MACHINABILITY PARAMETERS IN FINISH FACE MILLING OF LOW ALLOY Cr-Ni STEEL WITH THR K30 CARBIDE TOOL

PART I: CUTTING FORCES, SPECIFIC CUTTING ENERGY AND TEMPERATURES

عوامل قابلية التشغيل فى التفريز الراسى الدقيق لسبيكة صلب نيكل كروم باستعمال لقم كربيدية تى إتش ار كى ٣٠

الجزء الأول : قوى القطع ، طاقة القطع النوعية ، درجات الحرارة

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ملخص: إنه لمن الضرورى إدراك التغيرات السطحية الناتجة من عمليات التجليخ . لذلك فإن هذا البحث يقدم ويناقش عملية التفريز السطحي الدقيق لسبيكة صلب فى حالتها المصلدة بهدف استبدال عملية التجليخ السطحى . هذا العمل يمثل الجزء الأول من البحث الذى يتكون من جزئين حيث يناقش استعمال اللقم الكربيدية ذات الحبيبات عالية النعومة مع الكربيدات المكعبة بنسبة ٢٪ . نوقشت قابلية التشغيل في ثلاثة عوامل وهي قوي القطع ، طاقة القطع النوعية والحرارة المتولدة . تأثير تغيير شروط القطع وتآكل الحد القاطع على هذه العوامل تم مناقشته . أيضا سلوك زاوية القص وكل من اجهادى القص والعادى وطبيعة الإحتكاك على الحد القاطع الثانوى تم فحصهم .

وقد توصلت الدراسة إلى أن هذا النوع المتطور من اللقم الكربيدية يمكن استعماله بكفاءة حتى سرعة ١٧٦ متر / دقيقة وكانت قوى القطع الناتجة منخفضة بالمقارنة بأنواع أخرى من الكربيدات. لقد وجدت نسبة القص ثابتة مع تغيير تآكل آلة القطع فى حدود من ٥٠ إلى ٢٠٠ ميكرون . نسببت الزيادة الكبيرة فى قوى القطع الرأسية إلى انخفاض معامل الإحتكاك إلى قيمة ٠,٤ - كذلك التباين فى حسابات درجات الحرارة تم استعراضه . طاقة القطع النوعية عند سرعات القطع العالية وكذلك التغذيات كانت بقيمة ٢ و ٢,٥ جيجاجول/متر٣ على التوالى . هذه النتائج تؤكد على أن التفريز الرأسى الدقيق باستعمال هذا النوع المتطور من اللقم الكربيدية يمكن استعماله كبديل عن التجليخ الرأسى عندما يؤخذ فى الإعتبار طاقة القطع النوعية .

ABSTRACT

It is necessary to aware of the surface alterations that can be produced by grinding operations. This work deals with finish face milling of low alloy steel in its hardened conditions with view to replace surface grinding . This paper is the first of two dealing with the use of submicron grain cemented carbide with low percentage of cubic cabides of 2%. Three major machinability parameters were investigated; cutting force, specific cutting energy and the temperature. The effects of fundamental cutting conditions and the minor flank wear on the machinability parameters are investigated. Further, the behavior of shear angle and normal and shear stresses as well as contact condition on the minor cutting edge were examined. The THR K30 tools were found to be capable of operating at cutting speed up to 176 m/min. Forces with the THR tools are relatively lower than TTM tools at higher cutting speeds. It was also found that the cutting ratio is almost constant at worn minor flank wear of value between 50 to 200 μm. The substantial increase in vertical component Fz, was attributed to the low coefficient of friction of approximate value of 0.4. Descripancies of the findings of the calculated temperatures are also discussed. The specific cutting energy was found to be a constant value of order 2 to 2.5 GJ/m^3 at high speeds and feeds respectively. This proved that the finish face milling with THR K30 could be substituted for a vertical spindle surface grinding when judged on the basis of specific cutting energy.

NOMENCLATURE

a_e	width of cut; mm
f_t	feed; mm/tooth
a_p	depth of cut; mm
D	cutter diameter; mm
γ_r	tool cutting edge angle; deg.
γ_t	trailing cutting edge angle; deg.
$\Delta\delta$	Worn trailing end cutting edge angle; deg.
γ_p	radial rake angle; deg
γ_f	axial rake angle; deg
α_p	radial clearance angle; deg.
α_f	axial clearance angle; deg.
δ	Setting angle, deg.
ϕ_s	angle between tool entry and tool exit; deg.
ϕ_E	entry angle; deg.
ϕ_A	exit angle; deg.
ε	angle of engagment; deg.
i	initial contact angle; deg.
F_y	cutting force component; N
F_z	vertical force component; N
N_r	rotating direction.

1- INTRODUCTION

When a component is to be made from an alloy such as alloy steels exhibiting high surface sensitivity, attention must be given to surface integrity considerations. The quality of the machined surface can be decided by the surface integrity properties such as surface roughness, hardness variations, structural changes, residual stress etc. Various grinding operations tended to develop tensile stress in the machined surfaces. This agrees with the theory that tensile stresses are caused by high temperatures. These can cause an overtempered martensite to form at a very thin layer at the surface and untempered martensite to form at the surface. Since, the later can crack and so affect the fatigue and stress corrosion life of component, its presence is undesirable [1,2]. Clearly any way of improving and correcting surface damage produced during grinding operations would be most welcome.

