DRILLING FORCES OF Ti6Al4V WITH MINIMAL QUANTIFY OF LUBRICANT

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Abstract. *This paper presents a study of the forces exerted during drilling of the titanium alloy Ti6Al4V with the application of a Minimal Quantity of Lubricant (MQL). The drilling process was chosen to evaluate the effect of lubrification with MQL, where the lubricant was applied either with an external nozzle (MQL ext) or internally through the tool (MQL int). The feed force F_f and twisting torque M_t were obtained directly. The results show good potential for drilling with MQL applied internally through the tool. The forces obtained show characteristics similar to those obtained with the application of emulsion internally through the tool. However the process is restricted to shallow depths and is limited by the quality requirements of the hole, especially when the lubricant is applied via the external nozzle. A analyze the forces at different parts of the drill was made to evaluate the friction with the walls of the hole and to understand the factors which influence feed force and twisting moment.*

Keywords: *Carbide drill, Ti6Al4V alloy, MQL, feed force, torque*

1. Introduction

The utilization of lubricating fluids during machining was originally based on the desire to prolong the life of cutting tools by lubricating the tool – workpiece – chip interface during the machining process [Kőnig, 1997; Taylor, 1907; Tőnshoff, 1997]. Taylor measured the influence of lubricating fluids on the machining process. He applied a large quantity of water on the tool – workpiece – chip interface region and was able to increase the cutting speed by 30 - 40% without reducing the lifetime of the tool. More recently, however, environmental concerns have resulted in attempts to legislate controls on the products utilized as cutting fluids. These fluids, to maintain their stability, contain additives such as fungicides and bactericides, which are harmful to humans. Discarding these cutting fluids in an inadequate manner is prejudicial to the environment, so they must be disposed of with proper controls. Even so, some of the fluid is lost through evaporation, on the workpieces and chips and during cleaning of the workplace. This increases the costs of employing these cutting fluids.

Keeping in mind the necessity of reducing the problems caused directly or indirectly by the use of the lubricating fluid, attempts have been made to minimize the quantity of fluid utilized. The application of a Minimal Quantity of Lubricant (MQL) has been tested on a number of materials [Kőnig, 1997; Klocke, 1998; Hewson 1999]. As is well known [Shaw, 1954; Boston, 1955; López, 2000; Gerschwiler, 1997], titanium alloys present serious problems in regard to their machining due to their thermal characteristics. For this reason, experiments with MQL in these alloys are being undertaken to generate the initial technical information for these important materials. In this work, drilling forces in the widely-used alpha-beta alloy Ti6Al4V were determined for several different lubricating conditions in order to study the utility of using MQL for these materials. Our results show good potential for drilling with MQL applied internally through the tool.

2. Experiments

Plates of alpha – beta Ti6Al4V alloy (tensile strength R_m = 970 N/mm^2 and hardness 300 HB) with dimensions 200 x 150 x 20 mm were prepared for these drilling experiments. Holes were drilled with 8.5 mm diameter drills through the smallest dimension using a vertical machining center. Special care was taken to hold the titanium alloy plates in place and we estimate the run-out in the initial position of the tool to be about 0.012 mm. Cutting fluids were applied with a pressure of 3.5 bar. In this work, the feed force F_f and twisting torque M_t were obtained by direct measurement with dynamometers.

Three types of drill were used in these experiments, all of carbide class type K10. Their characteristics are given in Table 1. Those drills having holes for internal lubrification were not coated. However, drills without internal lubrification were coated with TiAlN, CrCN, and TiCN in order to test the utility of these coatings for improving the performance of the drilling process.

