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SURFACE FINISH AND LUBRICATION AT LOW CUTTING SPEEDS

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Abstract. *Surface finish is one of the most important parameters to be controlled during machining as it affects many functional properties of components. It can be effected by workpiece and cutting tool material, geometry, cutting fluid and cutting conditions. When machining at low cutting speeds a cutting fluid with good lubricant proprieties is often recommended to improve surface finish. This improvement is often thought to affect built up edge (B.U.E.) formation, which is a major cause of poor surface finish. This work studies the effect of sulphur, an extreme pressure (E.P.) additive, in an oil lubricant on the surface finish of an AISI 1040 steel machined with a cemented carbide cutting tool. The application of a lubricant, with and without sulphur, does not prevent the formation of B.U.E. but does affect the surface finish. This work suggests that the B.U.E is squeezed against the workpiece material close to the tool nose affecting surface finish. This region is where lubricant acts to improve surface quality and therefore very low volume of lubricant should be sufficient.*

Keywords: *Surface finish, Cutting fluids, Machining, Built up edge.*

1. INTRODUCTION

Surface finish of a workpiece is often the most important parameter to be controlled in an industrial machining process. It is dependent on the material, tool, process and cutting parameters (e.g. tool geometry, speed and feed rate). There is a special tool geometry that can be used in finishing operations to help form a good surface. A finishing operation is performed at high cutting speeds and low feed rates whenever possible to avoid the formation of a built up edge (B.U.E.), which gives poor surface finish. However, in some operations this is not possible. Small diameter tools such as drills and end mills would require prohibitively high spindle speeds to prevent B.U.E. formation even at their periphery. During the operation, tool wear and vibration of the tool and machine tool can also affect surface finish and so they need to be controlled.

Among the main functions of a cutting fluid are cooling (tool, workpiece, tool holder, machine and chip) and lubrication of the cutting zone. When the fluid is applied as a coolant (usually at high cutting speeds) it can help to increase tool life and excessive dilatation of the workpiece. Applying the cutting fluid as a lubricant can be effective at low cutting speeds with an aim of increasing tool life and improving surface finish. The improvement in the surface finish while using a lubricant is thought to be owing to the prevention of B.U.E. formation.

The widespread and normal way of applying a cutting fluid is called overhead flood cooling. Large volumes of lubricants are used compared with the small areas of contact in the cutting zone that should be affected. A very small volume of fluid should be enough to lubricate the entire contact area even though it may be removed by the chip flow. There are others methods and direction of application of a cutting fluid to penetrate the cutting zone, examples include the high-jet method (Piggot & Colwell, 1952), and mist lubrication.

There are many theories about the formation of B.U.E. but most indicate that it is a phenomenon dependent on temperature. If this is the case a coolant may change the range of cutting speeds over which there is B.U.E formation provided it can remove heat from the cutting area sufficiently quickly. Also the contact area between the B.U.E. and the tool may be affected by the lubrication which minimises the sticking and therefore suppresses its initial formation.

The present work investigates the effect of a lubricant and a sulphur additive (i.e. an extreme pressure (EP) additive) on the formation of the B.U.E. and its relation to the surface finish. In much of the literature the improvement in surface finish has been attributed to a change in B.U.E. size and shape. The present paper suggests that another phenomenon may be responsible for this improvement. It is observed that the B.U.E is squeezed and rubs against the workpiece surface close to the tool nose, altering the surface finish. Cutting fluid lubricates this contact improving surface quality and avoids possible sticking of part of the squeezed B.U.E..

2. THEORETICAL SURFACE FINISH IN MACHINING

In a hypothetical machining operation where the tool is infinitely sharp and there is no friction, no vibration, and no B.U.E., the surface finish will largely be the marks left on the workpiece by the tool as a result of the feed. These feed marks are illustrated in figure 1 for external cylindrical turning using a single point tool with nose radius r.

