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ELECTRICALLY-ASSISTED MACHINING OF TITANIUM ALLOY TI-6AL-4V AND NICKEL-BASED ALLOY IN-738: AN INVESTIGATION

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ABSTRACT

Despite their increasing use in leading industries, manufacture of alloys with superior mechanical properties have been a big challenge in the recent years. Researchers have been working on using assisted or augmented processes to overcome this challenge, with methods such as ultrasonically assisted, thermally assisted, vibration-assisted, magnetic field-assisted, and laser-assisted machining. Utilizing electrical assistance in manufacturing has not caught much attention due to its difficult-to-apply nature. However, it is possible to increase the ductility and machinability (through reduced flow stress) of certain metallic materials through the use of electricity. In this method, the electrical current resistively heats the material while aiding in deforming the material through the electroplastic effect.

The limited amount of work in this topic is mainly focused on exploring the forming characteristics of relatively softer materials. Application of this augmentation to alloys with superior mechanical properties at elevated temperatures, on the other hand, has not been explored. This study aims to fill in that void through an investigation of applying different currents through the tool concentrated on the tool-workpiece contact zone. Both the titanium alloy Ti-6Al-4V and the nickel-based superalloy IN-738 were investigated, and the results showed that for both materials, there are two separate thresholds that need to be considered in any analysis. The first threshold is where the material starts to get deformed, below which no significant divergence from the baseline (no current) tests was observed. After exceeding this value, machining forces start decreasing with increasing current up to a certain point (second threshold) where the effect of electric current is reversed. If the second threshold is surpassed, the machining forces increase rapidly. Findings of this study can be used in assisting the machining of such materials.

INTRODUCTION

It is known that with the choice materials in leading industries becoming stronger, manufacturing these materials have become more difficult [1-2]. In addition to optimization of machining parameters and tooling, researchers have also investigated the possibility of auxiliary assistance to the process to ease the manufacture of these materials [3-32].

The use of assistance during manufacturing has been conducted in various ways. Many researchers used laser energy as the auxiliary assistance to soften the material [3-9]. Fleischer *et al.* investigated different methods of manufacturing micro molds, and compared micro milling, micro EDM, and micro laser ablation techniques in their study [3]. Melkote *et al.* studied the effect of laser heating on the dimensional accuracy and surface finish of micro-milled A2 tool steel [4], and Ding & Shin investigated surface integrity of laser-assisted machined hardened steel in terms of surface roughness, microhardness, residual stresses, dimensional accuracy, and microstructural changes [5]. Anderson *et al.* studied machining IN-718 using laser assistance [6], Pfefferkorn *et al.* looked at surface temperatures during laser-assisted machining processes [7], Tagliaferri *et al.* analyzed the effect of laser parameters such as laser power and temperature and developed a finite element-based model for their study [8], and Garcia Navas *et al.* investigated the machinability of IN-718 in terms of machining forces and surface roughness through laser-assistance [9]. Although there are numerous studies on laser-assistance, these studies can be considered as a representative selection of work in this field.

Similarly, Muhammad *et al.* studied the effect of ultrasonic assistance in machining of a Titanium alloy on machining forces and surface roughness [10-12], Soleimanimehr *et al.* predicted machining forces and surface roughness in ultrasonically-assisted turning using neural networks [13], and Wu *et al.* unraveled machining characteristics in terms of machining forces and power, surface roughness, and dimensional accuracy during ultrasonically-assisted turning of Ti-6Al-4V [14]. Thermal assistance has also been of interest for researchers, although most of the studies focus on increasing the temperature of the workpiece using laser assistance [15]. However, examples of purely thermal-assistance also exist, such as Bermingham *et al.* study on prior heating Ti-6Al-4V using a furnace to understand the effect on tool wear mechanism during high speed turning [16], and Xi *et al.* expanded this work to develop a finite element (SPH/FE) model to predict the results of such a process [17]. Although there are fewer examples, magnetic field-assistance has also been utilized by researchers, such as the works of Zou and Shinmura [18], Mansori & Mkaddem [19], Cheng *et al.* [20], and Yeo *et al.* [21], although most of the work involving magnetic field-assistance is focused on assisting electrical discharge machining.

Electrical assistance has also been used by many researchers, although a big majority being on materials that are easier to machine compared to the materials studied in this paper [22-41]. Different manufacturing processes have been investigated in few studies such as blanking [22], micro-rolling [23], bottom bending [24], and friction stir welding [25], whereas most of the effort on electrical assistance has been on forming [26-40]. A previous study from the same research group [41] was among a very limited few examples of the application of electrical assistance in machining, as it is extremely difficult to experiment with this method. However, this previous study was conducted on A2 tool steel, a material that can be machined with significantly more ease compared to the materials under investigation in the current study.