Table 1. Drills utilized in these tests

Drill type	105	125	411
Coating	Yes/No	No	No
Cutting edges	3	3	2
Refrigeration ducts	No	Yes	Yes

There are few indications of cutting parameters for MQL conditions, and there are no indications of these numbers for drilling Ti6Al4V. Drill manufacturers furnish cutting parameters for the usual conditions, where the cutting fluid is applied in abundance. In this work, the conditions initially considered were those furnished by the manufacturers. However it is our intention to evaluate a more sizeable region of parameter space. Thus, drill manufacturers recommend the following parameters for drilling Ti6Al4V with a K10 class carbide drill: cutting speed v_c = 30 – 50 m/min, advance f = 0.1 - 0.2 mm, and an abundance of cutting fluid with concentration of emulsion above 3.5%. In the present experiments, the drilling of Ti6Al4V was investigated for cutting speeds v_c = 10 – 50 m/min, advance f = 0.1 - 0.2 mm, and for MQL conditions.

3. Results and Discussion

3.1. Direct measurements of feed force and twisting torque

The principal mechanical variables used to characterize the drilling process in Ti6Al4V with a minimal quantity of lubricating fluid are the tool lifetime and the machining forces. Figure 1 show the tool lifetime for different conditions of lubricating fluid. In this figure, the number of holes drilled with a tool (up to a pre-stipulated maximum of 30) is presented for three cutting speeds (15, 30, and 40 m/min). The figure shows that the application of emulsion through the interior of the drill (E_{int}) gives the best results. In this case, all of the drills tested reached the desired number of 30 holes, a number deemed adequate for evaluating the lifetime and wear characteristics of the drills. After executing 30 holes it was possible to characterize in a satisfactory manner both the tool wear and the surface of the hole. For the use of the emulsion, tests were not carried out for a cutting speed of 15 m/min, since the current usage is a cutting speed of 30 m/min.

For tests with MQL applied through the interior of the tool, the results were also good, although, in this case, there is a larger dispersion in the number of holes executed. For a cutting speed of 15 m/min, the minimum number of holes drilled was 5 and the maximum was 30 (in this case the drilling was interrupted and the drill showed no signs of wear). The explanation for this dispersion lies in the tool, a type 125 drill. For a new type 125 drill, the rounding at the corners was measured to be 19 µm, while for the remaining drills, the average value of the rounding was found to be 32 µm. With a smaller radius, the tip is less robust and with residual tensions concentrated at the extremity of the tool, it is more likely to suffer chipping. In spite of the fact that the type 125 drill had undergone a process of micropolishing of the corners and cutting edges to reduce residual tensions, it was clear that the polishing did not have the desired effect on the drills.

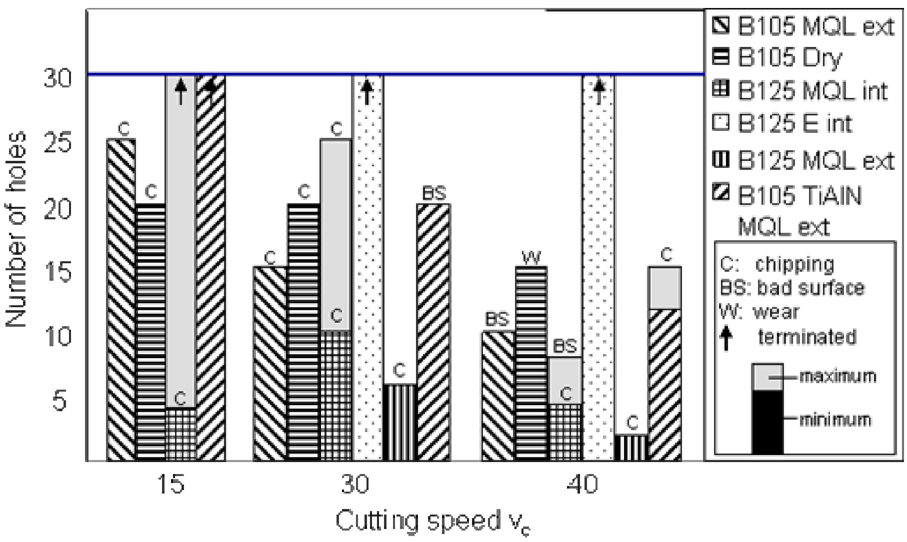

Figure 1. Number of holes drilled vs. cutting speed for different drills and lubrification conditions, illustrating the effect on tool lifetime. Testing was stopped after reaching the maximum number (30) of holes drilled.

