The Comparison on Tool Wear, Surface Finish and Geometric Accuracy when Turning EN8 Steel in Wet and Dry Conditions

Matthew Grover, Zulfiqar A Khan

Abstract— **This paper, by experimental and investigation, examines the effects of dry and flood cutting conditions by comparing the rate of tool wear during metal turning and the produced surface roughness to determine if dry cutting can be a cost effective solution. For efficient manufacturing, the surface roughness of the turned parts should be dependent on their intended application, factors such as environment of operation or further manufacturing processes will determine this level of surface roughness required, as the performance and mechanical properties of the material can be affected. EN8 steel has been selected as the work material for its popularity and low hardness. The results show both wet and dry conditions have their benefits in relation to the intended application of the part, but mostly dry turning produces competitive surface roughness's in finish turning when compared to wet, and acceptable levels of tool wear while rough cutting. It would be recommended that in most circumstance for rough cutting, dry conditions should be employed with the knowledge of slight increased tool ware and possibly shorter life but with reduced manufacturing costs and environmental hazards.**

Index Terms—**Build-up-edge, Dry turning, Surface roughness, Tool wear**

I. Introduction

TURNING is one of the most basic and common material removal processes, done via a rotating work piece, it along with machining has an overwhelming and increasing level of concern surrounding the use of metal working fluids (MWF's) during these metal removal operations as relayed by [1], [2], [3], [4], [5]. There have been numerous studies conducted on these concerns and the risks they impose on the operator and environment. Skin related problems have been linked with direct exposure to the coolants as well as health risks associated with coolants becoming airborne [1], [6], [7], which was linked to bacteria and fungi colonizing within the cutting fluids and serving as a source of microbial toxins. With attention of dry machining successively brought to the field of environmentally friendly manufacturing by [8], it was soon made apparent of its potential advantages. Unfortunately, without the presents of a cooling agent, certain characteristics of the turned work piece can greatly suffer, mainly caused by the excessive generation of heat. This lack of coolant can affect some of the most important requirements for a turned work piece, making dry turning sometimes less effective, as discussed by [9]. For many years now the tooling company "Sandvik" has encouraged and developed dry turning for the industry and have made great success in terms of tool life and surface quality by producing more geometrically suitable and stable cutting tips. Flood cooling is the most widely used approach in industry for both milling and turning [10]. Although in some circumstance coolant can prolong the life of the cutting tip, higher costs may be present through material removal stages when coolant is applied, as cutting fluids "*impact both stationary and rotating elements within the machine tool system*" [5], as opposed to a possible reduction in the life of the cutting tip, which may come at a lower, overall expense to the company or metal worker. With mechanical energy being transferred into the cutting fluid, higher surface energy is obtained by the coolant, that intern can cause it to atomise through reduced stability. As suggested by [11], [12], reducing the fluid will intern reduce the cutting force and improve surface finish.

Cost of coolants is not just a one off payment, but includes indirect costing that have been said to make up around 7 to 17% of the total manufacturing costs [3], [4]. The total cost of use for cutting fluids is comprised of several factors; first being the initial cost, top-up costs, life machine damage, health & safety issues, maintenance and most importantly and a growing concern, disposal costs [13]. To overcome this, minimal quantity lubrication (MQL) was developed and studied to reduce the amount of lubricants in metal removing operations due to these issues of ecological, economical and most importantly occupational pressure [1]. Despite the reduction, MQL still has an undesired by-product of airborne particles, which increase the health risks of the operator. Long exposure to these airborne particles can result in "*health problems ranging in severity from mild respiratory illness to asthma and several types of cancer*" [6]. While reducing the cost of coolant, MQL involves additional costs to pressurise the air and technological support that is required with the process, so although it may be considered a more environmentally friendly option, cost saving or operator health is not a key advantage. Therefore, the objective of this report is to compare the tool ware, surface roughness and geometric accuracy under wet and dry conditions when turning, thus to gain a better insight and understanding on the decision whether to use MWF's and potentially reduce manufacturing costs and environmental hazards, as well as determining if the rate of tool ware outweighs the use of MFW's to the point that it makes it feasible. Despite the

Manuscript received March 17, 2014; revised April 11, 2014.