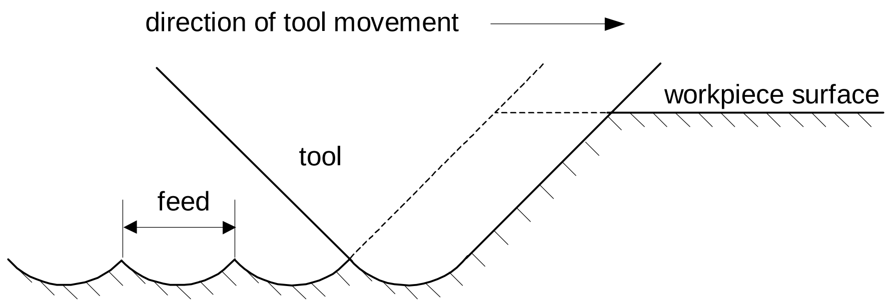


Figure 1-Feed marks left on the surface of the workpiece.

Surface finish for this case can be calculated as a function of the geometry of the process, i.e. tool nose radius and feed rate according to:

$$R_a = \frac{f^2}{18 \times 3^{\frac{1}{2}} r} \tag{1}$$

where:

Ra - average roughness (μm)
f - feedrate (mm/rev)
r - tool nose radius (mm)

There has been some attempt in the literature to include in the calculations other parameters like cutting speed and depth of cut (Jang, 1992).

Many factors will be responsible for the variation of surface roughness from the ideal value, among them B.U.E., tool wear, vibration, elastic recovery of workpiece material and flow of material perpendicular to the direction of the direction of cutting (side flow) (Selvan & Radhakrishnam, 1973). The material close to the cutting edge, on the primary shear zone, is under compression and can flow towards the sides. This can be responsible for the variation in the height of the ridges of the feed marks. The side flow of material during cutting can contribute to groove wear on the tool that in turn can affect the feed marks.

Another possible effect on feed marks in machining is attributed to the fact that there is a minimum depth of cut that will depend on many factors, but mainly on the proprieties of the material. At depths less than this minimum value the material will not be cut, it will just be deformed. In machining with a single point tool, like in figure 1, the depth of cut for the secondary cutting edge (or tool nose) varies from zero to this minimum value, and so a portion of material is left on the surface. This elastic recovery is called sponsipfil (Pekelharing & Gieszen, 1971) and also contributes to the variation of surface roughness by changing the feed marks.

3. EFFECT OF B.U.E.

In a real machining operations the under surface of the chip will normally seize to the rake face of the tool. This is because the area of contact is small and the pressure is high enough to cause adherence between the two materials. This adherence depends on the workpiece and tool materials as well cutting conditions and lubrication condition at the interface. At low cutting speeds in steels and other multiphase materials the adherence can cause the formation of a B.U.E. (Trent, 1988a; Trent, 1988b).

The height up of the B.U.E. is variable and can cause large changes in the cutting forces. As the B.U.E. replaces the cutting edges of the tool, these variations in size can affect surface finish by effectively changing the nose radius. Also cracks can start in the B.U.E. structure and associated flow zones, which lead to portions of the B.U.E. being deposited on to the workpiece surface. Depending on the size and shape of the B.U.E. it can even affect the depth of the cut.

With steels the conditions between chip and tool will change with the cutting parameters and temperatures. Increasing cutting speeds increases heat generation and the B.U.E. disappears. Instead of the B.U.E. there will be a flow zone and under these conditions the surface roughness remains unchanged at higher speeds (Sata, 1963).

4. EFFECT OF CUTTING FLUID

There are many reasons to apply a cutting fluid during a machining operation, but at low cutting speeds one of the main functions should be lubrication (a) at the interface between the chip and the tool and (b) at the contact between machined surface and tool flank face. Their effectiveness thus depends on their ability to penetrate the chip/tool interface in the time available and to form a film with lower shear strength than the strength of the bond between the work material and the tool (Shaw, 1958/59).

The importance of a lubricant in friction between metals is well known. Surface cleanliness is one of the most important parameters affecting the friction coefficient. Even a single molecular layer of contaminant from the atmosphere may produce a very large decrease in friction (Bowden & Tabor, 1967). In machining, the underside of the chip and the machined surface are newly formed surfaces and are in close contact with the tool. They rub against the tool surface removing oxide coatings and any other contaminant. Thus, the surface can metallurgical bond together. This bonding and the motion of the surfaces tend to exclude cutting fluid (Wright et alli, 1979).

