# Effect of Fiber Orientation on Surface Roughness Measurements of Machined Aluminum ( 6061) Matrix Reinforced with Mild Steel Fibers

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## ABSTRACT

This research is made to evaluate the effectiveness of surface roughness parameters in describing the machined surfaces of composite materials. The material used in this work is aluminum alloy 6061 matrix reinforced with mild steel fibers. The effects of fiber orientations ( angles ) are studied for machined specimens and scanning electron microscopy is used to evaluate the surface damage induced in composite specimens

The analysis of this investigation revealed that , fibers break in bundles during the cutting processes and the breakage length is found to be dependent on the fiber direction. The average roughness parameters such as ( Ra ) and ( Rq ) are found to be less sensitive than ( Ry) and ( Rz ) to surface changes in machined composite laminates. The surface roughness and profile are found to be highly dependent on the fiber orientations of Al (6061) and the direction of measurement. Surface profile of machined unidirectional composite laminates are found to be crescent shape and periodic in the direction of machining The edge-trimmed cross-ply laminate surfaces are crescent and random for profiles measured along the tool movement direction, but they are periodic and non-crescent in the direction perpendicular to the tool movement. The surface is better described using ( Ry ) and ( Rz ). In the longitudinal direction of the unidirectional laminate; surface roughness is low for fiber orientations (0° and 45°) but the roughness variations measured in the transverse direction are seemed to depend on the orientation of the fiber with respect to the cutting direction. Three dimensional topography measurements are necessary to characterize the machined surface of composite material.

## 1- INTRODUCTION

Surface roughness and tolerance are closely related and it is generally necessary to specify a smooth finish to maintain a certain tolerance in the finishing process. For many practical design applications , the tolerance and strength impose a limited maximum allowable roughness. The reliability of machined components ( especially for composite materials ) in high strength applications is often critically dependent upon the quality of surface produced by machining. The surface layer may affect the strength and the chemical resistance of the material. However, inhomogenity of composite materials caused by the difference in properties of fiber and matrix will result in a machined surface that is less regular and usually rougher than machined metal surfaces [ 1-3 ]. It has been shown that the machined surface of a fiber reinforced composite is highly dependent on the chip formation process and the fiber orientation with respect to the cutting direction [ 4 ]. The chip formation process during the machining of composite is different from that of machining metals , and appears to rely on three material removal mechanisms namely abrasion , ploughing and cutting [ 5 ]. When machining a unidirectional laminate with fibers oriented along the cutting direction , the main material removal mechanisms are rupture of fibers and debonding of the matrix and fibers , where as in machining of a laminate with fibers oriented at an angle to the cutting direction , the mechanism of chip formation is due to deformation and / or shearing and fiber ends often appear crushed and fractured sharply. These fiber ends protrude from the machined surface to produce a rough surface [ 6 ]. However , most of the previous researches used an average roughness parameters to describe the surface roughness , lay and texture of machined composites. Now , it is clear that , surface roughness characteristics of machined composites have not been studied in detail. In this work , more investigations to identify the best parameters to describe the micro geometric variations observed on the machined composite surface.

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## 2- EXPERIMENTAL WORK

Aluminum alloy 6061 matrix reinforced with mild steel fibers (0.41 mm, dia.) is used in this research. Both the unidirectional and cross ply of composites are used. The fiber volume is set 30%. The dimensions of unidirectional specimens are approximately 50×5×12 mm. Three different fiber orientations 0° , 30° and 60°, with respect to the cutting direction and a group of multidirectional laminates are used. The cross ply laminate dimensions are 50×5×300 mm. The mechanical properties and chemical compositions of the used materials are listed in Table (1).

| composite stress | UTS (MPa ) | e % | E (GPa ) |
|---|---|---|---|
| AL 6061 | 125 | 25 | 60 |
| *mild steel* | 805 | 24 | 207 |

Table (1-a ) Mechanical properties of the used materials.

| C | Si | Mn | Cr | Cu | Ti | S | P | Fe |
|---|---|---|---|---|---|---|---|---|
| 0.13 | 0.24 | 0.93 | 0.48 | 0.21 | 0.02 | 0.0012 | 0.011 | balance |

Table (1-b ) Chemical composition of mild steel.

| Si | Mn | Mg | Cr | Al |
|---|---|---|---|---|
| 0.6 | 0.28 | 0.1 | 0.2 | balance |

Table ( 1-c ) Chemical composition of Al 6061.

A milling machine is used to produce the required surfaces. The cutter specifications are; 10mm. diameter , 4 flutes , 30° helix angle and 13° rake angle. The depth of cut is taken 0.3 mm. and the cutting speed is 400 r.p.m.

## 3- MEASUREMENTS

The machined surfaces *are examined to study the amount of micro geometric variation and to* investigate the roughness characteristics of the profiles. Surface roughness is obtained using Talysurf 5-M60. The surface roughness heights are measured at intervals of 1.25 μm. Surface roughness characteristics are evaluated based on a cut-off length of 0.8 mm. Several surface profiles are taken in both longitudinal (parallel to the cutting direction ) and transverse directions (perpendicular to the cutting direction ). For both the longitudinal and transverse measurements the roughness measurement length met 2.4 - 8 mm., traverse length requirement for a cut-off of 0.8mm.

Scanning electron microscope ( SEM ) is used to assess and validate the surface roughness measurements and to describe qualitatively the damage due to the machining process. Micrographs are taken at various locations on the machined surfaces. The localized damage is examined at a higher magnification.

## 4- RESULTS AND DISCUSSION

The machined surface of unidirectional laminates appeared smooth to the naked eye , but microscopic fiber pull-out and matrix smearing are found on the surfaces. For the laminate surface machined parallel to fiber direction , spaced cuffs are found in the surfaces. For the other fiber orientations , the surfaces are covered with matrix smearing. Profiles and average roughness values are obtained for both longitudinal and transverse directions of the machined surfaces. Typical surface profiles measured in the longitudinal and transverse directions for each fiber orientation are shown in Figs. ( 1and 2 ) respectively. From these figures , it is obvious that , the surface profiles are dependent on the orientation with respect to the cutting direction.

Fig. ( 3 ) shows the typical average variation of parameters Ra , Rq , Ry and Rz as a function of fiber direction , corresponding to the profiles shown in Figs. ( 1 and 2 ). Within the experimental conditions, Ra and Rq values ranged from about 1 to 2μm , with variations of Ra and Rq for the different fiber orientations being insignificant. For the range of the fiber orientation studied , Ry and Rz values ranged from 8 to 11 μm and 6.5 to 9 μm respectively. It can be noted that , the variations of both Ra and Rq measured in the transverse direction are similar and varied between 1.5 to 2 μm. Also it is noted that, the ratio of Rq / Ra for both directions of measurement typically ranges from 1.24 to 1.27 μm which indicates that , the surface roughness profiles measured in both directions are crescent shape.