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numerous studies on dry and hard turning and the attractiveness of it, *"…implementation in industry remains relatively low*" [14] as some outdated companies are still performing flood cooling where it is unnecessary, either because they are unaware of the practice or do not know how to implement dry turning correctly in the right circumstances, which may be due to it being a relatively new processing technique with several questions remaining unanswered [14]. Certainly, coolant and lubricant is required in some aspects of machining and turning to remove excessive heat and chippings, but considerable costs and environment hazards can be reduced if dry turning is used appropriately when possible.

II. Background

Obtaining different levels of surface finish during metal turning should be dictated by its intended application, as high quality finishes and tight tolerances can induce increased machining times and costs, which may not be necessary or economical. In some circumstances a low surface roughness can be one of the most important requirements for many turned work pieces, where coolants and other cutting fluids are used to reduce heat dissipation to maintain this surface quality and geometric accuracy throughout the material removal process. Such applications include interference fits and surfaces that are to be polished. A good surface roughness influences the materials mechanical properties whilst in service. Lower surface roughness can prevent premature fatigue failure, improve corrosion resistance, reduce friction, wear, noise and finally, improve the life of the product [10]. Accepting a slightly shorter tool life for the chance to eliminate the cost and annoyances of maintaining cutting fluids could be the less expensive choice [15]. In other instances, higher levels of surface roughness may also be desired, i.e. to allow coatings to adhere correctly to the part.

Surface finish is highly controlled by many different factors, including the cutting parameters [9], [16], [17], [18] tool type, rigidity of the lathe and geometry of the cutting tip, which includes rake and flank angles [10]. The surface finish also directly relates to and is an important measure of the overall quality of the part, as this influences the performance, mechanical properties and cost of production [19]. As [20] states "*Surface quality significantly improves fatigue strength, corrosion resistance, or creep life*", which stresses the importance of specifying surface requirements during design stages so that the tools maybe be set up appropriately to achieve it. One of the major causes of surface quality loss is through material build-up on the rake face of the cutting tip, also known as build-up-edge (BUE), which can be seen circled in figure 1. It is an unwanted, semi stable body of material on the cutting tool that is created by work piece material welding onto the tool during cutting. Layers of build-up weld to the tool face under the heavy pressure and heat generated at the tip of the tool face, also associated with lower cutting speeds and feed rates; it is therefore more common during dry turning. BUE has been linked in studies [20, 21] to causing low quality surface finish and cutting edge frittering when the built-up edge is torn away [22], as well as increasing the wear rate of the tool [23], although with an increase in surface cutting speed the BUE phenomenon has a tendency to minimise ware by creating a protective layer on the tool [23], which is not always possibly with dry turning due to the limited controllability of excessive heat generation.

Figure 2 (Right) shows the effect of the BUE being dragged down under the tool tip and becoming an imperfection on the turned face, while figure 2 (Left) shows a partial shearing of the surface also caused by the BUE. This can be overcome by increasing the cutting speed and the shear plane angle, which has been marked in figure 1. During testing procedures, to ensure that no unnecessary wear is taking place on the tool tip caused either by the BUE or by the cutting parameters, chip formation needs to be closely monitored. Ideally, chips should be of a helical shape and no more than 5cm in length [24]. A blue appearance on the chips should be present, indicating the correct depth of cut and feed rate are being used and that sufficient heat is being taken from the work piece via the chip and intern maintaining a high shear plane angle, thus causing the BUE to move off with the chips and not in the turned surface.

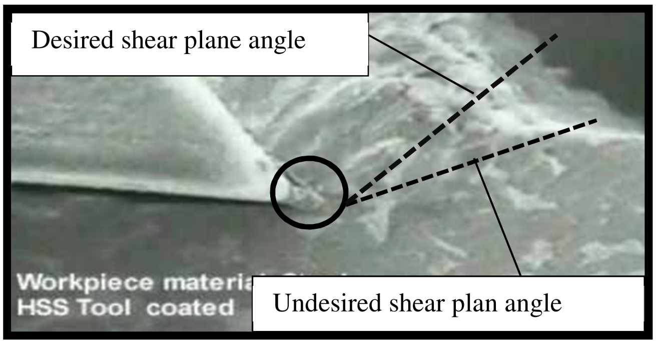

Fig.1. (Amended from Balzers 2010)