It is not clear yet what access a cutting fluid has to these interfaces or how it can get there. The average normal stress on the chip tool contact zone is extremely high, being in the range 200-800 MPa for steel (Trent, 1988b). At high cutting speeds, where the temperatures are high, further problems are encountered as the lubricant may boil or decompose before penetrating the cutting zone. On the rake face during cutting (at higher speeds), there is a seizure zone and a sliding zone. The length of these depends on the stress distribution on the tool. There is some support (Childs & Rowe, 1973) for the theory that a lubricant cannot gain access to the seizure zone and so attention should be focused on the sliding region. If a lubricant is applied and it penetrates only the sliding zone, which has only a small contribution to the total forces, it will only affect the total force marginally. The sliding zone has the lowest compressive forces and as such can be influenced by small changes in the cutting process (e.g. the inertia of the chips or external vibration). Lubricants may be able to decrease the effective stick/slip situation in this zone and give a smoother cutting action. This same phenomenon could happen at a flank face. As the cutting speed increases the temperature increases, which means that coolant properties become more important as lubrication becomes much more difficult. Neat oils used at high speeds often exhibit signs of decomposition in the form of smoking which renders them unsuitable. However, if lubrication at the chip/tool interface can prevent the formation of a B.U.E. at lower cutting speeds, the surface finish normally improves

5. EXPERIMENTAL WORK

The machining process used was external turning of an AISI 1040 rolled steel bar with an average hardness of 199HV (load of 30Kg). The composition of the material was (wt-%):

0.43%C 0.83%Mn 0.19%Si 0.035%S 0.007%P 0.19%Cu 0.11%Ni 0.14%Cr 0.05%Mo 0.027%Al 0.04%Ti

The maximum diameter used was 180 mm and the minimum used was 100 mm. This large diameter is necessary to allow the use of an infrared sensor to measure the temperature of the machined surface during cut. This technique and the results from it are presented in another paper Da Silva & Wallbank, 1997).

The tool was a cemented carbide designated ISO M35 with a TiN-TiC-TiN coating. The tool tip was a square insert with zero clearance angle, and therefore with eight possible cutting edges to be used for each insert. The length of the cutting edge was 12mm with thickness 4mm. The tool had a nose radius of 0.4mm. This is designated SNMG 120404. When mounted in the tool holder the approach angle was 45°, the rake angle was 5°, the clearance angle was 5° and there was zero inclination of the cutting edge.

During machining the cutting force, feed force, and thrust force were recorded using a piezoelectric dynamometer. The surface roughness Ra was measured after each test using a Taylor-Hobson Surtronic 3 with a cut off length of 15 mm and the final result presented is the average taken from three different positions on the workpiece.

Three cutting speeds, 22, 30 and 40m/min, and three feed rates, 0.05, 0.1 and 0.15mm/rev were used in these tests. These conditions are the minimum cutting speed for the lathe and the maximum cutting speed before the oil based lubricant produced excessive smoke (which is cause by the contact of the oil with the chip after it leaves the cutting zone). The depth of cut was held constant at 2mm.

The oil was a refined mineral oil, BP100 SP having no additives and the EP additive was Additin RC 2415. This additive is a sulphurised vegetable fatty acid ester, with approximately 15 wt-% sulphur and 5 wt-% active sulphur. The oil was used with 0 and 5 wt-% of this additive. The lubricant was applied using traditional overhead flood cooling at an average rate of 25ml/s. In later tests the flow rate was reduced to 4ml/s and then to 0.03ml/s using a surgical needle to replace the cone shaped nozzle.

Chip specimes using a quick stop device were cut from the workpiece for examination using scanning electron microscope and also polished to reveal the microstructure in an optical microscope. The quick stop device is used to remove the tool from the cutting zone at high speed. This is done using a humane killer gun to propel the tool from the workpiece (Hasting, 1967). This sudden action retains important details of the cutting action.

6. RESULTS

Figure 2 shows the results for surface finish Ra measured after machining with no lubricant, oil and oil with 5% sulphur.