The present study attemps to cary out investigations on finish face milling of a low alloy steel in its hardened conditions with the THR K30 tools to replace the vertical spindle surface grinding procedure. In this paper force components are studied with the purpose of finding the conditions to improve the quality of machined surface. Cutting experiments were conducted to present in depth study the effects of cutting speed, feed, minor flank wear on force components. In order to arrive a better understanding of the performance of the THR K30 inserts, we have paid particular attension to the shear angle, specific cutting energy, normal and shear stresses, condition of contact on the minor flank area as well as temperatures.

2- CONDSIDERATIONS ON THE CABIDE TOOLS

With recent develoments in tool material technology, the application of cost saving operation such as finish face milling in finished machining of steels appears to be a practical alternative to grinding.

To achieve this substitution, cutting tools capable of machining the alloy steel should combine good wear resistance at high temperatures with adequate thermal and mechanical fatigue strength and toughness. Conventional sintered carbides of ISO TTM of grade P30 partially meet the requirements and their modified compositions of ISO THR of grade K30 to provide the required properties are suitable. Conventional and modified compositions of each grade can be seen in Table (1).

Trent [3], suggested that the large improvements in tool performance, in terms of increasing the transverse rupture strength and toughness, can be achieved by the introduction of the cubic carbides (Tic, Tac and Nbc) in relatively small amounts. In this respect, the current research will be conducted with the steel cutting grades TTM, 17.5%, and THR, 2%, of high and low percentage of cubic carbides respectively.

The use of THR of grade K30 as a cutting tool suitable for milling steel with a tensile strength of up to 500 N/mm^2 especially titanium alloys, stainless, heat resistance steels, nickle alloys, high temperatures alloys, non ferrous metals and aluminum and zink alloys. On account of its high binder metal content, this fine grain Wc-Co alloys exhibits greater toughness and excellent transverse rupture strength, the THR is therefore suitable for cutting under adverse conditions.

3- LITERATURE REVIEW

Most of the research work conducted in the past was concerned with the performance of H.S.S., carbides and sialon cutting tools in which the workpiece ranged from nickle base alloys to titanium [4,5]. They presented namorous valuable data on surface integrity. Later research work was concerned with the optimum cutting conditions based on the tool behaviour that led to significant understanding of machining process, the effects of cutting parameters on surface integrity in turning were also investigated [6,7]. Experiments on the finished surface produced by diamond turning tools [8] and by Cubic Boron Nitride [9] were conducted. Imperfictions in the finished surface were inspected and related to the form and behaviour of the diamond tool [8], while turning with Cubic Boron Nitride did provide an alternative to the cylinderical grinding of hardened tool steel [9]. However, generally high costs are typical of Cubic Boron Nitride tools. Experiments with face milling of a hardened steel using a sintered carbide P20 and sintred carbide of modified composition and structure THM K10 based on the tool wear behaviour have been carried out by Philip [10]. This investigation presented a very little information of a systematic kind in which the relationships between the cutting forces, surface finish, tool life and surface integrity was not clarified in face milling. Previous work on the machinability of metals were discussed from viewpoints of the chip formation, cutting forces, temperatures and the surface integrity of the workpiece [11-23]. So, sound understanding of the machinability factors are of prime importance for further development of machined surface quality and better choise of cutting tool materials. Abo-Gharbia [24] studied the mechanism of surface generation in face milling of air craft alloys. The surface topographical parameters were improved with an increase in cutting speed after the welded layers on the minor cutting edge had disappeared. In the light of this work [24], it seems diserable to increase the frictional heating and subsequent softining of the workpiece surface. Thus, tools that are very refractory will be called for.

4- EXPERIMENTAL CONDITIONS

4.1- Choise of Tools

For the sake of comparison, the TTM grade was used in the present tests as a basis on which to determine an improvement in tool life based on cutting forces and surface roughness brought about by THR grades. Widia indexable inserts for face milling ISO designation TPJN THR K30 were used for the test program as well as TPJN TTM P30 inserts . These throwaway inserts were 16.5 mm in length, 3.18mm in thickness and the cutting edge was of a land width of 1.5 mm and having three possible cutting edges each.

One insert at a time was used throught the present research. The method used is not a new concept when studying a face milling process, since a number of other workers used a single tipe i.e. fly cutting.

4.2- Experimental Set-up and Design of Specimen

Fig.(1a,b) show the experimental set-up with front and rear views. The as received low alloy 1-1/4% Cr-Ni steel were machined into rectangular shaped specimen shown in Fig. (1c) to dimensions according to standard industrial practice and testing for face milling [25], recommended that the ratio between the milling cutter diameter and the width of the workpiece is 1.6. The specimen used for force and wear measurements were held by means of bolts to a quartz three component cutting force dynamometer, Kistler type 9265B. The dynamometer is normally used in the horizontal plane and a fixture of a solid piece of gray cast iron had to be made to hold it vertically as shown in Fig. (1d). It was necessary to raise the surface roughness test specimen above the table to enable the cutter to make contact with it. However, it was considered a better support for test peice to be bolted onto a bolster over hanging the rear of the machine table of about 150 mm and this raised the test piece of about 170 mm above the table.