In order to study the surface statistics and randomness , the typical longitudinal surface profiles shown in Fig. ( 1 ) are evaluated with height distribution for fiber orientations of 0° , 30° and 60° as shown in Figs ( 4 and 5 ) respectively. Fig. ( 4-a ) shows the surface profile of 0° laminate that consists of a short wave length fine irregularities superimposed on a long wave length coarse irregularities. Fig. (4-b) and (4-c) shows the height distribution and cumulative height distribution curves of the 0° profile respectively. It is observed that the surface profile does not skew and has a crescent shape. A crescent surface is represented by a straight line when the comulative height distribution is plotted on a probate scale as shown in Fig. ( 4-c ). In the machined surface of fiber orientation 60° , the surface profiles are similar to that of the 0° laminate. It is observed that the profiles for 60° surfaces are also periodic. It can be noted that , the most prevailing wave lengths for all the profiles measuring along the longitudinal direction are between 70 and 170 μm.

For machined surface of unidirectional laminate measured in longitudinal direction , it contains a substantial periodic component ,as shown by the height distribution function of the profiles , the surface profiles of all fiber orientations do not seem to skew. The auto correlation function of the profiles obtained for each orientation demonstrates the close surface texture obtained in the longitudinal direction.

The characteristics of profiles measured in the transverse and longitudinal directions , are similar except for the difference in periodicity. Therefore , the transverse profiles are not presented. Profile characteristics measured perpendicular to the cutting direction are found to be less periodic than those of the longitudinal direction as shown in Fig. ( 2 ). The transverse direction profiles are found to be symmetrical and less dependent on the fiber orientation. From the previous results , it is clear that , the surface roughness height distribution and bearing length do not vary significantly over the different fiber orientations studied.

Scanning electron microscopy analysis is made to assess the roughness of surface profiles. Fig. ( 6 ) shows the machined surface at high magnification for different fiber orientations. Fig. (6-a ) shows the machined surface of the 0° fiber orientation. It is clear that the machined surface is vastly different from that of other angles. From the same figure , it is obvious that , the matrix surrounding the fibers seem to be pulled out during the machining process , leaving behind clear fibers. Bands of fibers seem to fracture simultaneously and bundles of broken fiber of length 80 - 100 μm are left on machined surface after the cutting process. The distance between the cuffs is approximately 80 - 120 μm. In the case of non-parallel or angular fiber orientations , matrix smearing is noticeable over a portion of machined surface. The fiber orientation and cutting direction are playing a vital role on the machined surface of composite material. In comparing the 30° laminate with 60° laminate , the first has less matrix on machined surface.

Two extreme cases of matrix smearing are observed in magnification of SEM photographs. On one extreme , only a small amount of matrix smearing exists in pockets on some of the machined surface. On the other extreme , the surface is entirely covered by matrix material , and small pockets of fibers are scattered over the machined surface. From the previous results , it is obvious that , some of the machined surfaces are between the extremes and have a moderate amount of smearing. From Fig. ( 6 ) it is often possible to see fiber fracture surfaces at higher magnification.

More of the fiber body is seen on the surface at lower fiber orientations ( angles) , while the fiber fracture surface can hardly be seen. As the fiber orientation increases , the amount of fiber fracture surface increases. The increase in the angle of orientation leads to smaller lengths of crushed fibers. The crushed length at 0° is about 4 - 14 μm , while it is about 2 - 7 μm at 30° .The length decreases to about 1 - 5 μm for 60° laminate.

In multidirectional laminates , the machined surfaces are similar in some ways to those of unidirectional laminates. From Fig. ( 7 ) , it is clear that , no matrix smearing is observed on the 0° plies. Surface of plies oriented at the other angles are covered by matrix , and severe fiber pull-out can be seen on the 45° and 90° plies. The surface roughness profiles measured in the longitudinal direction are significantly different from those measured in the transverse direction as shown in Fig. ( 8 and 9 ). However Fig. ( 8 ) shows the surface profiles measured along the longitudinal direction , these machined surfaces are nearly crescent shape as the cumulative height curve is almost a straight line and non-periodic. But in the transverse direction , the surface profile measured is non-crescent shape and periodic. From Fig. (8-c ) the surface cumulative height distribution can be approximated by two straight lines that define the different layers in the profiles. The two layers intersect at about 15% , which means that approximately 15% of the surface roughness profiles measured in the transverse direction are covered by valleys. The surface profiles measured in the longitudinal direction of a cross-ply laminate appeared to be random as shown in Fig. ( 9 ) which is mainly dependent on the measurement path. Figs. ( 9-a and 9-b ) show the profiles measured along random measurement path which is approximately parallel to cutting direction , while Fig. (9-c ) is obtained along the 0° ply. The surface profile measured along the 0° ply has a less variation in profile height than the other two profiles and is similar to the surface of 0° unidirectional laminate.

The previous figures show the rupture of the fibers and fiber matrix debonding occurred during cutting of 0° laminate. The matrix in machining zone is pulled off with the ruptured fibers during the cutting process , leaving a layer of clean fibers on the uncut surface. Rupture of the fibers along the cutting direction seemed to occur in a quasi-periodic fashion as shown in Fig. ( 2 ). From the previous results , it is obvious that , if the fiber is assumed to be in a square packing sequence , the surface profile measured along the longitudinal of a 0° laminate will be a straight line with high variation. This is due to the long strands of fibers that cover the machined surface. In addition , as these strands of fibers are smooth the variation in micro geometric height of surface is low and the surface is expected to be smooth. For the other fiber orientation 30° , the surface profile is expected to have many fine irregularities , and the long surface roughness is expected to be higher than that of 0° laminate. The surface roughness is expected to be rougher for 30° laminate under ideal conditions. This is due to the geometry and packing sequence of fibers. Now , it is clear that , matrix smearing and chip formation mechanism corresponding to the different fiber orientations will alter the roughness values significantly. When the matrix is smeared over the entire surface the roughness values are low ; and are high when the matrix is smeared in small pockets. The matrix smearing is more extensive for 30° than 0° laminate and created pockets of exposed fibers that increase the surface roughness. But for 60° laminate , the surface is rougher as the fiber pull-out except at high fiber angle ; also increases the surface roughness. Due to the extent of fiber pull-out and the rupture of fiber , periodic wave form components are understood.

