

A study of the machinability of Ti-6Al-4V compacted powders

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Abstract. Machining is an integral shaping process for most titanium alloys based components. However, the ease of machining (machinability) of Titanium and its alloys is generally poor because the alloys have low thermal conductivity, high strength at high temperatures, which both combine to speed up the tool deformation and wear. The poor machinability of the titanium alloys contributes to their high cost, which prevents their widespread industrial application. In this study, this challenge of poor machinability is investigated for the most common titanium alloy, Ti-6Al-4V. The envisaged approach was to machine and characterise the machinability of the alloy in the green state. Green compacts of blended powders of Ti-6Al-4V were pressed at room temperature. To enable machining, a minimum green strength to handle clamping and withstand mechanical forces during machining was required. The green strength of this study was varied by changing the compaction load and the binder during pressing. The compacts were subjected to a drilling operation where the tool type, feed rate and the cutting speed were varied. The machinability was evaluated by measuring average edge breakout and the drilling forces. Results indicate that high strength steel (HSS) twist drills, low feed rate and high speeds generally reduce machinability of the Ti-6Al-4V compacted powders. The drilling forces were independent of the green strength of the compacts.

1. Introduction

Ti-6Al-4V is a lightweight metal alloy with a high specific strength and high corrosion resistance. Despite the alloy superior properties, it has not found widespread use due to the high inherent cost of producing components [1]. The cost is from extraction as well as manufacturing, which almost always includes machining steps. Ti-based alloys are known to have low machinability due to the inherent properties of low thermal conductivity and high chemical reactivity. During machining of Titanium and its alloys, temperature at the tool/chip interface rapidly increases and the cutting tool quality deteriorates quickly [2].

Powder metallurgy (PM) has the potential to reduce the cost of Ti-based alloys because near net shape components that require minimal machining are possible. PM also, offers better material utilization because of the reduced machining. The buy to fly ratio of powder metallurgy parts is way less than the traditional method of producing parts of wrought and casting. The simplest PM technique, which also offers the most advantages, is press and sinter (P&S). In P&S, features that are perpendicular to the pressing directions such as holes, threads and undercuts cannot be accommodated



during compaction; they have to be introduced on the part after sintering by machining [3]. Such features are prime candidates for green machining.

Green machining refers to the production of features in compacted powder (also called green bodies). This work evaluates the machinability of Ti-6Al-4V alloy green bodies. It is hoped that machining the green bodies/compacts can improve machinability because of their low green strength. This has the potential to increase productivity and prolong tool life. Green machining requires compacted powders with adequate green strength to permit the green compacts clamping and also withstand the machining forces [4]. The green strength also affects the quality of the drilled holes: low green strength leads to poor surface finish and an allowance of average breakout that occur by pulling of powder particles [5]. The average breakout is one the distinct criteria that is used to characterize the machinability of the green compacts. In this study, the machining operation used was drilling as it is one of the most widely used manufacturing operations. Another criterion to access the machinability is the measuring of the cutting forces that are generated during the metal removal process. The resultant cutting force is generally resolved into three components, namely feed force (F_x), thrust force (F_y) and cutting force (F_z). The cutting forces acting on the tool are an important characteristic of machining; they can be used to indicate tool and workpiece deflections [6]. The strength of the material strongly influences the cutting forces. Other factors that affect cutting forces are cutting speed, feed rate, depth of cut, cutting fluids and tool geometry [7], [8].

2. Materials and Methods

The material used was blended elemental Ti-6Al-4V made by blending hydrogenated, dehydrogenated titanium (Ti HDH) with particle sizes of less than 45 μm (325 mesh) with a 60Al40V master alloy. A one weight percent of polymeric binder was used as an admixed lubricant. The base powder, master alloy and the polymeric binder were mixed dry by blending in a tubular mixer for an hour to make a homogeneous mixture. Cold compaction of the blended powder was done using an Enerpac 100T laboratory hydraulic press. Lubrication was applied on the walls of the die to minimize friction between the powder particles and the die walls. A cylindrical die of 43 mm diameter was used to press 10 mm thick samples. The compaction pressure used for this study was 430 MPa and 600 MPa. Some samples were cured in air at 200 $^{\circ}\text{C}$ for 1hr. The green strength of all the samples was determined using Brazilian disc test according to ASTM D3967 standard. Table 1 shows the green density and green strength of the uncured and cured Ti-6Al-4V samples.

Table 1. Properties of green compacts used.

Compaction pressured	Cured/ Uncured	Density (%)	Green strength (MPa)
430 MPa	Uncured	72 ± 1	12 ± 2
430 MPa	Cured	73 ± 1	15 ± 2
600 MPa	Uncured	76 ± 1	20 ± 3
600 MPa	Cured	78 ± 1	27 ± 1

Drilling experiments were performed on a CNC Leaderway V650 milling machining. In these experiments, through holes of 3mm diameters were drilled using two types of drills: High Strength Steel (HSS-Co) tool and a carbide tool. The characteristics of the drill tools are provided in Table 2. The drilling speeds used were 2000 rpm, 4000 rpm and 6000 rpm, and the feed rates were 0.02 mm/rev and 0.06 mm/rev. For each parameter, 3 holes were made. Air was used as the cooling medium for the tools during drilling. Tool wear was regarded as insignificant.