4.3- The Cutter

The cutter selected was a standard WIDAX M60 high shear milling cutter for positive indexable inserts, having an enterence angle of 45° and a nominal diamter of 125 mm. The face mill was mounted on a stub arbor and secured in the main spindle of the FW 400-VI milling machine of cutting motor of 13.5 kW and feeding motor of 2.2 Kw.

4.4- Cutting Conditions

Three cutting parameters were chosen, namely, cutting speed, feed per tooth and cutting edge condition. The safe width of the minor wear that could be produced without causing surface damages was 250 μm as a standard worn tool [25], provided the surface roughness of values 1 um should not allowed to exceed. In this work actual machinability tests were conducted in order to determine the best use of the carbide tips type TTM P30 and THR K30.

A summary of the cutting conditions used in the experiments are given in Table (2).

4.5- Contact Condition

The initial point of contact between tool and workpiece was determined using the Kronenberg graphical method [26]. Initial contact may occurs at any of the corners of the parallelogram defined by the intersection of the tool face by the uncut chip Fig. (1e). In the present tests, the conditions were adopted to produce contact at the point V.

4.6- Cutting Action

The technique of down milling as shown in Fig. (1c) should be used whenever possible when machining steel alloys because the tool life is higher, as the tool is required to cut immediately on contact with the workpiece when using this method.

5- EXPERIMENTAL PROCEDURE AND MEASUREMENTS

Cutting force measurements were carried out on every pass as well as the wear. The effect of cutting speed, feed and the amount of minor flank on cutting force was investigaed for both TTM P30 and THR K30 carbide tips. The cutting was carried out dry. The magnitudes of the vertical force Fz and cutting force Fy, were measured as the average of the recorded values when the tool was nearly approaching the end of the cutting pass.
After one pass along the length of the workpiece, the single insert was removed from the cutter and the measurements of the minor wear width were taken. This procedure was repeated using the same cutting condition untill the end of tool life reached, which defined on the bases of surface roughness. Because of the comparison with surface grinding, a mean surface roughness of 1 μm was taken to define the end of the tool life.

6- EXPERIMENTAL RESULTS AND DISCUSSIONS

6.1- Cutting Forces

a- Effect of Cutting Speeds.
A serious of short time experiments were carried out to determine the variation of cutting force Fy and vertical force Fz produced as a result of changing cutting speed. It can be seen in Fig. (2), that the force Fy and Fz are dependent on the cutting speed. At the lower speeds from 70 to 90 m/min, the force components Fy, Fz for both TTM and THR tool slightly increased and then decrease with a further increase in cutting speed for only THR tool tending to become constant at high cutting speeds. From Fig. (2), it can also be seen that the THR tool perform better than TTM tool at higher cutting speeds.

b- Effect of Feeds
Two sets of results were obtained at cutting speed of 110 m/min, one set using TTM and a second set using THR tools. Successive cuts were taken using feed varying from 0.05 to 0.25 mm/tooth in increments of 0.05 mm. The graph of the force components plotted against feed per tooth is shown in Fig. (3). Within the range of feeds used, the results show a strong linear relationship between Fy force and feed for both sets. The other Fz force increased with increased feed but the rate of increases reduced as feed incrased. The exception is at the lower feed of 0.05 mm/tooth where a tendency to constant is appearant in the forces. The pattern for both sets was similar except that the THR tool produces slightly lower Fz force than TTM tool. This means that the THR tool has lesser sliding contact with increasing feed per tooth compared with TTM tool.

c- Effect of Minor Flank Wear

Fig. (4) indicates that up to about 100 μm minor wear, it appeares that the force component almost independent of the wear, but as the wear increased it appeared that the force were directly proportional to the amount of flank wear. It can be also seen that, the minor flank wear increase the force component Fy only a little, whereas increases the vertical force Fz remarkably in both the TTM and THR inserts. An explanation was given by Zorev[27] of this increases in vertical force to the effect of the elastic reaction of the layer of machined material lying under tool provided that the built up edge or secondary shear zone on the tool face were disappeared. As the THR tools has a high resitance to failure through mechanical fatigue in addition to the resistance to flank wear and deformation, they are more stable and offer some protection against adheasion by workpiece material. With progress of cutting, the adheasion of workpiece material on minor flank decreased and this was confirmed by X-ray distribution image of iron through all the tests conducted. This means that the increase in vertical force Fz of THR tool was due to the increase of elastic reaction of the machined layer as the tool was more stable.

6.2- Shear Angle

The values of rc was measured and indicated in the upper part of Fig. (4). It can be seen that, in spite of the variation of the minor flank wear width (50 to 200 μm), rc is almost constant of about 0.6. Zorev[27] indicate that the constancy of cutting ratio means that the force acting on the minor flank do not take part in chip formation. The force increments must therefore be attributed to an increase in the force acting on the minor face due to the minor flank wear. In addition, no change in the appearant coefficient of friction at the tool rake nither the geometry of cutting as a result of increasing the minor wear. In order to achieve better understanding of the relation between force and hardness with a worn tool, a short machinability test was carried out on four different heat treatment work materials in respect of their hardness. The variation of force components with work material hardness indicates that the increase of work hardness increases the force component Fy only a little, whereas the force component Fz was substantially incrased as shown in Fig. (5). This can be explained by the fact that, the hard materials accelerate the wear on the cutting tool rapidly and increase the force components especially the vertical force.