Now , it is clear that , the surface topography is not only a function of manufacturing process and process conditions , but also the materials surface geometric integrity in terms of homogeneity and isotropy.

From the previous figures , it can be noticed that the surface profiles are similar for all fiber orientations , with Ry at round 6-12 μm. The fine irregularities are discovered when the surface profiles are measured in the transverse direction of the fiber orientation. Periodicity of the transverse direction profiles may be due to the weak inter-ply bond that breaks during the cutting process.

Three parameters of surface roughness are measured to evaluate the surface profiles in different fiber orientations , and to describe the amount of surface damage due to fiber pull-out or matrix smearing. These parameters are Ra , RMS and Rq . Within the experimental conditions of the surface roughness studied , almost all the average Ra and Rq values are less than 2μm. Maximum peak to valley roughness Ry and ten point heights Rz parameters are able to distinguish the surface profiles of the different fiber orientations , and quantify the amount of micro geometric variations such as fiber pull-out. Rz is an average which vary significantly within the fiber orientations studied , so , Ry and Rq are the parameters of choice to describe the damage observed on the machined surface.

From the cumulative height distribution curves , the unidirectional laminate surfaces are approximately crescent shape as they can be approximated by a single straight line. The height distribution of all the machined surfaces of unidirectional laminate is symmetrical about the center line. The auto correlation function describes the general dependence of the surface height of one position on the measured profile. However , periodic irregularities observed on the machined surface must be quantified to properly describe the distance between the cuffs.

Surface roughness characteristics of the edge-trimmed cross-ply laminates are similar to those of unidirectional laminate surfaces. Ry and Rz are better to assess the composite surface roughness than Ra and Rq as it is necessary to quantify the extent of fiber pull-out that existed on the surfaces. Multidirectional laminate profiles differ from unidirectional laminate profiles mainly in existence of two layers in the cumulative height distribution curve when surface roughness is measured in the transverse direction. It is important to obtain the cumulative height distribution function plotted on the probit scale to determine the amount of the surface where the fiber pull-out is dominant as it will affect the fatigue life performance of the machined laminate Figs. (9 and 10).

*From the previous discussions , it is clear that , an ideal surface roughness parameter , if one* exists , for describing a machined composite surface will thus have to include three main characteristics. The first parameter which will describe the depth of fiber pull-out region and thickness of matrix smearing. The second , the strata distributions of the surface roughness profiles have to be determined , and the third is the periodic irregularities seen in most of the machined surfaces must also be described to determine the spacing between the deep valleys caused by fiber pull-out. From the previous analysis , no single parameter studied sufficiently described the amount of micro-surface variation. However , the parameters *of choice obtained from the unidirectional surface profiles study namely ; Ry , Rz and* cumulative height distribution on a probit scale are also appropriate for edge trimmed cross ply laminate.

The surface generation process is highly dependent on the material , manufacturing process and machining parameters. It is necessary to use three dimensional micro-geometric surface variation parameters to characterize the surface of composite material laminates.

## 5- CONCLUSIONS

The results and discussion of this research lead to the following conclusions :

1- The fibers break in bundles during the cutting process and the length of this breakage is found to be dependent on the fiber direction. The crushed fibers decrease with increasing fiber angle.
2- The average roughness parameters , such as Ra and Rq are found to be less sensitive than Rz.
3- Roughness of the unidirectional laminate surface in the longitudinal direction is low at fiber orientations of 0° and 30° ; but the roughness in the transverse direction is not dependent on the fiber orientation with respect to the cutting direction.
4- It is accurately to describe the surface profiles of the cross-ply laminate by using Ry and Rz as severe fiber pull-out is observed.
5- Three dimensional topography measurements are necessary to characterize the machined surface of the composite material.

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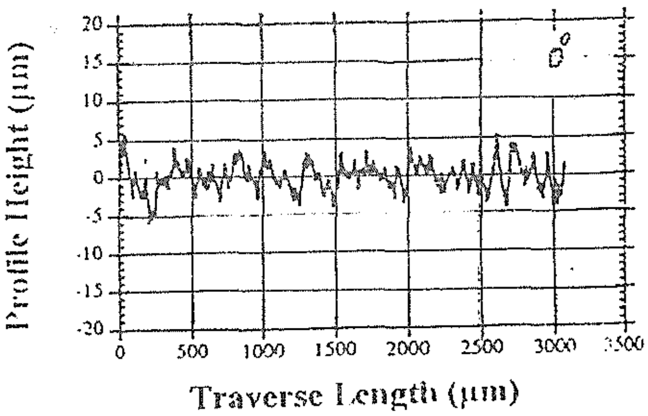
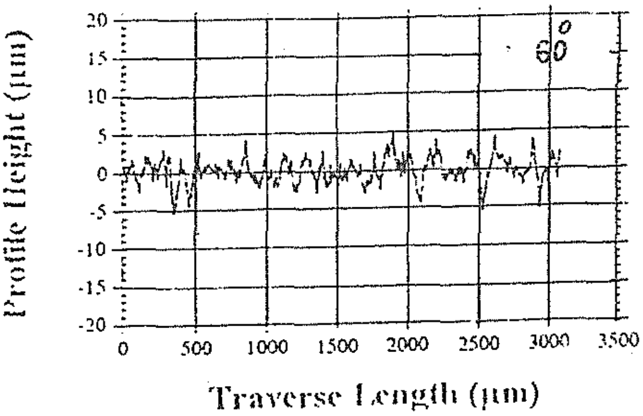