Fig.2. (amended from Balzers 2010)

Due to the large influence on surface roughness, the phenomena of the build-up-edge has been investigated extensively, with the central focus being why and how it is bonded to the tool, but is still not completely understood as the mechanism of adhesion is very complex [20] as well as being a dynamic process and microscopic in nature [23]. However three facts are determined undeniable: temperature of cutting zone and tool being lower than the work piece melting point, contaminant layers present between work piece and tool interface and if the welded work material is severely deformed. Several parameters have been studied that have been found to effect the formation of the build-up edge, as [20] discusses, tool geometry, tool material, machine tool, cutting fluid etc., most influential being tool geometry for it frictional effects in regards to rake angles.

ISBN: 978-988-19253-5-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

III. Cutting Parameters

There have been numerous studies and investigations on the cutting parameters under wet and dry conditions to gain a better understanding on the numerous variables and their influences on the surface roughness, dimensional accuracy and other contributing factors that dictate the overall quality of the turned part. Experiments carried out by each study concluded with similar results, where cutting parameters, such as low cutting speed having no noticeable difference between dry and flood turning [19], [10], [25]. There were also other notable similarities within the results of the studies, where factors would be more beneficial in conjunction with other parameters. These results, as well as material suppliers recommendation and professional guidance will be used and tailored to provide the best set up for the experiment, in terms of feed rate, depth of cut, cutting tip type, thus avoiding any unnecessary testing or factors that will corrupt the results, as they have already been proven to provide the best results.

IV. Machine Setup

As specified on the material suppliers website [26], the through hardened EN8 has a Vickers Hardness of 210-265. This can be used to determine the appropriate surface cutting speed, which when a carbide tip is being used, 91.44 meters per minute is recommended [16]. From this, the required RPM for the lathe can be calculated for a given diameter of work piece, which for a 30mm diameter bar is 970RPM. The material could have been tested to provide a more accuracy reading, however this was considered unnecessary due its minimal influence on the RPM.

V. Experimental Procedure

EN8 Steel is to be used as the testing material that will be turned down. It is a very popular grade of through-hardened medium carbon steel, which in this case, is in the form of 30mm diameter bar. EN8 is suitable for the manufacture of parts such as general-purpose axles and shafts, gears, bolts and studs. Little testing has been performed on low hardness steels in regards to tool wear, making EN8 and ideal candidate due to is chemical composition and popularity with-in the industry. Two unused cutting tips will be used to turn down two EN8 bars, one for each cutting condition. New tips are being used as company recommended cutting parameters are based around cutting tips in top condition that have no rake or flank wear, which will impede cutting performance. Cuts of 250mm long and 0.7mm deep will be made with each tip on the bars under the two conditions with a feed rate of 0.25mm/rev at 970 RPM or the next closes speed on the lathe, Thus ensuring ample heat generation and exposure to the tip during the dry cut, making a notable and comparable influence on tool wear. A finishing cut in each condition will be taken at a reduced feed rate of 0.08mm/rev. Although in many cases, a shallower cut is required to achieve a more desirable finish, the nature of EN8, with its lower HV when compared to materials that meet hard turning criteria and as studies suggested, will require the same depth of cut to allow the tool to penetrate the surface and maintain a high shear plane angle. For more of a comparison, a sample of the roughing and finishing cut in both conditions will be produced, cleaned and inspected under 3D surface analysis equipment on all surfaces of interest; this will also be the case for both cutting tips rack face and cutting edges. A micrometre will be used to measure the bar with a finishing cut of 25mm diameter.

The coolant being used is specified for steel, stainless and titanium and is of an oil-based solution, which has been mixed between 7% and 10% concentration. It is considered a high performing coolant, which will provide adequate cooling during testing. As one factor of surface finish is vibration and due to the length of the work piece extending from the chuck, a live centre is used to stabilise the bar during turning so that any surface roughness caused by vibration is minimised allowing truer comparison to be made between tool wear and surface roughness caused by wet and dry cutting.