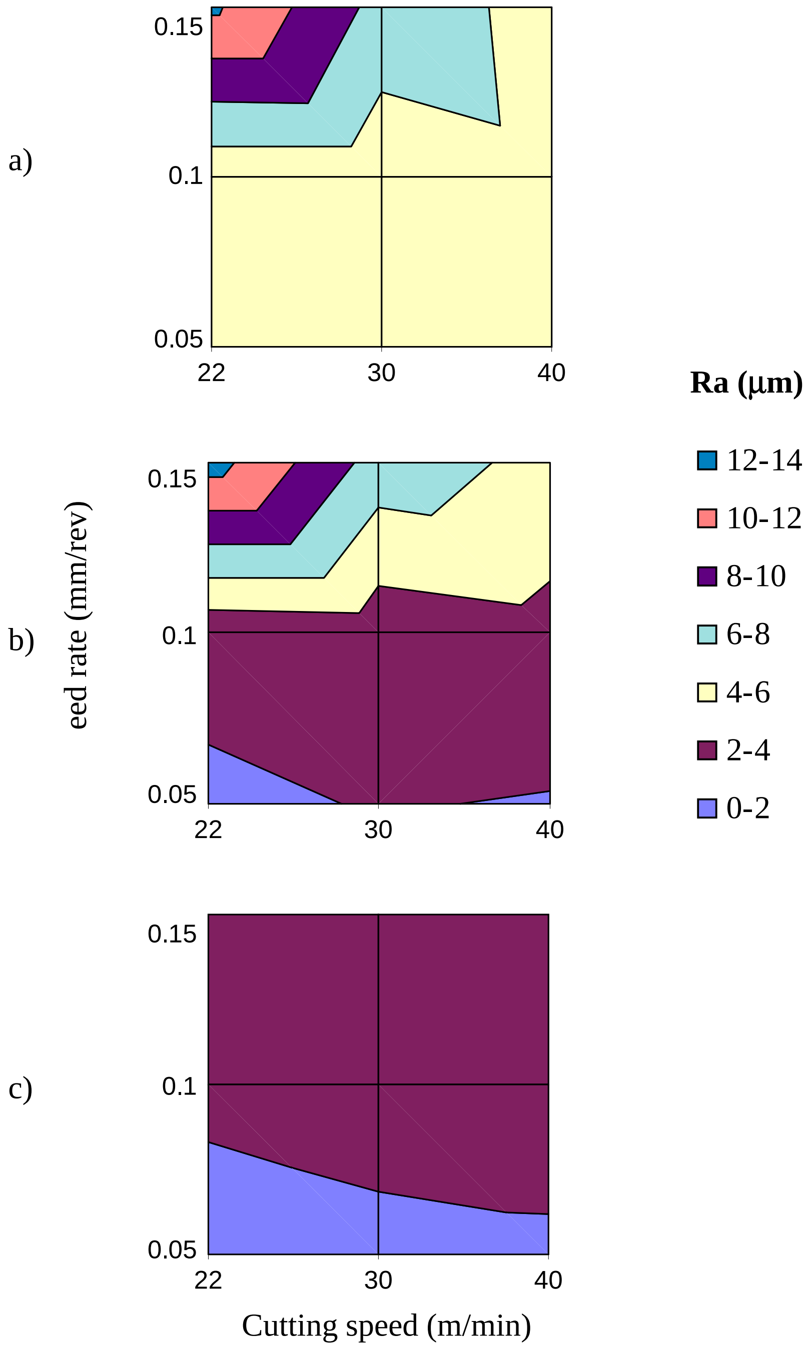


Figure 2-Surface Finish, Ra (µm). a-dry; b-oil without sulphur; c-oil with 5 wt-% sulphur. AISI 1040 steel machined with cement carbide, d.o.c.=2mm.

For dry and with oil conditions, the effect of speed for feeds higher than 0.1mm/rev was to increase the surface roughness and the results in both cases are very similar. This does not happen when sulphur is used as an additive at the 5 wt-% level. In this case there is no significant change in the surface finish, which seems to be independent of the cutting conditions.

For feed rates of ~0.1mm/rev and below, the oil improves surface finish compared to cutting dry. The effect of adding the active sulphur was to marginally improve the surface finish at the higher speeds and lower feed rates.

All the above results are for flow rates of the cutting fluid of 25ml/s, but similar values were obtained when rates of 4ml/s and 0.03ml/s were used.

Cutting forces were recorded during the tests and no significant difference was observed between dry and lubricated conditions. There was also no significant difference in the standard deviation that may have indicated that the cutting fluid was reducing vibration, or the intermittent contact of the chip on rake face.

Chip specimens from quick stop tests were used to indicate the size and shape of the B.U.E.. These were also used to check the conditions of the surfaces: (i.e. the transient machined surface produced by the primary cutting edge, the workpiece, and chip surfaces). The quick stop test is not always reliable in indicating the size of the B.U.E., because the movement of the tool may damage the cutting zone and its size and shape change with time. These tests however did not suggest a change in size of the B.U.E. with the different lubrication conditions (dry, oil and oil with sulphur).