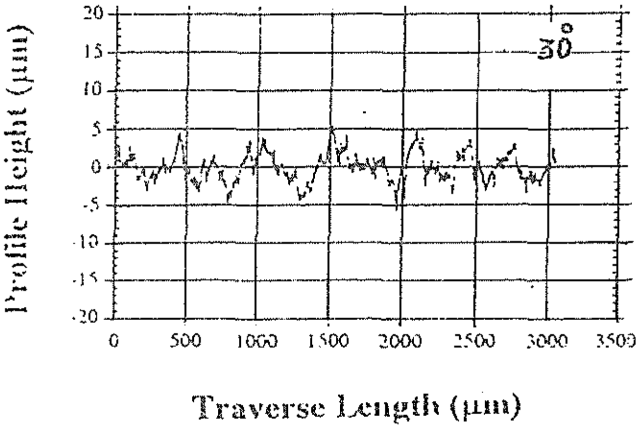
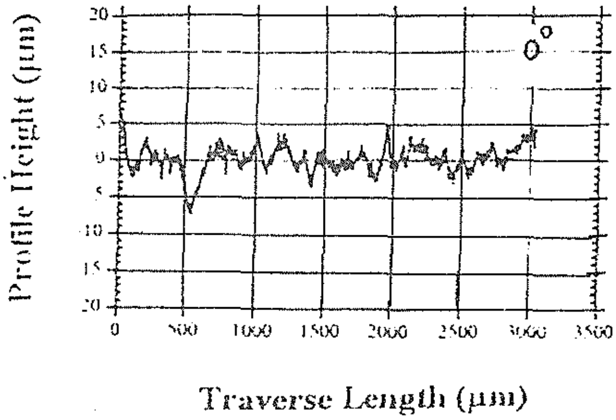
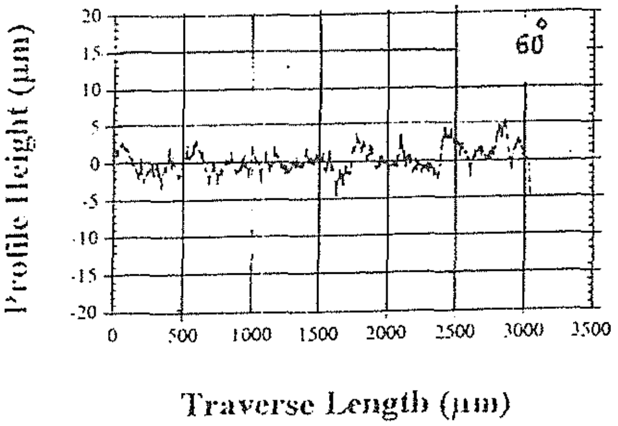


Fig. ( 1 ) Surface Roughness Profiles - Measured Longitudinal to the Cutting Direction.





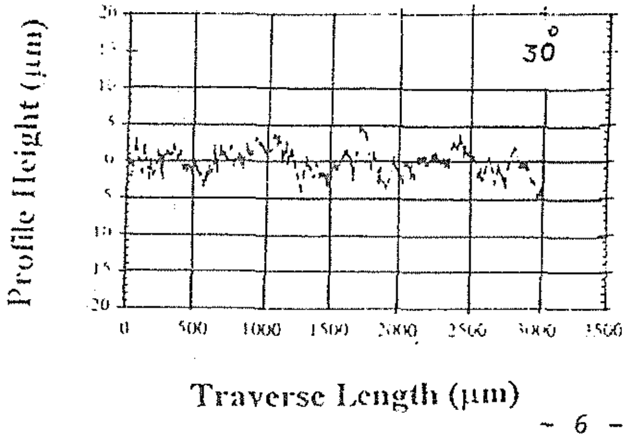


Fig. ( 2 ) Surface Roughness Profiles - Measured Transverse to the Cutting Direction.

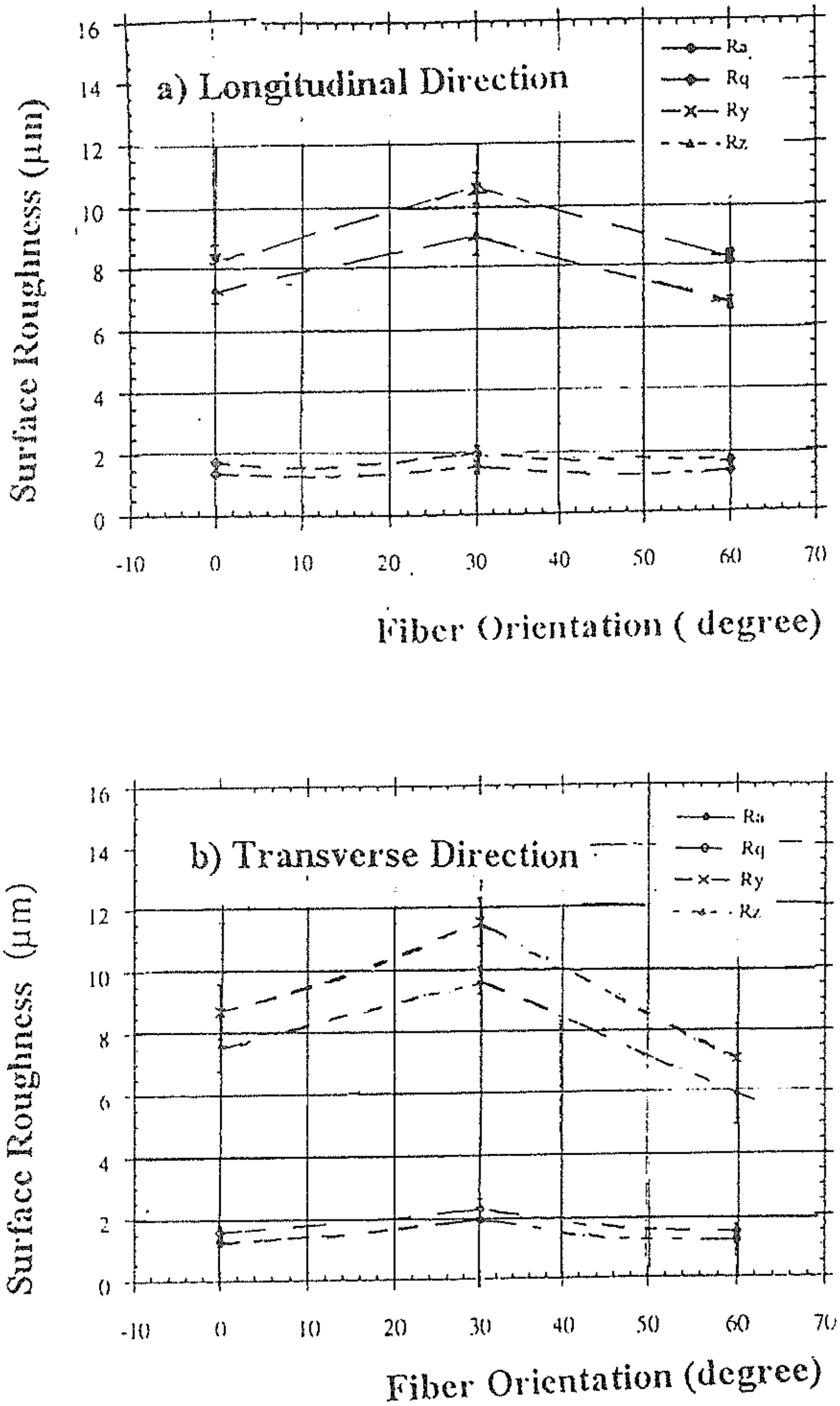
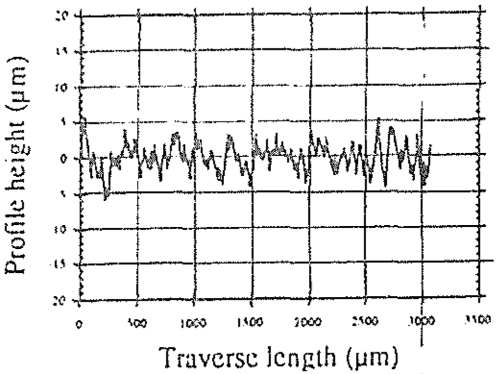
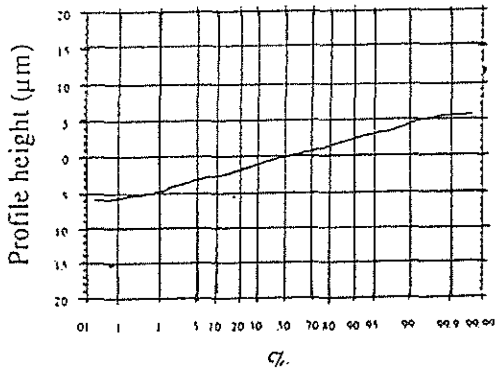