VI. Intentions

This report hopes to determine the physical, environmental and practical elements of dry turning in regards to tool wear, the quality of surface finish and the dimensional accuracy of the cut, which will eventually lead to and aid in determining the point at which the rate of tool wear and error in dimensions out weights the cost of lubricants to consider using them while turning. It is also intends to provide further information to make an informed decision into which method is most appropriate when faced with different applications and environments that the part is intended to be used in.

VII. Results and Discussion

During the cutting procedure, chip formation for the dry condition was as expected and showed appropriate heat removal via the chips. However a jagged edge was present on the inside of the helical chip, which could potentially be caused by a too high feed rate. Despite this, alterations were not made to the setup, as other signs, such as excessive vibration where not present and suggested safe operating conditions and indicated no risk to breaking the cutting tip. When comparing the surface finishes of both wet and dry roughing cuts, there was a notable difference, as illustrated

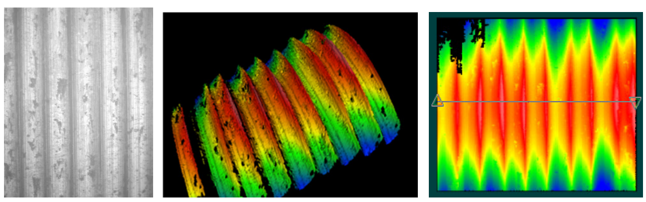

Fig.3. 3D surface analysis results for roughing wet cut.

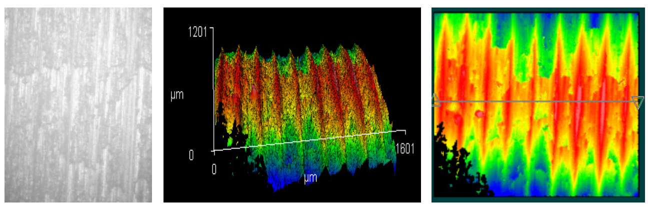

Fig.4. 3D surface analysis results for roughing dry cut

in Figure 3 & 4. When sampled on a plane longitudinal to the work piece (perpendicular to the cut), both wet and dry

ISBN: 978-988-19253-5-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

had similar surface roughness's at 4.899µm and 5.119µm respectively. The similarity in roughness values is due to the peaks and troughs created by the cutting tip, which, as proven by the numerous studies is dictated by feed rate and tool radius. In terms of the quality of cut from an industry point of view, these roughness values would be considered common during turning; siding towards less frequent and unacceptable finishes [18] as a result. Despite this, conditions of the wet cut are noticeably different on simple examination. When sampling on a plane parallel with the cut, and thus excluding peaks and troughs, a better understand on how the material has sheared is presented. Wet conditions greatly out performed dry, with 0.874µm and 2.218µm respectively. The level of disturbance and deterioration on the surface of the dry cut is a clear indication that excessive heat was present despite maximum heat removal via the chips, during the cut and consequently leading to a low shear plane angle, causing an unstable BUE that would have passed beneath the tool, causing the surface to tear. It must be noted that because of the cylindrical shape of the specimen, sampling was kept considerably short to avoid the curvature that would be perceived as a higher surface roughness. Unlike hard turning, these results conform to the findings of the several investigations on cutting parameters and BUE, as with the lower cutting speed for EN8, BUE is more likely to form [23].

As expected and in agreement with other studies, the reduced feed rate of 0.08mm/rev for the finish cut improved surface roughness for both wet and dry conditions, with 0.559µm and 1.139µm respectively. With reduced feed rate, less material is being removed per revolution by the flank face and tool edge and therefore reduces heat and pressure. The now closer cutting lines form a more uniform surface, where peaks and troughs of the cuts are less profound. In terms of the suitability of the finishes, dry finish turning does not produce an acceptable level of surface roughness for such application as polished faces or high tolerance interfacing parts, such as interference fits and would not be recommended for such applications where aesthetics of the surface are