6.3- Normal and shear stresses

In the following an attempt will be made to determine both normal and tangential stress on the minor flank. Figure (6) is a typical plot of calculated normal stress, σ_{mf}, and tangential stress, τ_{mf}, on the minor flank. In the calculation of both stresses, the tool force components were corrected for the ploughing force where the force components with using a sharp tool were deducted. The results of this test showed that normal stresses, σmf, on the minor face rises substantially with an increase in the hardness, while the tangential stress, τ_{mf}, rises slightly. In addition, these calculated stresses were higher than the ultimate tensile strength of the material, approximately 1235-1389 N/mm^2, indicating that the work hardening effect of the material has exceeded the thermal softening effect as the tool of 100 μm minor flank wear was passed on the machined surface. The higher value of microhardness found on the deformed layer of the machined surface is also evedent.

Considering the material properties in terms of ductility index γ/p as suggested by Robenstine [28], where γ is the surface free energy and p is the hardness. He suggested that the crack propagations are the result of high stresses during cutting. Such considerable stresses were produced on the machined surface of the tested alloy as shown in Fig. (6). The production of crack, however, consists in the generation of two new surfaces and this requires a certain amount of surface free energy of material γ, [28], accordingly, the metal becomes less brittle and more machinable. Thus, the stressed layer associated with high hardness in addition to the cracks left in the machined surface due to the segmented chip formation [29], will have a higher surface free energy than with an unstressed region. Therefore, the residual stress locked in the deformed layer under such condition will be compressive. The evedence in support of the suggestion that the trapped residual stresses are compressive can be found in ref. [24].

6.4- Condition of Contact on the Minor Cutting Edge

In Fig. (7), the change of coefficient of friction, μ, at the minor flank of a high value of 0.93 with low hardness number to a low value of 0.2 with high hardness number indicates that low hardness metals have an adhesive nature friction. Whereas, the low coefficient of friction associated with machining hard alloys will cause an increase of the verticla force component Fz relative to other force component as in Fy. When machining was carried out on the tested alloy of hardness of, 360-415 BH. with an inserted tip of THR K30 having a minor flank wear breadth of 100 μm. the substantial increase in vertical component, Fz, can be attributed to the low coefficient of friction of approximately 0.4.

6.5- Specific Cutting Energy

It is obtained by dividing the tengential force component, Fy, at any instance by the corresponding chip-section. The relationship obtained for the current material investigated and the THR tool show how the P_s, various with the cutting speed and the feed as shown in Figs. (8) and (9) respectively.

The P_s, tends to a constant values, of approximately 2.0 and 2.5 GJ/m^3 at the higher values of feed and speed respectively. This indicates that both speed and feed had similar type of behaviour.

Figure (10) shows Ps plotted against cutting speed and feed on log log scale. It can be seen that the specific cutting energy various slightly with speed while the feed has more pronounced effect on the P_s and yielding the relationship;

$$P_s \, \alpha \, \frac{1}{V^y} \text{ and } P_s \, \alpha \, \frac{1}{S^x}$$

where y and x takes values of -0.0088 and -4.0 respectively. The indices obtained by least square analysis.

For the sake of comparison, the specific cutting energy found in grinding of order 20 GJ/m3 for alloy steels [30]. This is about 10 times greater than that required to cut similar material with face milling. This substantial increase is a result of the relatively small depth of cut normally used in grinding which, in turn, leads the stresses twards tension due to the increased cutting energy. Therefore grinding is an insufficient metal cutting process when judged on the basis of specific energy.

6.6- Computation of Temperatures

Since the increasing cutting temperature is considered to play a role to eliminate the surface troubles associated with steels, thus the attension will be paid to study the temperature rise in the well known three cutting zones. The primary and secondary temperature rise calculated by the method proposed by Boothroyd [31].

In most practical circumstances, the cutting tool is not perfectly sharp and therefore the theird heat source would be existed owing to a friction between the tool and the new workpiece surface. However, more energy dissipation and existence of very high instantaneous surface temperature in milling was reported by Schmidit [32].

Figure (11) shows the calculated temperature rise in the primary deformation zone, Q_p, the temperature rise along secondary deformation zone, Q_s, and the average maximum temperature in surfce layer, t_2. It can be seen that at the lower part of Fig.(11), the temperature in the primary and secondary deforamation zones reduces slightly with an increase in cutting speed. This slight decreasing in temperature with increasing cutting speed can be explained in term of shear strain γ. It is confirmed by the consideration of the fundamental aspects of chip formation that the increasing of the cutting speed will increase the cutting ratio r_c, and accordingly the shear angle, ϕ_c. In machining hard materials, the inclination of cracks [33] is to be determined only by the work material and is expressed by;

$$\phi_c = \frac{\pi}{4} - \frac{\gamma}{2}$$

From this expression, small shear strain, γ, or less ductile work material, gives large shear angle, ϕ_c. Since the temperature rise at shear zone is proportional to the shear strain, γ, and since the 75 to 90% of the total heat in the chip is due to the shear of the chip. It follows that the decrease in cutting speed increases the amount of shear zone heat because of the increase in shearing strain.