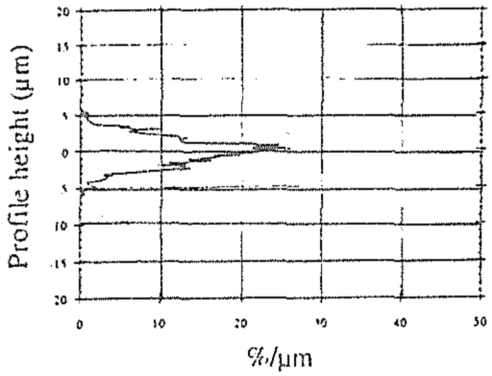
Fig. (3) Surface Roughness Highest as a Function of Fiber Orientations (Two Cutting Directions).



a) Surface Roughness Profiles.

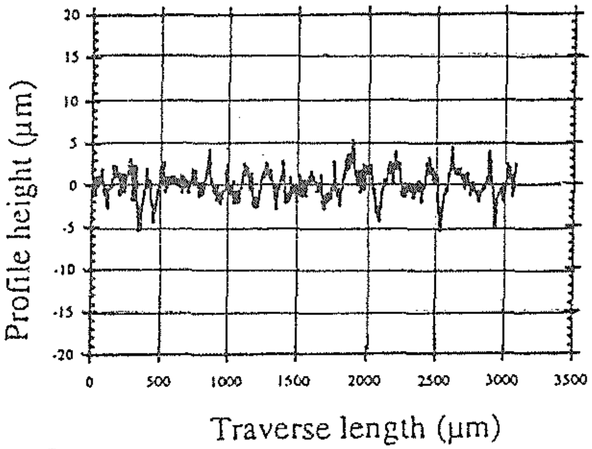


c) Cumulative Height Distribution.

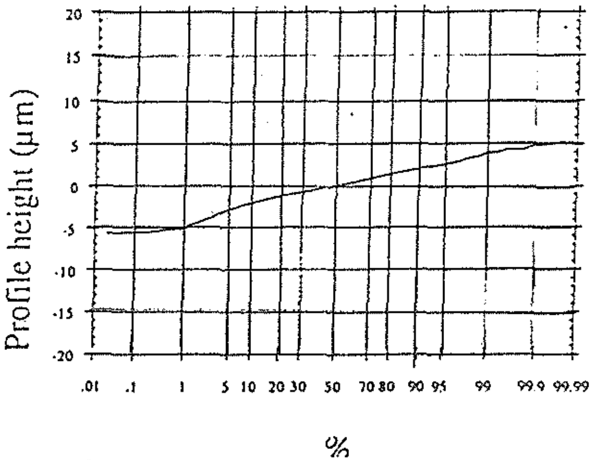


b) Roughness Height Distribution.

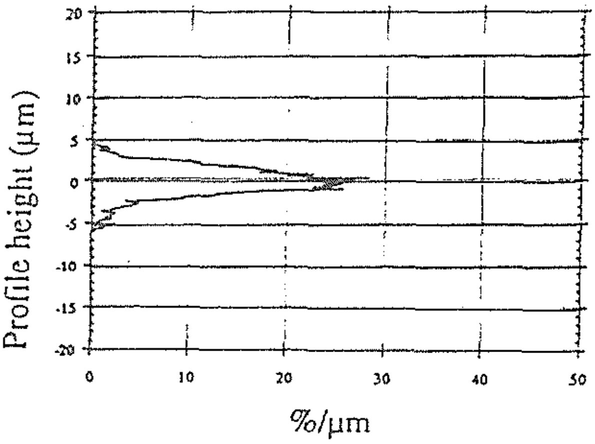
Fig. (4) 0° laminate.



a) Surface roughness Profiles.

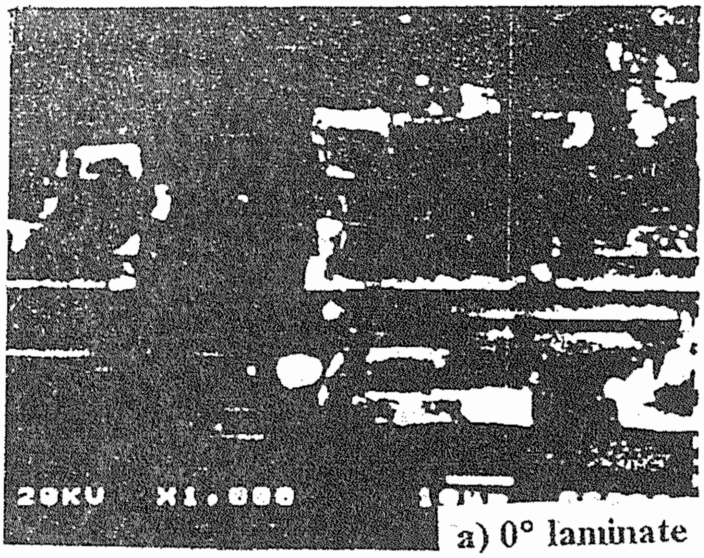


c) Cumulative Height Distribution.