On measuring the accuracy of the finishing cut, it is found

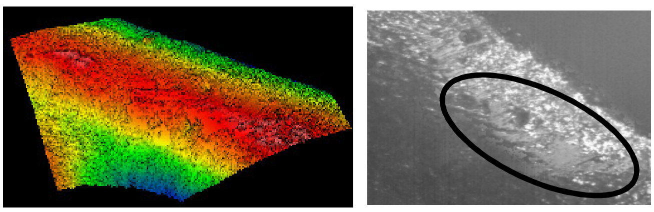

Fig.5. 3D surface analysis on cutting tip for wet conditions

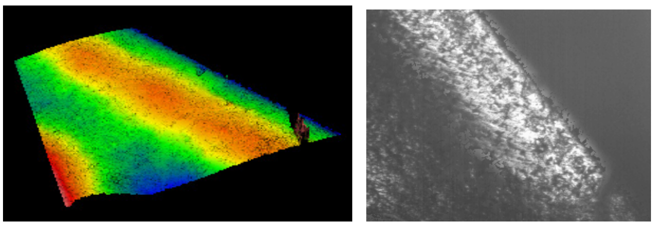

Fig.6. 3D surface analysis on cutting tip for dry conditions

that in dry conditions there was an overcut of -0.01mm, while for wet cut conditions there was an undercut of +0.006mm. Due to minor variations it would be incorrect to directly link them to the cutting conditions, although in some cases the heating of the metal can cause thermal expansion and thus causing a deeper cut to be taken by the tool. In this instance, the variations would be accepted in most machine shops for non-interfacing surfaces and can be put down to machine and human error.

With regard to tool wear, there were two anomalies present on the wet cutting tip (Figure 6). Examination and investigation strongly suggests that these where present before cutting took place, as they are far too small to be considered notch wear and more possibly associated with the manufacturing of the tip.

On first inspections, it was clear that the dry cutting tip had encounter more direct and pin pointed wear on the rake face, (marked in Figure 5). This would have been caused by the hotter and harder chippings coming off the job with less deformation, while the cooled chips from the wet cut have deformed with less force against the rake face of the tool (Figure 6), creating an overall smoother and distributed wear. Sampling was roughly taken 100µm parallel to the cutting edge, over a distance of 400µm on the rake face of the tool. Roughness values being 3.934 µm for wet and 5.121µm for dry, with values before testing of 3.823µm and 3.991µm respectively. Unfortunately, results for edge wear and deformation amount were un-obtainable; however values provided for crater wear on the rake side will provide a strong indication on the expected level of wear during the two conditions. Crater wear, seen in figure 5 & figure 6 is localised to the rake side of the insert and can lead to fracturing of the tip as the wear weakens the cutting edge. With a more distributed wear during wet condition, it is likely to prolong cutting tip failure when compared to dry conditions.

VIII. Conclusion

Caution should be taken with the results presented in this paper, as there are many factors that will contribute to the surface roughness. It can be concluded that although an increased wear rate is present during dry condition; the direct and indirect costs of coolant alone will outweigh the increased frequency for purchasing of new cutting tips. During rough cutting it was noted that a high surface roughness was present with dry conditions, but was still at an acceptable level for non-interfacing surfaces, which would suggest that for pure material removal operations, dry cutting is the most cost effective despite the slight increase in tool ware. Comparing wet and dry finish cutting, it will be highly depended on the intended application and the required amount of material needing to be removed, as a compromise needs to be made between the use of coolants and a slightly higher surface roughness, as well as time of manufacturing. With coolant, it will be possible to further increase cutting feed rate without over heating the tool, however, for single one off jobs, fluid is not justifiable and a slower feed rate should be employed with dry conditions. As a result of the slight increase in tool ware, it is recommended that for prolonged cutting jobs, dry conditions can be used for material removal with coolant applied for the finish turn as this will drastically reduce the volume of coolant used during the operation, while still providing an acceptable level of surface roughness. It should also be noted that heat generated during long cutting operations in dry conditions can possibly alter the material characteristic, particularly to smaller parts, which are less able to dissipate heat away, causing weakness in the material, through increased malleability, resulting in a change in cutting performance and strength and therefor affecting surface roughness.

The results discussed during this report have been derived from one off experiments that were performed on single sample test pieces for each condition, due to a limiting time frame. Given that surface quality can be affected by numerous parameters, a stronger case could be presented, where additional results from multiple samples for each condition are performed and inspected to ensure results collected for this report are as accurate as possible. It would therefore be recommended that for further experimentation, at least 3 samples are produced in each condition, which can be combined to find the mean result and identify any errors that may have occurred, producing constant and reliable data.

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ISBN: 978-988-19253-5-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)