Therefore, this work aims to widen the scope of current literature in electrically assisted machining through a study on increasing the machinability of the titanium alloy Ti-6Al-4V and the nickel-based superalloy IN-738. It is established that the electroplastic effect of using electrical assistance in forming can lower the flow stress of the material to allow easier deformation, increase the amount of deformation in the material before failure, and reduce (if not eliminate) the springback effects in forming [42]. This electrical field effect and how it applies to orthogonal machining was explained in a previous study [41], and is used throughout this work. This study targets to apply the findings of this theory in higher strain rate processes (milling) by running experiments on the two materials of interest, with and without the use of electricity. Then, the results are presented in order to demonstrate the capabilities of electrical assistance, as well as the two-threshold nature of the current density observed on both materials.

EXPERIMENTAL SETUP

In this study, two materials, titanium alloy Ti-6Al-4V (Ti-6-4) and nickel-based superalloy IN-738 were used. The sample parts to be tested on were machined to size from a single block of material to avoid small differences between batches in material properties. A knee-mill was set up in an inverted manner, where the workpiece is connected to the spindle that rotates and the tool is fitted in the Kistler 6-component dynamometer that is set on the table that feeds (FIGURE 1). Plastic fiber composite bars between the toolholder and the dynamometer were used to provide electrical insulation, and similar pieces were used between the bar that holds the workpiece and the spindle to avoid short circuit. Samples were cut to discs small enough to avoid wobbling while big enough to avoid machining too close to their center: 38 mm in diameter and 4 mm in thickness. A Darrah 4kA power supply was utilized in circulating the required current through the system, where one end was connected to the toolholder and the other end was connected to the workpiece. Therefore, the circuit never closes before the tool-workpiece contact, and to make sure that the effect of electricity assistance was observed, the switch that enables current flow was set to flip to "on" position only after 200N of radial force measured by the dynamometer. A LabView program was developed to control this aspect, as well as making sure the correct amount of current was fed to the system. Fresh unworn Sandvik inserts that are suitable for each material were used for each test to avoid the effect of tool wear on the results.

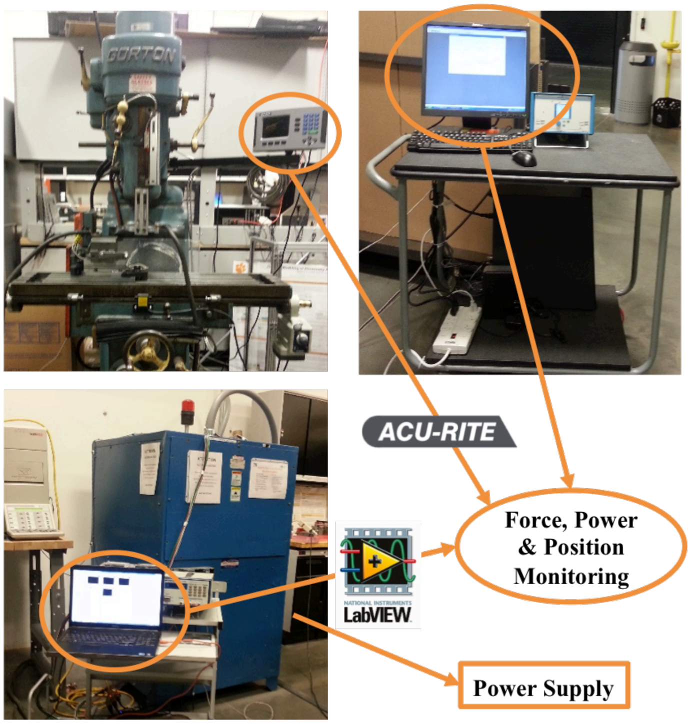

FIGURE 1: EXPERIMENTAL SETUP

For the experiments, since the parameter under investigation was the electrical current, the machining parameters were set to constant values at proper values previously determined for each material. For the titanium alloy

Ti-6-4, spindle speed was set to N=350 RPM (~42 m/min cutting speed), feed was set to f=0.06 mm/rev, and the cutting distance was set to 2 mm (4 mm reduction in diameter). However, since the displacement control was manual, and a researcher needed to stop the experiments at the stopping distance, there were small differences in total cutting distances. For the nickel-based superalloy, feed was reduced to f=0.04 mm/rev, since that value is more similar to the industrial applications for such a mechanically strong material. Also, due to high tool wear characteristic, in order not to affect the current comparison results, the total cutting distance was set to 1 mm (2 mm reduction in diameter). During these tests, best efforts were made to keep the total machining distance constant to ensure consistency; however, due to the lack of an automated position control within the system, there are slight differences in total experimental times.

RESULTS AND DISCUSSIONS

The results for the experiments on the nickel-based superalloy IN-738 in terms of the resultant machining force are shown in FIGURE 2, where the black solid line is the baseline experiment (no current), pink dashed line is where 50A of current was applied, orange dash-dotted line was where 100A of current was applied, blue solid line is at 200A, green dashed line is at 300A, and the red solid line is at 400A. It was observed that when 50A of current was applied, no significant change from the baseline experiment was observed. Therefore, it can be said that 50A of current was too small to employ any electroplastic effect on the process. At 100A current, there was a very small change from the baseline experiment, but the machining forces decreased approximately 10%. At 200A, the electroplasticity effect was more pronounced with ~30% force reduction, while at 300A, a drastic 70% machining force reduction was observed compared to the baseline tests. When the current was increased further to 400A, a significant adverse effect of electricity assistance was observed, where the machining forces increased over 50% compared to baseline tests, and approximately 300% compared to the experiments at 300A current. Therefore, two thresholds of current application were observed: First between 50-100A after which the effects of electrical assistance started to become apparent. The second effect was between 300-400A where the assistance of electricity changed to a significant adverse effect.