7. DISCUSSION OF THE RESULTS

The effect of the additive on the performance of the oil in terms of surface finish is clear. While the oil without sulphur has little effect at ~0.1mm/rev feed rate and above, oil with active sulphur results in a better surface under all conditions compared with dry cutting. There appears to be a critical value for the feedrate above which (independent of the cutting speed) oil without the additive has no effect. The addition of sulphur therefore is critical above this feed rate.

The theoretical roughness that is possible should be owing to the marks left on the workpiece by the tool geometry, i.e. the feed marks. If there is no B.U.E., the tool is sharp and wear is not present then the theoretical roughness can be calculated according to equation (1), which is a function only of the feed and nose radius of the tool. For the cutting conditions used in this work the values of Ra are:

0.05 mm/rev - 0.7 μm
0.10 mm/rev - 1.4 μm
0.15 mm/rev - 2.1 μm

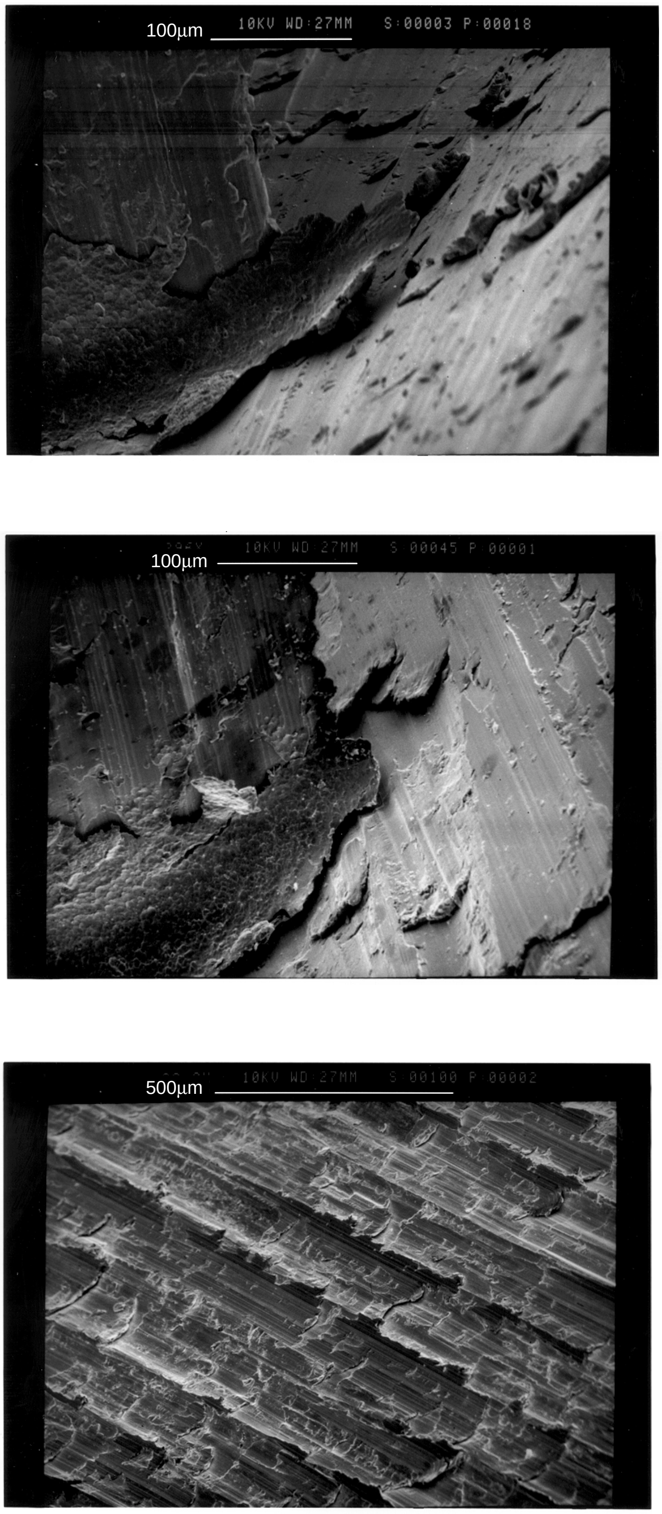
Compared with all the experimental results these theoretical values are considerably different.