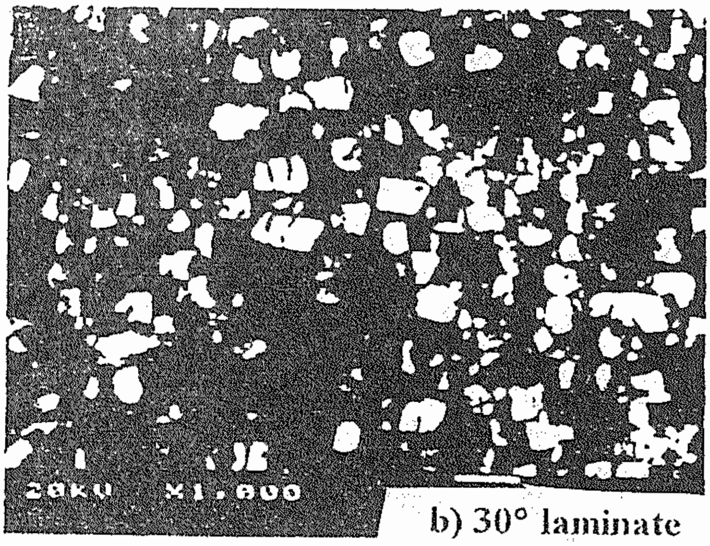


b) Roughness height Distribution.

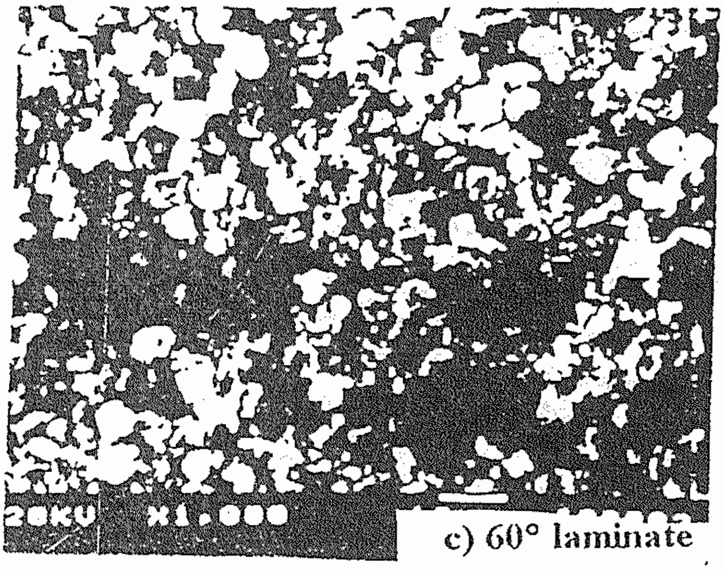
Fig. (5) 60° laminate.