Drilling without lubricating fluid or with MQL applied through external nozzles using an uncoated type 105 drill gave good repeatability but the number of holes was reduced drastically as the cutting speed increased. The most unsatisfactory results were obtained when MQL was applied with external nozzles. Here again the explanation lies in the geometry of the drill which presents a sharper cutting edge and less rounding of the corners, facilitating the chipping.

For all methods of applying the lubricating fluid, the chipping near the corner was representative of the damage which determined the end of tool life. This was certainly so for MQL applied internally to the work area. In this case, for almost all tests, the end of life was determined by chipping, without the appearance of noticeable flank wear. For the case of this drill showing chipping, flank wear was not yet measurable. At the corner of the cutting edge, the cutting conditions are the most severe during drilling. The cutting speed is highest and the temperature is highest due to the friction between tool and chip as well as between the wall of the hole and the drill body. The corner also presents the worst heat dissipation conditions since this region has less mass than the rest of the cutting edge. Thus the demands on this part of the drill are the most severe. The fluctuations in the machining force, due to the formation of lamellar chips, and the thermal shocks to which the corner of the tool are submitted at the end of drilling can also be responsible for the preferencial chiping of this corner region.

Initially the feed force F_f and twisting torque M_t were evaluated for the conditions usually employed in industry: cutting speed v_c of 30 and 40 m/min, an advance f of 0.1 mm, with abundant application of cutting fluid applied internally to the tool/workpiece interface. For this situation, these two quantities present the behavior shown in Figure 2 where there is certain regularity in the force, except for the entrance and exit of the drill into the workpiece. At the entrance of the drill, the cutting section is varying, giving rise to an almost linear increase of the force and the twisting moment. Because the temperature is maintained nearly constant by the abundant quantity of cutting fluid (160°C), the machining forces remain practically unaltered over the course of the drilling.

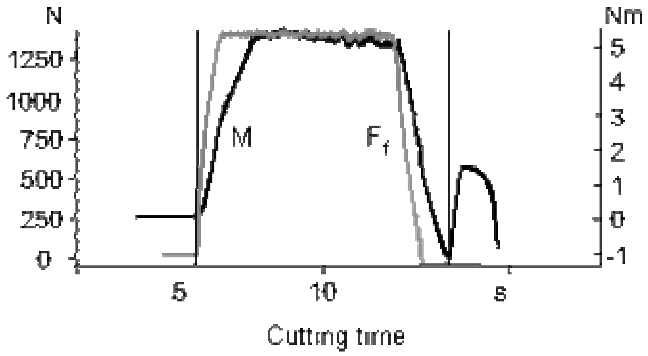

Figure 2. Feed force F_f and twisting moment M_t vs. cutting time for K10 drill with l/d = 2.3. Cutting speed was v_c = 30 m/min, feed f = 0.10 mm, with Blasocut emulsion applied internally (P = 3.5 bar, q = 12 l/h) through the drill.

For the same type of drill (type 125) and maintaining the same cutting parameters, the cutting force and twisting torque show a different behavior when MQL is applied by external nozzles. See Figure 3. In the beginning, the workpiece is cold and the evolution of the cutting force and twisting torque are similar to those encountered with an abundant supply of cutting fluid. As the drilling proceeds the refrigeration capacity of the cutting fluid (now MQL) is not sufficient to maintain the temperature of the workpiece or the tool. The decrease in the cutting force is explained by the increase in temperature (600°C) and the consequent reduction in material resistance [Gerschwiler, 2001].