As far as the workpiece temperature is concerned, there is more shear zone heat and more time is allowed for heat transfe to the workpiece because a contact for a longer time at low speeds, one would excepted more heat at lower speed. The results of the calculated temperature presented in Fig. (11) may be held true as it was based on sharp tool. It is not possible to make similar calculation with a tool having a minor flank wear. However, with a tool having flank wear Zorev [27] stated that, most of the specific cutting work consists primarily of the specific work of friction on the clearance face. Smillar results had been obtained by Konig etal[34]. Konig explains that, this friction results in high levels of temperatures that will not to be dissipate with the chip, but most of it flows into workpiece.

In the light of this discussion it would be expected that the high temperatures would be attained at high speed, with tools having minor flank wear. On the other hand, noteced that the chips produced, using a worn tool of minor flank value of 100 µm at the higher speed range between 140 to 176 m/min, were all segmented and less burned at the edges compared with chips produced at low speed range. In the light of this evedence, it is now clear that the THR K30 inserts performed better at high speed range because the tool temperature was not allowed to reach its steady state value[35].

CONCLUSIONS

The surfaces of low alloy Cr-Ni steel in its hordened conditions were face milled using conventional sintred carbides of TTM P30 and submicron grain cemented carbides with low percentage of cubic carbides of 2% of THR K30 to find if surface grinding can be replaced by fine face milling. On the basis of the experimental results, the following conclusion can be made.

1- A short time face milling tests carried out at cutting speed up to 176 m/min showed that the modified compositions THR K30 carbide performed better than the conventional TTM P30 carbide in terms of force components. With respect to the THR K30 tools, the force components were found to be decrease with cutting speed and then remain fairly constant at a higher cutting speed.

2- The THR K30 carbide inserts of minor wear values between 50 to 250 µm can be successful applied in face milling at a high cutting speed range up to 176 m/min in comparison with the conventional tools. This because they provided stranger cutting edge due to the stabilization of the worn tool under the higher cutting conditions.

3- Minor flank wear caused by a brasion, the most likely wear mechanism, was found to be the predominart wear tupe observed in this study. Therefore, in finish face milling, the cutting conditions has to be determined on minor flank wear.

4- The sudden increase in the vertical force Fz associated with THR K30 tools was related to elastic deformation on the machined surface when the minor flank wear exceeds a certain value of about 100 μm. This was attributed to the constancy of cutting ratio of about 0.6 as well as the low coefficient of friction of about 0.4.

5- A smooth minor flank surface was found to exist in all tests conducted between cutting speed of values 110 to 176 and feed of 0.1 mm/tooth. While, decreasing the cutting speed caused the minor flank wear conditions to be severe. Since the minor flank wear affect the produced machined surface during back cutting action, therefore a high surface quality values can be achieved within the high speed range.

6- The value of calculated normal and shear stresses were found to be higher than the ultimate tensile strength of the tested alloy. An explination for this differences is that the work hardening effect of the tested alloy has exceeds the thermal softening effect as the tool of a 100 μm flank wear passed on the surface with a cutting speed of 110 m/min and feed of 0.1 mm/tooth.

7- The value of the specific cutting energy in the current tests was found to be almost the tenth as low as the value in surface grinding of simillar alloy found in literatures.

8- The calculated temperatures rise in primary and secondary deformation zone and workpiece temperature using a sharp tool were found to decreased with the increasing in cutting speed. This was explained by the fact that the high cutting speed will shorten the heating cycle in interrupted cutting.

9- At higher cutting temperatures encountred when the worn tool is applied at high speed range between 140 to 176 m/min. the chip produced were all segmented and less burned at the edges compared with chips produced at low speed. This suggests a greater stability of the tool - workpiece - machine system where the tool softening was not likely to occure.

10- In some cases, it is now possible to machine the tested alloy using fine face milling without the need for subsequent grinding operations.

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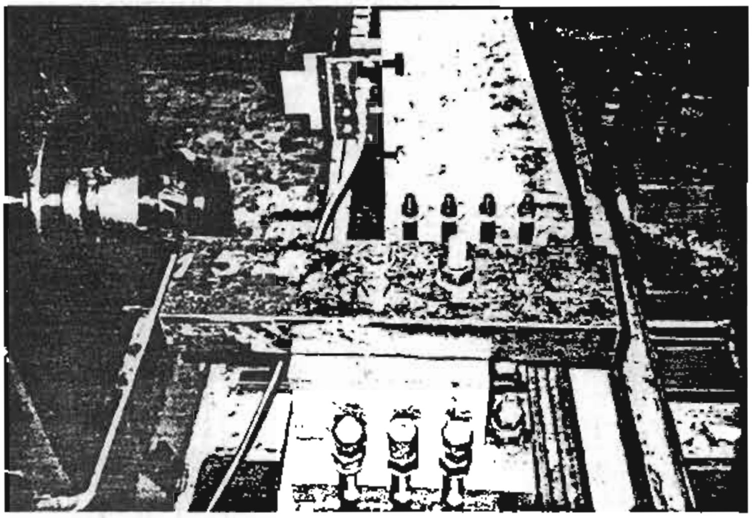
Table 1: *Composition and Physical Properties of WIDIA milling grades