a) 0° laminate

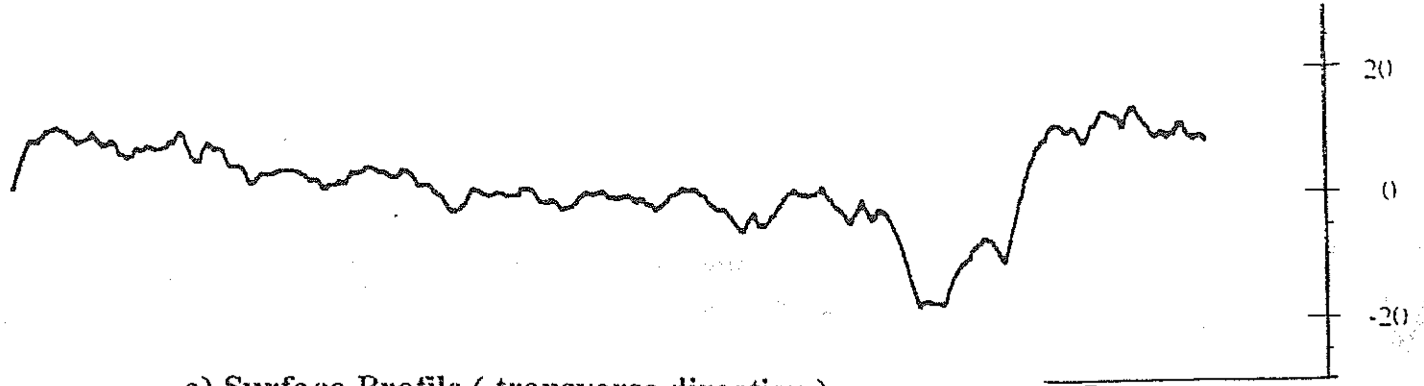


b) 30° laminate

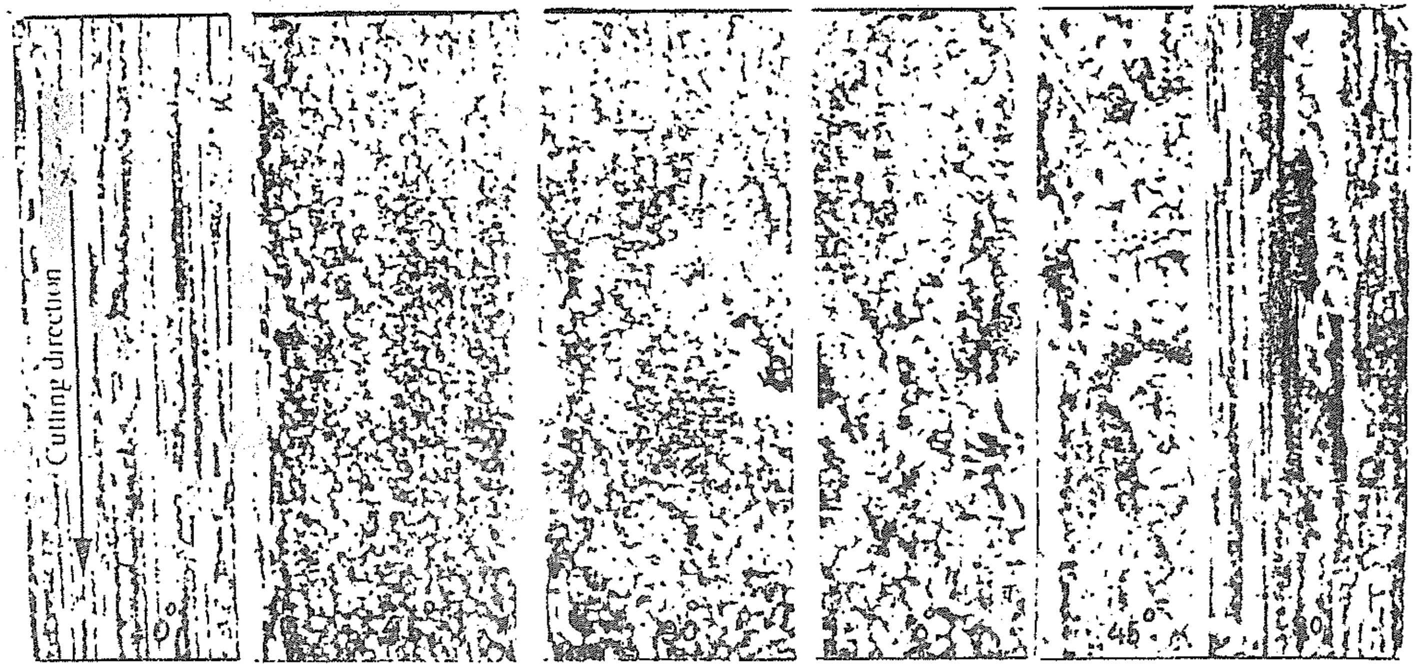


c) 60° laminate

Fig. (6) SEM High Magnification Micro graphs of Machined Surface

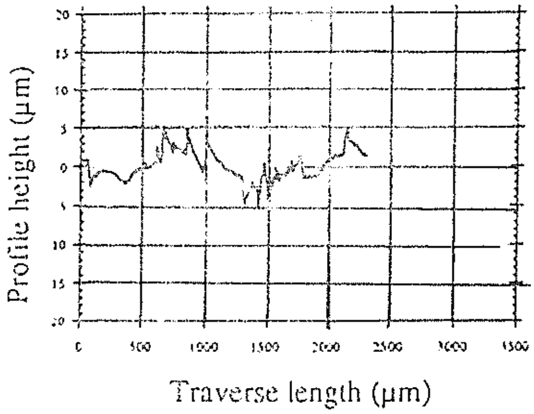


a) Surface Profile ( transverse direction )

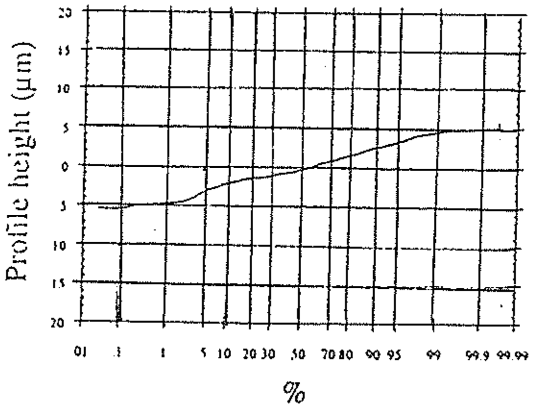


b) SEM Micro graph of Multidirectional Laminate

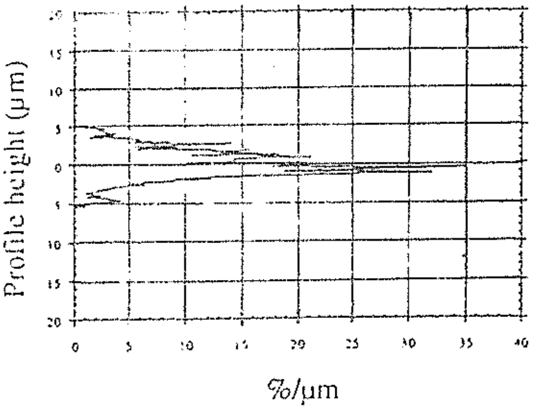
Fig. (7)



a)Surface Roughness Profiles

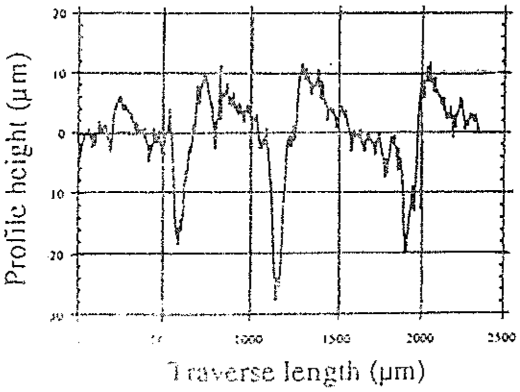


c) Cumulative Height Distribution



b) Roughness Height Distribution

Fig. (8)



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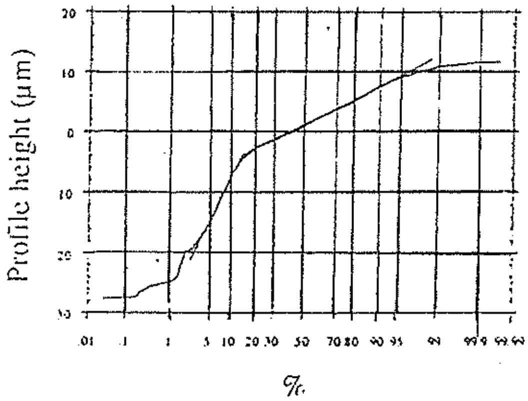
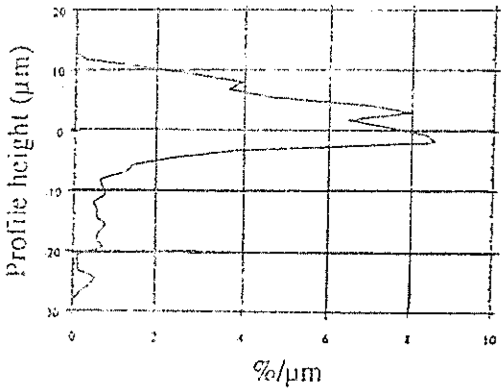
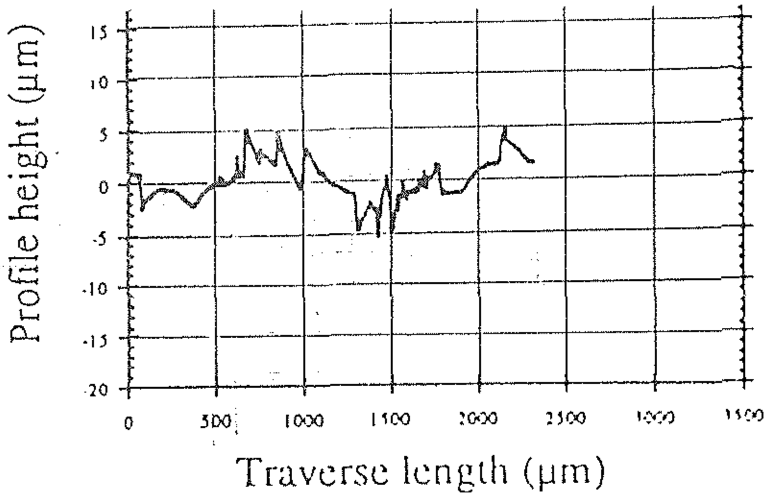