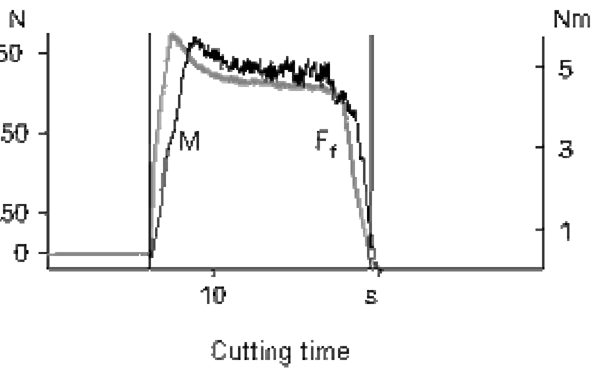

Figure 3. Feed force F_f and twisting moment M_t vs. cutting time for K10 drill with l/d = 2.3. Cutting speed was v_c = 30 m/min, feed f = 0.10 mm, with FD1-30 oil applied externally (P = 3.5 bar, q = 50 ml/h).

Applying MQL through the interior of the drill, the behavior of the cutting force F_f and the twisting torque M_t presented a behavior different from that seen above. In the majority of cases the curves were as shown in Figure 4.

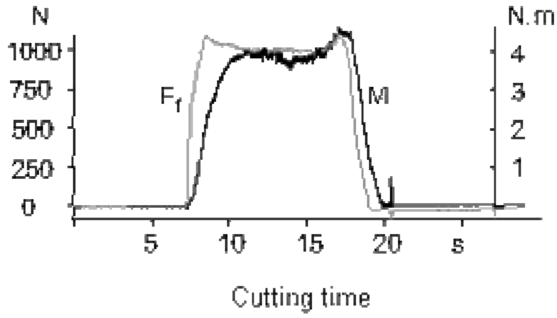

Figure 4. Feed force F_f and twisting moment M_t vs. cutting time for K10 drill with l/d = 2.3. Cutting speed was $v_c = 30$ m/min, feed f = 0.10 mm, with FD1-30 oil applied internally (P = 3.5 bar, q = 50 ml/h) through the drill.

Initially there is a reduction in the force and torque. However, at about a depth of 1.5 d (d = drill diameter), both the torque and the force tend to increase. The increase in the twisting torque can be explained by an increase in friction at greater depths. For smaller depths, the micro film of lubricant is still sufficient to diminish the friction, thus reducing the twisting torque. But as the depth of drilling increases, the friction increases and, with it, the torque.

To understand the relation between forces, temperatures, and advance, both the cutting speed and the advance of the drilling were varied. An increase in the cutting speed resulted in a sizable increase in temperature at the chip/tool interface. However, this resulted in only a slight reduction of the cutting force and the twisting torque. See Figure 5.

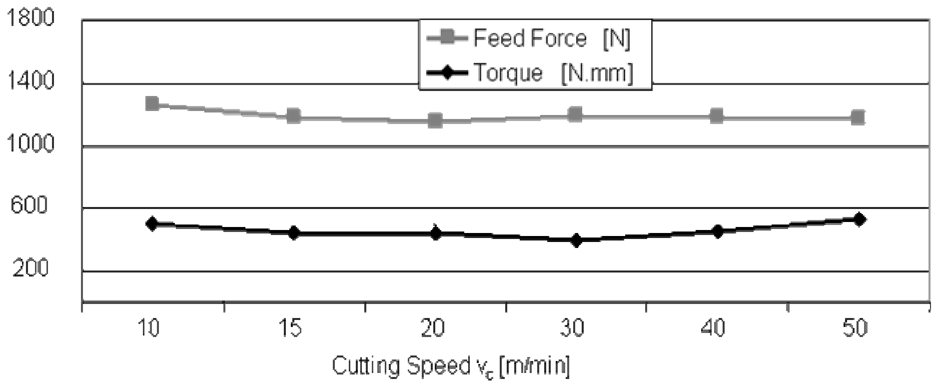

Figure 5. Feed force and torque are independent of cutting speed.

On the other hand, an increase in the feed results in a much stronger increase in the cutting force and twisting torque. See Figure 6.