The formation of the B.U.E. is a major cause of poor surface roughness and it should be avoided when good surfaces are required. As both the B.U.E. and the flow zone are formed on the rake face of the tool and occur as a result of adherence between chip and the tool, it could be argued that lubrication should affect them both. However the forces and pressure on the tool rake face in both cases are high and so it is difficult for a cutting fluid to penetrate and lubricate the contact.

Statistical analysis (analysis of variance) did not detect any significant variation in the cutting forces to support a lubrication effect.

Depending on its size and form, a B.U.E. may avoid contact between the machined surface and the flank face. However a B.U.E. does not form along the whole contact of the rake face and contact on the end clearance face may still exist. In a cylindrical turning operation particularly using a single point tool with an approach angle it is possible that the material, which accumulates, is squeezed on to the sides of the tool.

Figure 4a shows a scanning electron microscope view of a quick stop specimen for a dry cut. This figure shows the end cutting edge of the tool at a point where it looses contact with the material and the new surface is formed. The B.U.E. formed (or the dead zone that forms at the cutting edge) seems to be rolling or squeezing towards the fresh surface of the workpiece. Periodically small pieces of that B.U.E. are broken off, as suggested by micrograph, and the surface of the material has some smooth paths on the grooves between the feed marks separated by some material, which look like burrs. These burrs are higher than the grooves formed by the feed marks and will contribute for the poor surface roughness.



a)

b)

c)

a dry; b and c oil + 5% sulphur

Figure 4-Micrographs of a and b point where cutting edge looses contact with workpiece and c surface of workpiece: AISI 1040 steel, Vc=40m/min; f=0.15mm/rev, d.o.c.=2mm.

The same kind of configuration of B.U.E. or dead zone is observed when cutting with oil and oil with 5 wt-% sulphur. Figure 4b is the specimen for oil with sulphur for the same cutting condition as in figure 4a. In figure 4b the feed marks are clearer and there are no burrs formed inside the grooves. There is a damaged area caused by the quick stop device, this can be ignored. The material squeezed on to the sides of the B.U.E. is acting as a wiping edge. For dry cutting this wiping edge adheres to the workpiece surface forming the burrs. When lubricant is applied it prevents this adherence.

Figure 4c shows the surface of the workpiece relating to figure 4b. For the cutting conditions used in the tests in figure 4 the surface finish Ra is 5.2μm for dry, 5.42μm for oil, and 3.7μm for oil with 5 wt-% sulphur addictive.

Squeezing can be a very important aspect of surface finish and it is where the lubricant is most important. In tests using lower flow rates of lubricant the surface roughness results are the same. Even when the lubricant, (applied at the rate of 4ml/s), is applied 10mm from cutting edge the results are similar. In this case even though the amount of lubricant reaching the rotating workpiece (owing to spreading) is very low it still seems effective.

The flow rate of 0.03ml/s is not continuous instead the lubricant was applied in a rate of 1.3 drops/s directly on to the region where the chip looses contact with the workpiece. This low volume of lubricant is enough to improve the surface roughness because the area that requires lubrication is small; and as the area affected is so small, there is no effect on the cutting forces.

With these low volumes of lubricant and the way they are applied, i.e. indirectly, it is probable that the oil does not reach the chip/tool interface. This fact suggests that the lubricant does not prevent the formation of the B.U.E., or lubricates the rake face of the tool (even if this were possible), but only needs to lubricate the region near to the tool nose.

It should be noted that others functions of the cutting fluid will not be performed when very low lubricant volumes are applied in this manner (e.g. cleaning the swarf from the cutting area and protection to the machine tool).

8. CONCLUSIONS

The material at the top of the B.U.E. is squeezed and deposited on the workpiece surface after it has being formed. This and other effects contribute to the surface roughness of the workpiece. Surface finish can be improved using lubricant even without preventing the formation of B.U.E. The improvement as a result of lubrication is brought about by avoiding the deposit of parts of the B.U.E. on the workpiece surface close to the tool nose. Mineral oil improves surface finish for low cutting speeds, but this effect seems to be dependent on feed rate. The extreme pressure additive, sulphur, has an effect on performance of the mineral oil in respect of surface finish. As the area to be lubricated is small a very low quantity of lubricant should be enough to give an improvement to the surface finish.

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