Grade designation	Composition % Wc	Ti+TaC+NbC	Co	Density, g/cm^3	Hardness HV30	Transverse rupture strength, N/mm^2	Modulus of Elasticity, N/mm^2	Thermal Conductivity W/m.K	Thrmal Expansion $10^{-6}/K$
TTM P30 (TPJN)	72.5	17.5	10	12.5	1500	2100	560000	45	6.7
THR K30 (TPJN)	86	2	12	14	1399	2450	580000	60	5.9

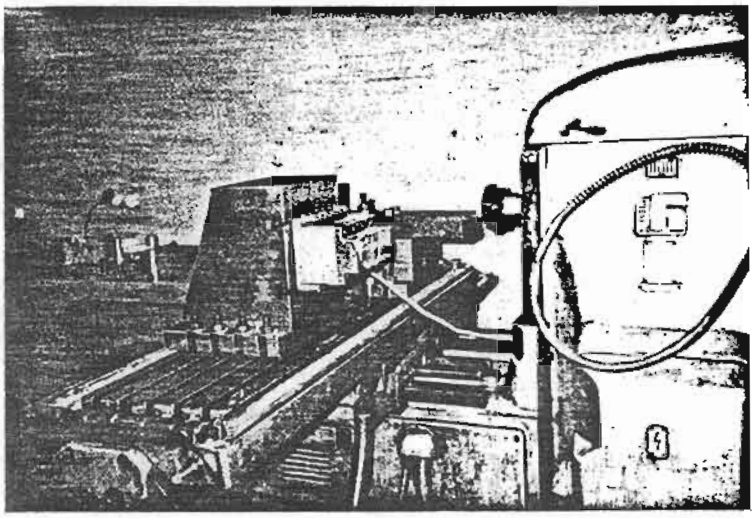
*Data reproduced from an outlines of grades, Krupp, Widia.

Table 2 : The cutting conditions used in the experiments

Cutting Speed, Vc , m/min	70,90,110,140, and 176
Number of revolution, N, rpm	(180)(224),(280),(355)&(450)
Feed, ft, mm/tooth	0.05,0.1, 0.15,0.2 and 0.25
Depth of cut, ap, mm	1
Cutter diameter, D, mm	125
Tool cutting edge angle, γ_r, degrees	45°
Radial rake angle, γp, degrees	-12
Axial rake angle, γf, degrees	14
Angle between tool entry and tool exit, ϕ_s, degrees	81
Entry angle, ϕ_E, degrees	77
Exit angle, ϕ_A , degrees	158
Angle of engagement, degrees	14
Initial contact angle, i, degrees	18
Dist.from CL to the engaged plane,mm	16
Ratio of milling diam. to width of workpiece,non dimensional	1.6
Work Material	Low alloy steel 1-1/4 Cr-Ni Steel.