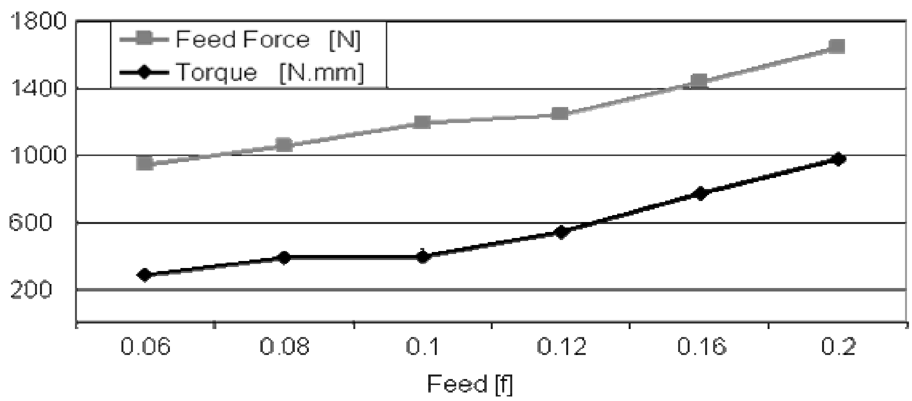

Figure 6. Feed force and torque are more strongly dependent of feed.

To see whether an increase in friction between the sides of the drill and the wall of the hole would lead to an increase in drilling force, long holes with l/d = 3.5 were also drilled. The results show that, for depths greater than 1.5 d, the friction with the side of the hole has a significant influence on the feed force and the moment. See Figure 7.

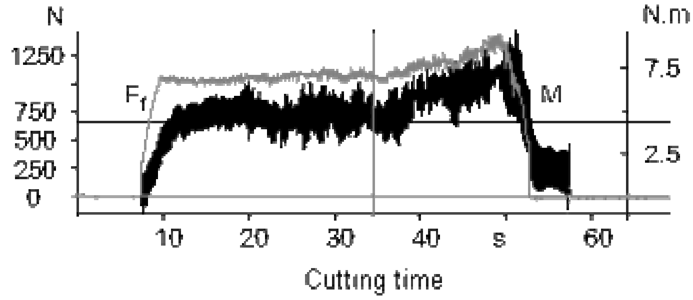

Figure 7. Feed force F_f and twisting moment M_t vs. cutting time for K10 drill with l/d = 3.5. Cutting speed was v_c = 30 m/min, feed f = 0.10 mm, with cutting fluid applied internally (P = 3.5 bar, q = 50 ml/h) through the drill.

The bar graph of Figure 8 summarizes the results for the forces and torques measured while drilling this titanium alloy and shows that processes with reduced lubrification present lower values of both the feed force and the twisting moment, compared to drilling with abundant quantities of cutting fluid.

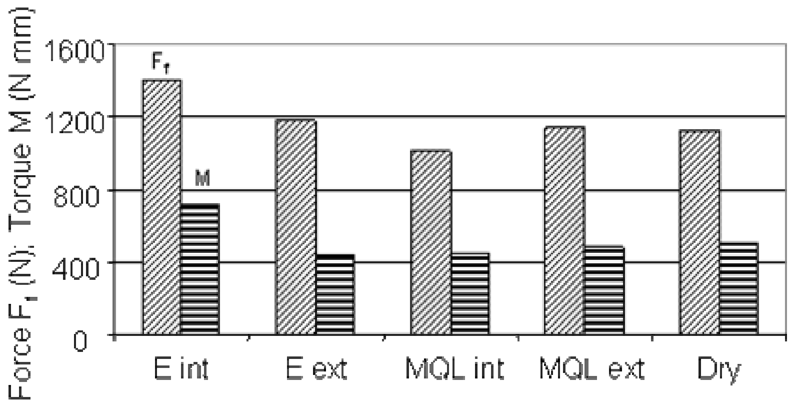

Figure 8. Comparison of feed force and torque for different lubrification conditions.