Table 2. Characteristics of drilling tools.

Material	Coating	Helix angle (°)	Point geometry	Point angle (°)
High strength steel-Co	TiAlN	35	Split	120
Solid carbide	Coated	30	Split	118

The surface integrity was analyzed by measuring the average width of breakout near the outlet edge. The outlet edge is the edge that is last drilled by the cutting tool, whereas the inlet edge is the edge where drilling starts. Micrographs were captured using a stereo microscope and analyzed using Image pro software. The thrust force and torque during drilling were determined only for the HSS drill bit using a speed of 6000 rpm and 0.06 mm/rev. The force was measured using a Kistler piezoelectric dynamometer.

3. Results and discussion

Figure 1 shows the variation of the size of breakout zones versus drilling speed, feed rate, compaction pressure and drilling tool. For both the uncured and cured specimens, the size of breakout zones generally increased with cutting/drilling speed, indicating that as the cutting speed increased, the mechanical bonds of the green compacts increasingly failed to hold the particles together. Even though intuitively, productivity can be increased by using higher speed, the results here show that very high speeds can lead to high scrap rates due to the size of breakouts. Furthermore, regardless of the type of sample, breakout zones were generally larger for samples drilled with the HSS drill bits. There is a possibility that the HSS tool reacted with the samples forming bonds that acted over a larger area.

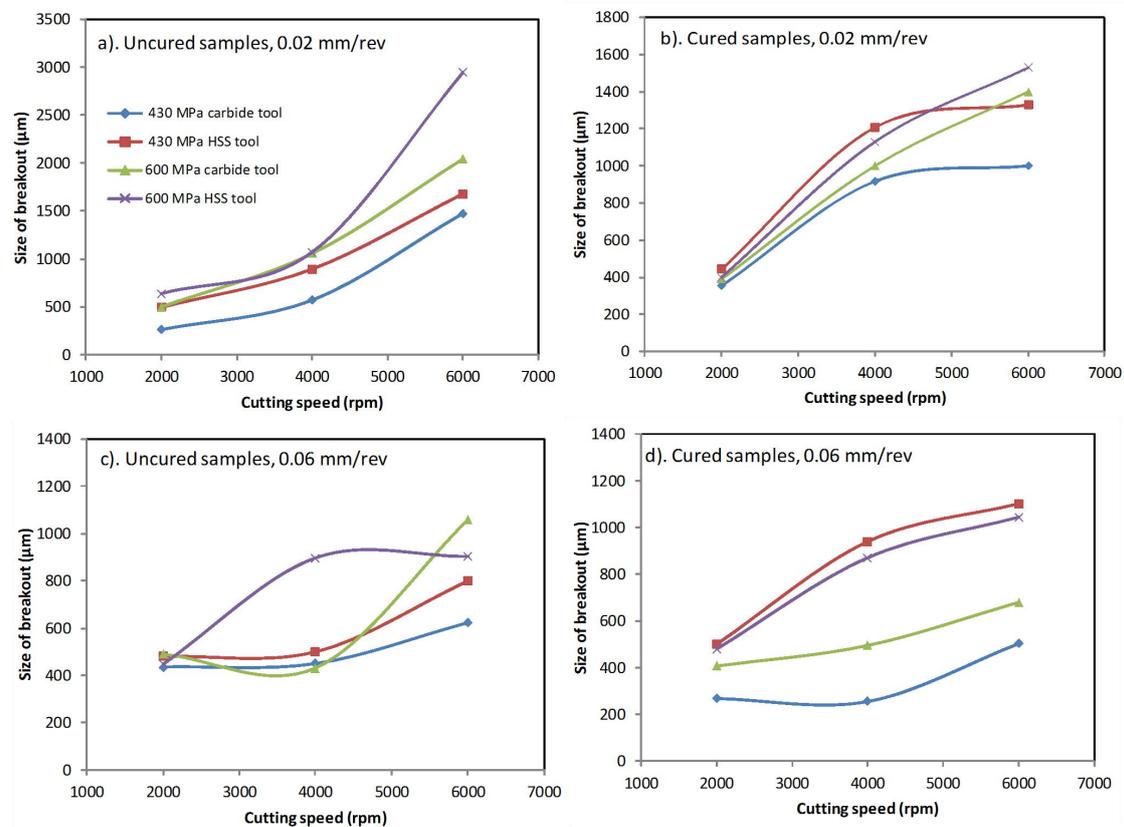


Figure 1. Average breakout of Ti-6Al-4V samples: a) Uncured, 0.02 mm/rev, b) Cured, 0.02 mm/rev, c) Uncured, 0.06 mm/rev, d) Cured, 0.06 mm/rev. Legend in Figure 1a) applies to all graphs.