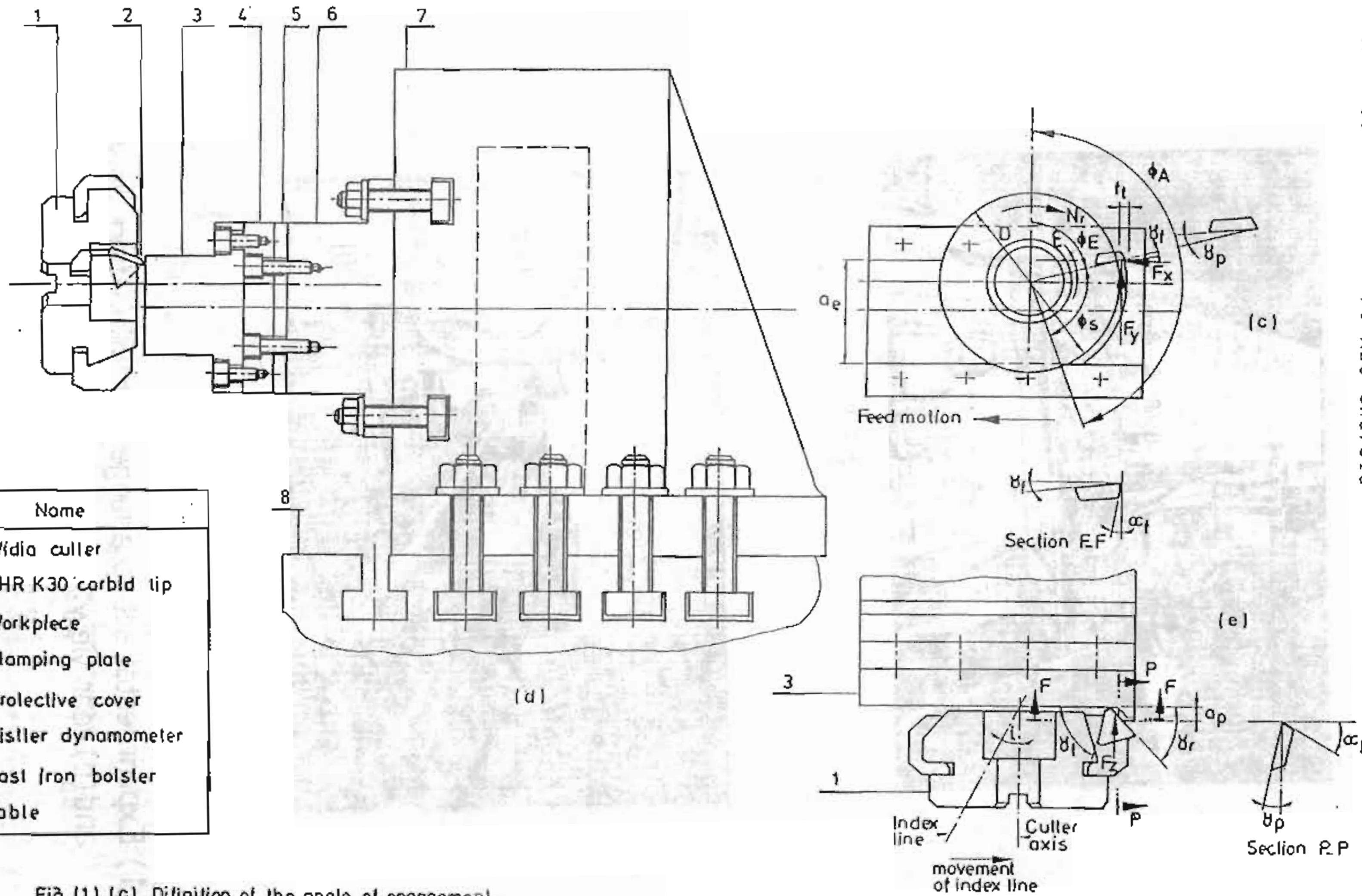


(a)



(b)

Fig(1) Experimental set up arrangement with(a) front view and(b) rear view.



No.	Name
1	Widia cutter
2	THR K30 carbid tip
3	Workpiece
4	Clamping plate
5	Protective cover
6	Kistler dynamometer
7	Cast Iron bolster
8	Table

Fig. (1) (c) Difinition of the angle of engagement.
(d) A bolster specially designed for clamping test specimens and the dynamometer vertically.
(e) Difinition of points of initial contact conditions in face milling.

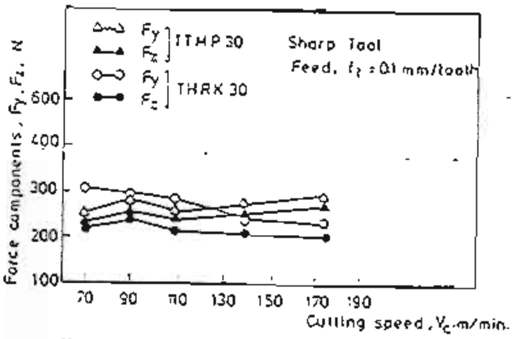


Fig.(2) Force components due to change in cutting speed.

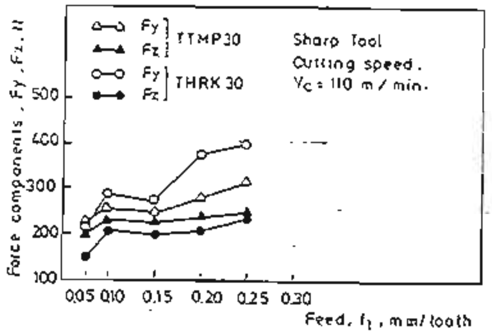


Fig.(3) Force components due to change in feed / tooth.

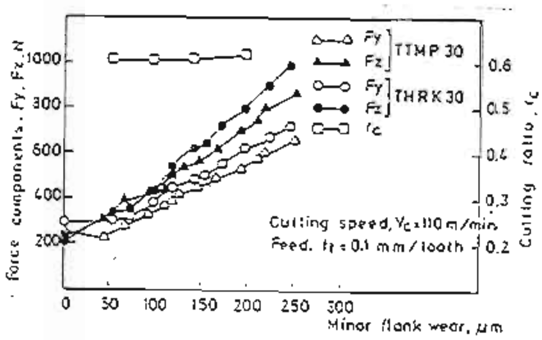


Fig.(4) Force components due to minor flank wear.

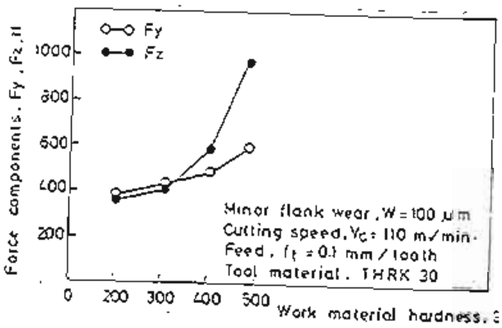


Fig.(5) Effect of workpiece hardness on force components.