The largest values of the feed force and the twisting torque are encountered when the emulsion is applied through the interior of the drill, where the temperatures (about 50%) are believed to be the lowest. This result demonstrates the influence of the temperature on the drilling process.

For all situations tested here, it was found that the largest forces and torques were encountered when the emulsion was applied through the drill center. The larger values of the feed force during the application of emulsion and MQL via external nozzles or without fluid can be explained in terms of the lubrification and softening of the material as well as the wear on the cutting tool.

In Figure 9, the feed force and twisting moment are presented for the type 105 drill, both uncoated and with different types of coating, for cutting speeds of 15 and 30 m/min. For this drill, the tests were carried out with MQL, applied via external nozzles. The feed force for different cutting speeds has the same average value for the uncoated drills and for those coated with TiCN.

For the drills coated with TiAlN and CrCN, the average values are slightly superior to the rest. However, for a cutting speed of 15 m/min, the drill coated with TiAlN had a feed force about 40% greater than that of the other drills. The differences encountered here may be related to the temperature variations found during the drilling, which are influenced directly by the different coatings and their characteristics.

The twisting moment at a cutting speed of 15 m/min for the drill coated with TiAlN has a slightly larger value than that found for the other drills.

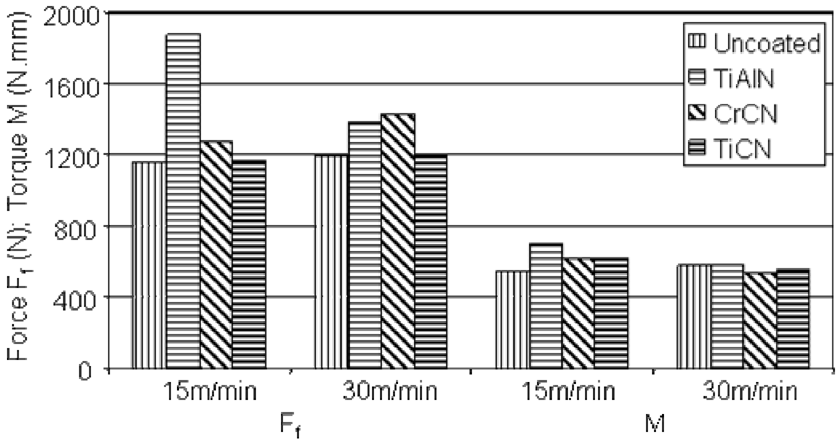

Figure 9. Feed force and torque for different coatings and cutting speeds.

3.2. Analyze of machining forces

For a better understanding of the machining forces, an attempt was made to evaluate the friction with the walls of the hole and analyze the forces at different parts of the drill. For the analysis of the influence of different regions of the cutting edges on the feed force and the twisting torque, experiments were carried out to isolate the effects of each region. The methodology employed is described schematically in Figures 10 and 11 and was developed following Witte [Witte, 1980].

The type 1 measurement refers to the complete drilling process and includes the cutting at the main cutting edge, together with the friction of the drill sides with the wall of the hole. The type 2 measurement is carried out using a starter hole whose diameter is equal to that of the drill and allows one to obtain the frictional contribution of the twisting moment due to the drill side with the walls of the hole. The type 3 measurement is carried out on a bar whose diameter is equal to that of the drill. This should give the forces without the friction from the drill sides with the wall of the hole. Drilling a starter hole with diameter equal to the central portion of the drill, the type 4 measurements, allows one to evaluate the forces exerted without the transverse cutting edge of the drill. Finally, a type 5 measurement is made on a bar with diameter equal to the diameter of the central part of the drill to evaluate the effect of the transverse cutting edge on the drilling forces.

In Figure 10, the torque M_t is shown for measurements of type 1, 2, and 3. From these it is possible to evaluate the effect of friction with the walls on the torque M_t. (Friction with the walls of the hole had a minimal effect on the feed force F_f, representing perhaps 1% of the total value. The feed force is necessary to overcome the resistance to the principal cutting edge and is not affected by the wall friction.)