Concerning the compaction load, it appeared that the samples compacted at 430 MPa had smaller break-out zones than the samples pressed at 600 MPa. This, according to most literature, was a counter-intuitive observation given the green strength was lower for the former samples pressed at 430 MPa, and a higher green strength is associated with smaller breakouts [7–9]. However, the observation tallies with others that argue that a high green strength is not beneficial because the stronger mechanical bonding between powder particles leads to bigger breakouts [5]. Characteristic break-out zones are shown in Figure 2, for uncured and cured samples drilled using HSS and similar parameters.

The effect of feed rate on the size of breakouts was very pronounced at high speeds, where increasing the feed rate from 0.02 mm/rev to 0.06 mm/rev reduced the size of the breakouts (Figure 1a) and c) (for uncured) and Figure 1b) and d) (for the cured) samples).

This observation was in line with literature [2], where a low feed rate is associated with an increase in temperature of samples, leading to loss of green strength and accelerated particle removal. In the current study, it is possible that the low feed rate led to an increase in temperature and caused the polymeric binder to over-cure, leading to a brittle network.

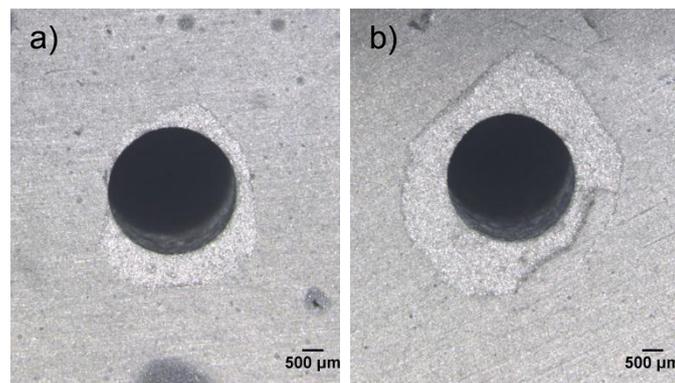


Figure 2. Micrographs of Ti-6Al-4V showing the average breakout on samples drilled using a HSS tool at 0.06 mm/rev and cutting speed of 2000 rpm: a) cured sample b) uncured sample.

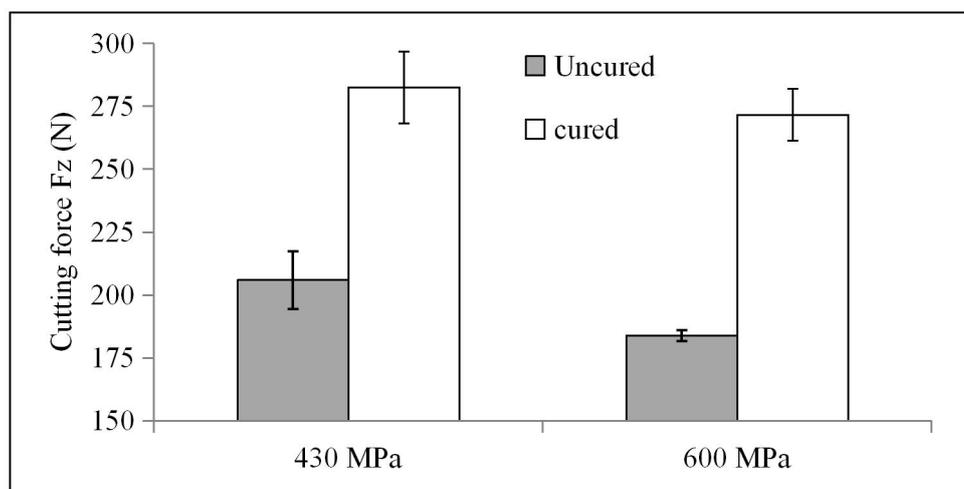


Figure 3. Axial force obtained using 3 mm HSS tool: feed 0.02 mm/rev and speed 6000 rpm.

Figure 3 presents the cutting forces measured when drilling with a HSS tool at a speed of 6000 rpm and feed rate of 0.06 mm/rev. The cutting forces for the uncured samples were lower than for the cured samples. It is highly possible that the uncured polymeric binder partly acted like a machining lubricant, hence lowered the cutting forces. The least cutting force was obtained on uncured samples pressed at 600 MPa, while the highest force was obtained for the cured samples, regardless of the compaction load. The similarity of cutting forces for the cured samples, which had different green strengths, indicates that the green strength had only a marginal role in determining the cutting forces. It is possible that the high cutting forces obtained for the cured samples were caused by clogging of twist drill by the machined powder, as has been observed in other alloy systems [10].

4. Conclusion

It may be concluded from the present work that the interaction between the strength and the machinability of Ti-6Al-4V green compacts is not straightforward, but dependent on the drilling parameters. The cutting speed displayed significant impact on machinability where high cutting speeds reduced machinability. The effect of feed rate was muted at the lowest cutting speed, but increasing feed rate at high speeds reduced size of breakouts and improved machinability. HSS twist drills marginally reduced machinability compared to carbide twist drills. The cutting forces were highest for the cured samples, regardless of the compaction load, indicating that it was independent of the strength of the compacts.

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