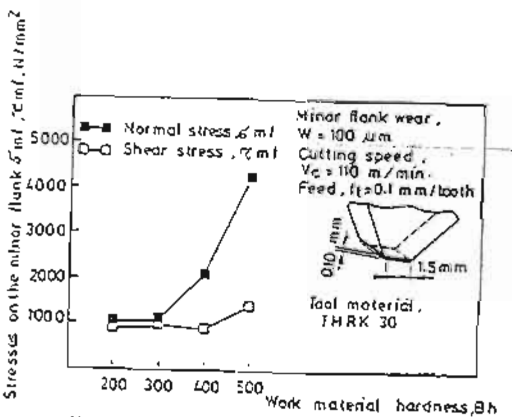


Fig.(6) Effect of workpiece hardness on stresses.

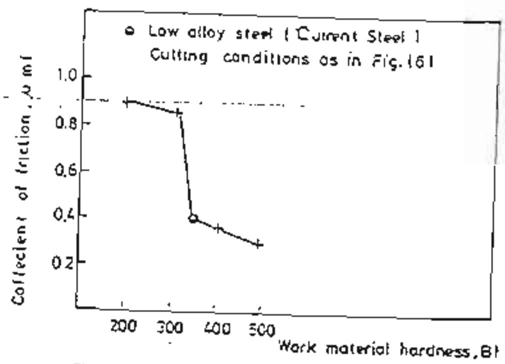


Fig.(7) Effect of workpiece hardness on coffecient of friction.

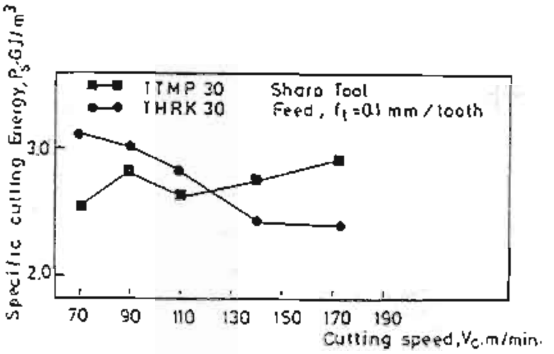


Fig. (8) Effect of cutting speeds on the specific cutting energy.

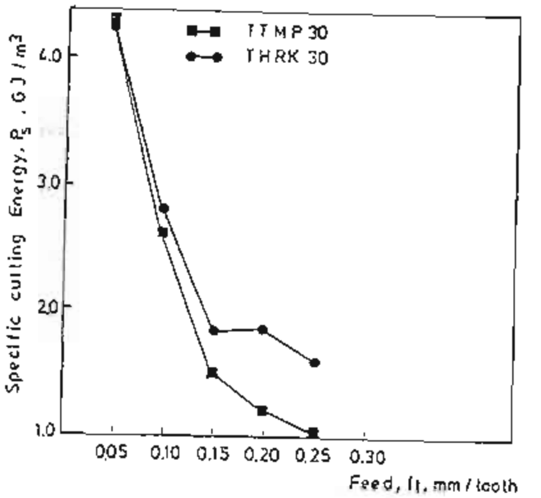


Fig. (9) Effect of feed on the specific cutting energy.

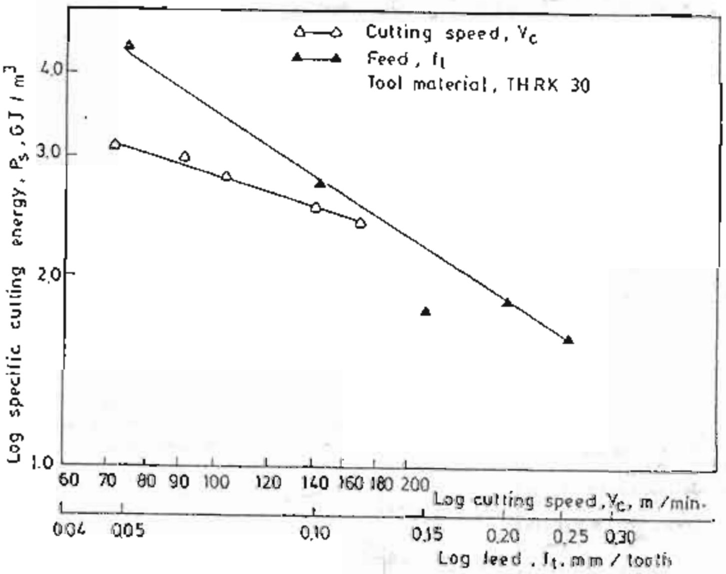


Fig. (10) Plot of log cutting speed and feed against log specific cutting energy.

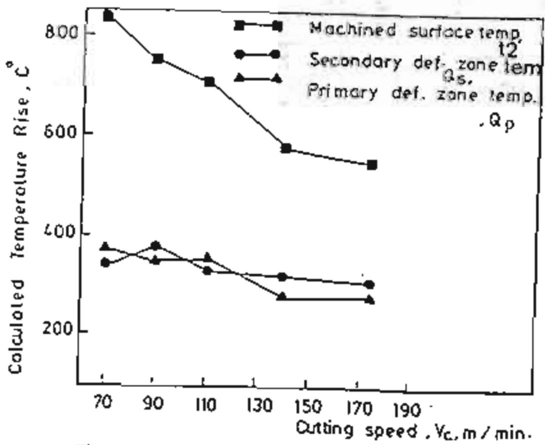


Fig. (11) Effect of cutting speed on calculated cutting temperetures, θ_p, θ_s and t_2 (theoretical)