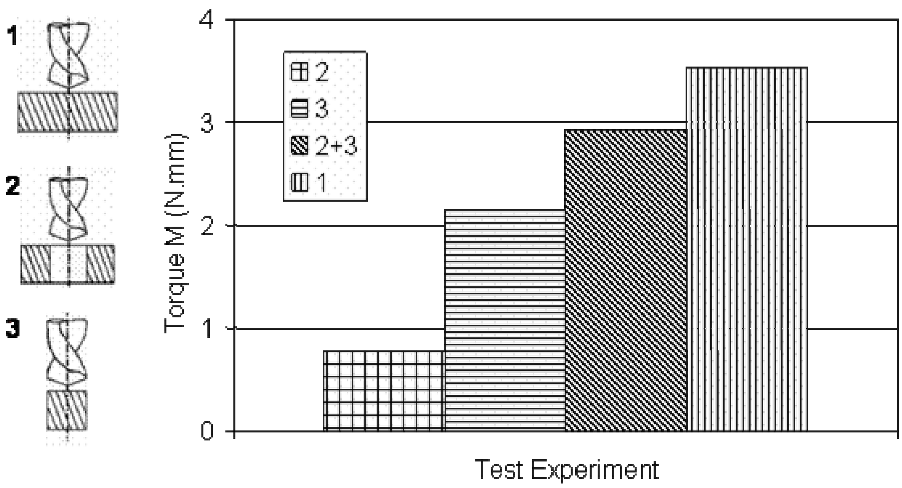

Figure 10. Decomposition of feed force and torque to determine the influence of friction.

The influence of the friction with the walls on the twisting torque was, however, sensitive to the lubrification conditions utilized. For example, for MQL applied by means of external nozzles, the effect of the friction with the walls (measurement 2) corresponds to about 25% of the total torque obtained in measurement 1. A difference of about 15% was observed between the complete drilling measurement (type 1) and the sum of measurements 2 (pre hole equal to the drill diameter) and 3 (bar equal to the drill diameter). This difference may be explained in terms of the different conditions for the removal of the drilling chips. For both tests 2 and 3, the chips can be removed more easily since there is no friction with the wall of the hole as there is in the complete drilling measurement (type 1).

Consider now the contribution from the center of the drill. Figure 11 shows that part of the feed force corresponding to the center of the drill (test 5). This measurement can be compared with the real process (1 = 4 + 5) and the part corresponding to the center of the drill (4). Our measurements confirm those of other researchers (using an abundant supply of lubricating fluid) which indicate a sizeable part of the feed force coming from the central part of the drill [Witte, 1980; Eisenblätter, 1999]. This can be explained by the low cutting speeds and the fact that, in the central region, cutting is practically substituted by a plastic deformation which results in material being pushed from the central region to the cutting region of the main cutting edge.

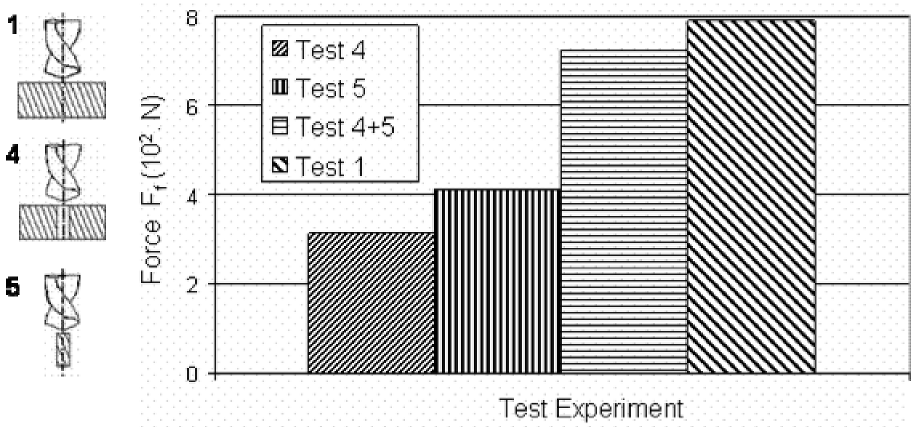

Figure 11. Influence of drill center on the feed force.