c) Cumulative Height Distribution

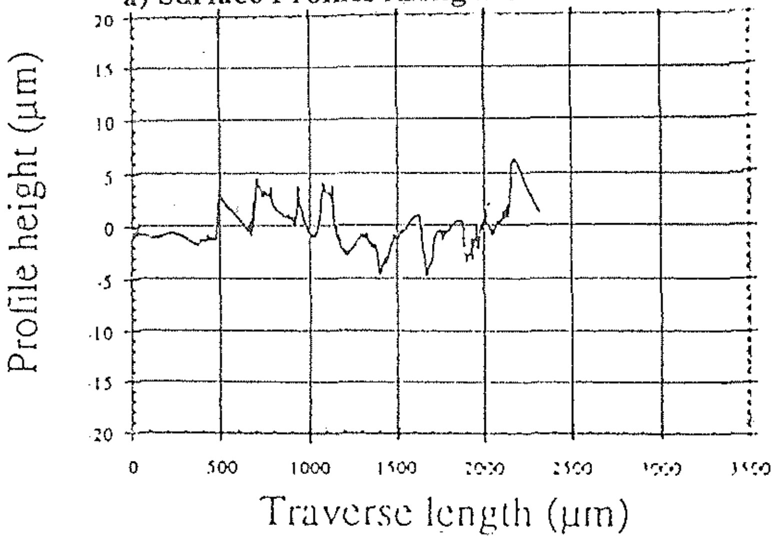


b) Roughness Height Distribution

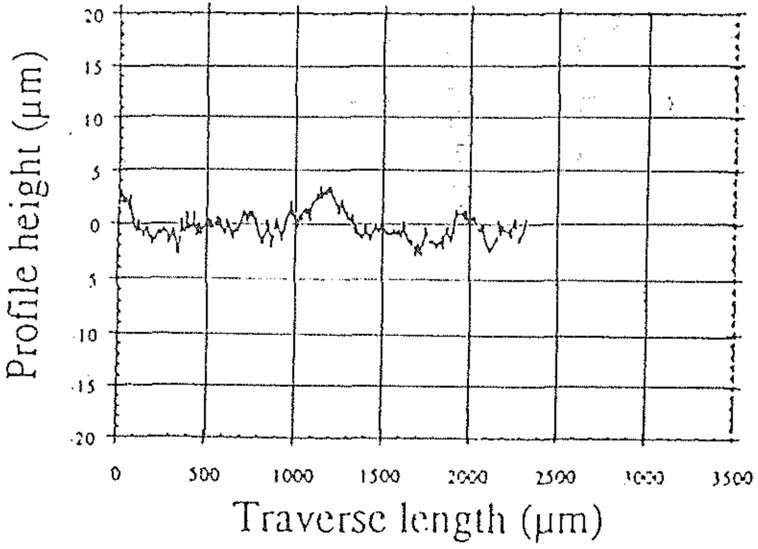
Fig. (9) Surface Roughness of a Machined Multidirectional Laminates(Transverse Direction).



a) Surface Profiles Along a Chosen Path.



b) Surface Profiles Along a Chosen Path.



c) Surface Profile Along 0° Ply.

Fig. (10) Surface Profiles of Multidirectional Laminate Measured Along the Longitudinal Direction.

عنوان البحث باللغة العربيه :

## تأثير إتجاه الألياف على قياسات خشونة السطح المشغل للالومنيوم (٦٠٦١)
## المعزز بألياف الصلب الطري

المشتركون : د./ محمد أشرف سعد – مدرس بكلية الهندسه بشبين الكوم

## ملخص البحث :

إجري هذ البحث لتقييم إستخدام عناصر قياس خشونة الأسطح المختلفه في وصف الأسطح المشغله للمواد المؤلفه – ولقد تم إستخدام سبيكة الألومنيوم (٦٠٦١) المعززه بألياف من الصلب الطري والتي قمنا بتصنيعها خصيصاً لهذا العمل.

وتمت دراسة تأثير إتجاه الألياف ( صفر° ، ٣٠° ، ٦٠° ) على خشونة الأسطح المشغله للعينات المؤلفة، وإستخدام الميكروسكوب الالكتروني الماسح لتقييم العيوب الناتجة عند تشغيل سطح هذه العينات.

ولقد أظهرت نتائج تحليل قياسات خشونة هذه الأسطح مايلي : أن الألياف يتم كسرها أثناء التشغيل في مجموعات – القيم المتوسطة لـــ Ra, Rq تعطي نتائج أقل دقة من Ry , Rz – خشونة السطح المشغل وجانبيته يعتمدان بدرجة كبيرة على إتجاه الألياف وأيضاً إتجاه القياس – جانبية السطح للعينات ذات الألياف الموحدة الإتجاه وجد أن تموجات السطح بها هلاليه وتتكرر بإنتظام عند القياس في اتجاه حركة أداة القطع وأيضا وجد أن حافة السطح الناتج تكون تموجات السطح بها هلاليه ، أما الجانبية فتكون عشوائية أثناء القياس طوليا في اتجاه حركة أداة القطع – ولكن عند القياس عمودياً على اتجاه حركة القطع – تكون تموجات السطح الناتج غير هلاليه وغير منتظمه .

من هذا يتضح أن : إستخدام عنصري القياس Ry , Rz يعطي توصيفاً أدق للسطح الناتج مقارنه بالعنصرين الآخرين – خشونة السطح الناتج والمقاس في اتجاه طولي للعينات ذات الألياف الموحده الاتجاه يعطي نتائج أقل للعناصر السابقه وذلك في حالتي الزاويه (صفر ، ٤٥ درجه) ، ولكن خشونه السطح تختلف عند إجراء عملية القياس في إتجاه معاكس لاتجاه حركة القطع وتعتمد على إتجاه الألياف وإتجاه أداة القطع .

وعلي هذا يتضح أنه من الضروري لتقييم الأسطح المشغله المؤلفات أنه يجب أن تتم عملية القياس بثلاث عناصر من عناصر القياس السابقه ليتم التقييم السليم لخشونة هذه الأسطح .

## مساهمة هذا البحث في الصناعة :

نظرا للتطور الذي يتم في تصنيع المؤلفات والتوسع في استخدامها – أصبح طرق جانب تقييم خشونة الأسطح المشغله لهذه المؤلفات هاما وضروريا وأيضاً للتأثير المباشر لخشونة الأسطح على المساحات المطلوبه أثناء التصميم .