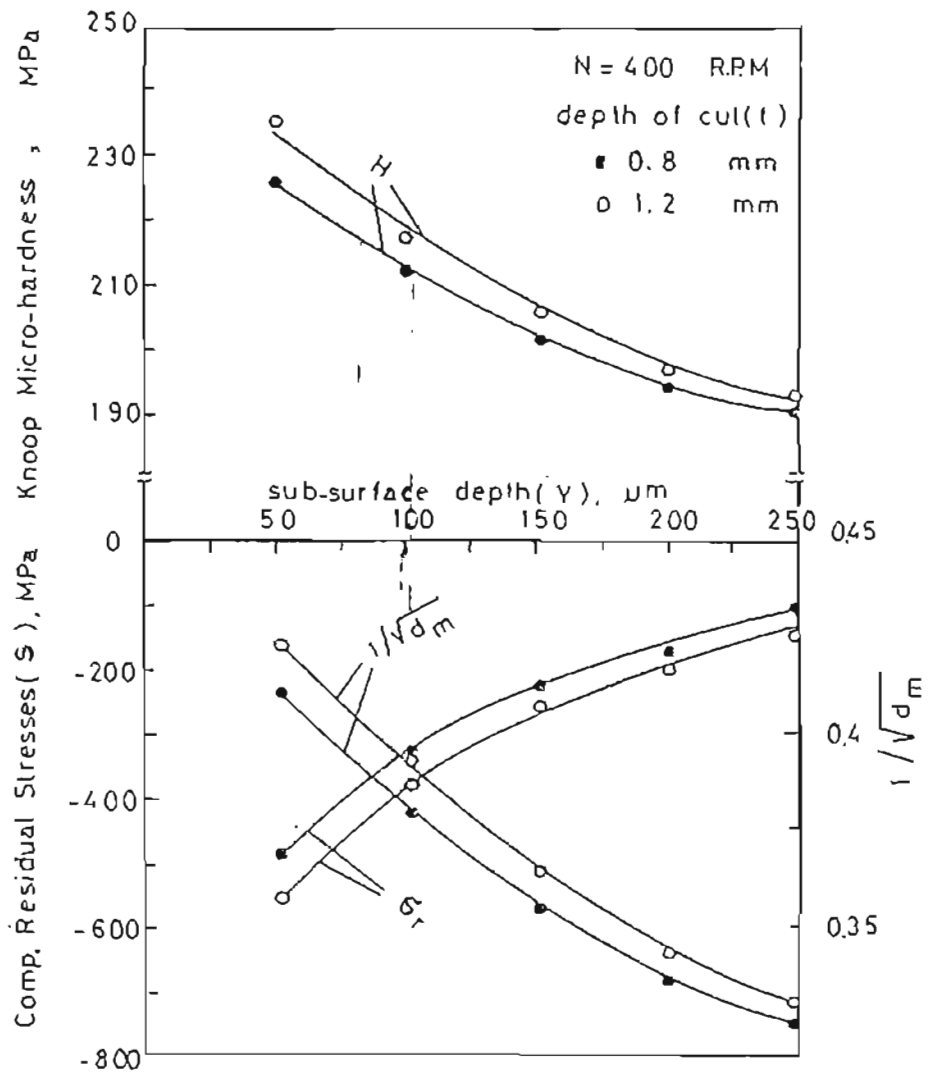t = 0.8 and 1.2x10⁻³ m.

Fig. (9) : Relationships among the compressive residual stresses, the mean grain size and the mcirohardness under-neath the surface of vertically milled free machining brass plates