The feed forces measured for the central part of the drill vary according to the cutting parameters and the geometry of the tool. For drills with a sharper leading angle (drill type 105), force values equivalent to 68% of the total feed force are observed. In this case the diameter of the central region is about 30% of the drill diameter.

Figure 12 shows values of feed force components measured for two different types of drill, one of which has two cutting edges (type 411) and the other of which has three cutting edges (type 105). The results show that an increase in the number of cutting edges and a change in the drill geometry have a clear influence over the feed force, mainly over F_f. This difference can be explained by the fact that, for the drill with two cutting edges, the reduction of the transverse edge reduces also the effect of the central part of the drill, since the cutting part of the edge is increased by a value equivalent to the reduction in the transverse edge.

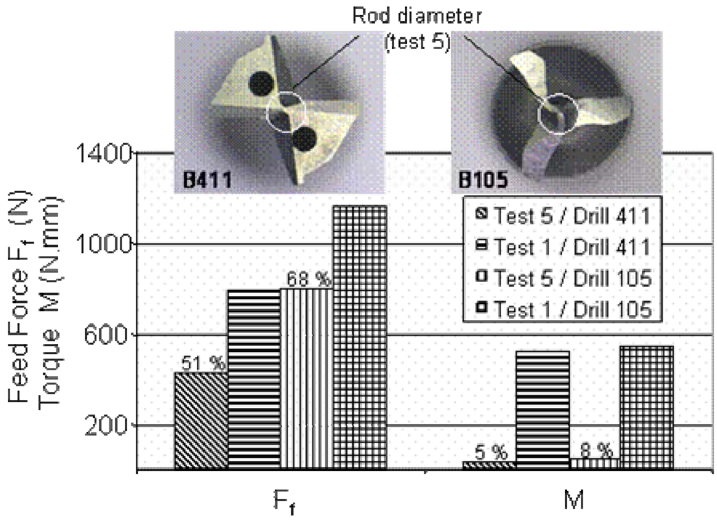

Figure 12. Influence of the drill type on the feed force and the twisting moment.

For the drill with three cutting edges, the cutting parts of the central region have an effective angle of incidence smaller than the effective cutting direction. Thus a sizeable part of the central region is not cut but is pushed plastically to the sides until it reaches the central region of the cutting edges. For the drill with 2 cutting edges, the drilling of a bar with diameter equivalent to the central part of the drill required a force corresponding to 51% of the total drilling force (test 1). In the case of a drill with 3 edges (type 105), the force corresponding to the central region was 68% of the total force. For all of the experiments realized, the effects of the geometry of the central part of the drill on the twisting torque were not significant. The difference remained in the range 5 – 8% of the torque found for the complete drilling measurement.

This analysis emphasizes the importance of having a geometry for the central part of the drill which is adequate for the severest conditions to be encountered in service, such as those imposed on the tool while drilling the alloy Ti6Al4V with MQL.

4. Conclusions

Drilling the alloy Ti6Al4V with minimal quantities of lubricant (MQL) is possible. Applying the fluid by means of external nozzles, the drilling remains limited to depths on the order of the diameter of the drill. Supplying MQL internally through the drill furnishes results as good as those obtained when abundant quantities of lubricating fluid are utilized. On the other hand, the reliability of the process seems to be lower with MQL applied internally since we observed a greater dispersion in the results obtained. When drilling with the application of MQL by means of external nozzles, wear measurements were more difficult due to the adhesion of the material on the drill cutting edges. Coatings did not influence significantly the drill lifetimes when MQL was applied by external nozzles.

The larger part of the feed force is necessary for the central region of the drill and reaches 51 – 68 % of the total feed force. Friction with the walls of the hole influences only the twisting torque, but not the feed force.

5. Acknowledgements

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7. Responsibility notice

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