The results for the experiments on the titanium alloy Ti-6-4 in terms of the resultant machining force are shown in **FIGURE 3**, where the black solid line is the baseline experiment (no current), blue dash-dotted line is where 100A of current was applied, green dashed line is at 400A, and the red solid line is at 600A. It was observed that when 100A of current is applied, there was a very small change from the baseline experiment in the mean value of the resultant machining force, but there were significant (>10%) oscillations in the filtered transient response. This is most likely due to the fact that the effect of electricity was not significant enough to reduce machining forces continuously, but still in effect to have slight occasional reductions. At 400A, these oscillations diminished, and the mean value of the resultant force was significantly lower than the baseline (>20%). When the current was increased to 600A, the resultant force increased to over 40% more than the baseline case, repeating the adverse effect shown for IN-738. Therefore, the aforementioned two thresholds were observed once again, the first one (start of electroplastic effect) around 100A current, and the other one (start of adverse effect) between 400-600A of current application.

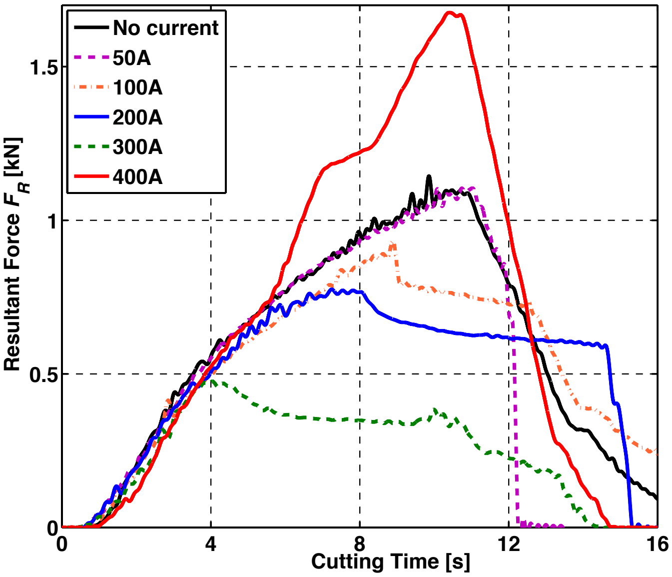

FIGURE 2: EFFECT OF CURRENT IN MACHINING IN-738

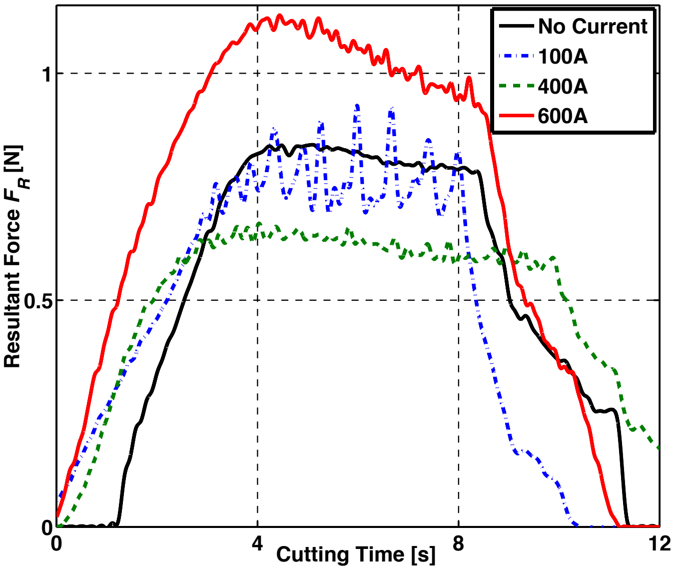

FIGURE 3: EFFECT OF CURRENT IN MACHINING TI-6-4

As a result of these findings, it can be concluded that the electroplasticity effect was observed for both materials. Also, this effect can be used in favor of easing the machinability of both materials as long as the two thresholds of electric current are determined and applied with care.

CONCLUSIONS

In this study, an investigation into experimentally validating the electroplastic effect in machining difficult-to-machine titanium alloy Ti-6-4 and the nickel-based superalloy IN-738 has been presented. It was shown for both materials that until a certain amount of current was applied (50-100A), no significant change was observed in terms of machining forces. After exceeding this current, the electroplasticity effect started to affect the material by lowering its flow stress thus making it easier to machine. After this threshold, increasing the current increased the amount of flow stress reduction, until a certain value (~400A) was reached. It was shown that if the current exceeds this value, not only the benefits of using electrical assistance were diminished, but also adverse effects started to occur in terms of significantly elevated machining forces. The reasons behind this behavior need further investigation as well as the effects of using current on tool wear, but it can be pointed out that as long as the two thresholds are determined and taken under consideration, it is possible to increase the machinability of materials, even those that are conventionally considered as difficult-to-machine.

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