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INVESTIGATING THE EFFECTS OF CUTTING PARAMETERS ON THE HOLE QUALITY IN DRILLING THE Ti-6Al-4V ALLOY

PREISKAVA VPLIVA PARAMETROV REZANJA NA KVALITETO IZVRTINE, IZVRTANE V ZLITINO Ti-6Al-4V

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In this study, the effects of cutting parameters on the surface roughness, burr height, hole-diameter deviation, cutting temperature and structure of a chip formation were investigated during the drilling of the Ti-6Al-4V alloy. For this purpose, the Ti-6Al-4V alloy was drilled at different cutting parameters, longitudinally in the 10 mm depth with Ø = 10 mm high-speed-steel (HSS) drills, having 90°, 118°, 130° and 140° point angles on the CNC vertical machining centre. Experiments were carried out at the (12.5, 18.75 and 25) m/min cutting speeds and the (0.05, 0.1 and 0.15) mm/r feed rates without using the cutting fluid. As a result, as the feed rate and the drill-point angle were increased, the surface roughness increased as well; however, as the cutting speed increased, the surface roughness decreased. When the feed rate and drill-point angle increased, the burr height decreased. On the other hand, an increase in the cutting speed increased the burr height. In general, an increase in the feed rate and drill-point angle increased the hole diameters, and the hole diameters obtained were close to the nominal size when the cutting speed was increased.

Keywords: Ti-6Al-4V, surface roughness, chip, drilling, burr height, hole diameter

V tej študiji so bili preiskovani vplivi parametrov rezanja na hrapavost površine, višino zarobka, odmike premera izvrtine, temperaturo rezanja in strukturo nastalega izvrtka pri vrtanju zlitine Ti-6Al-4V. V ta namen je bila zlitina Ti-6Al-4V vrtana na vertikalnem CNC obdelovalnem stroju pri različnih parametrih rezanja vzdolžno v globino 10 mm s svedri iz hitroreznega jekla (HSS) premera 10 mm, ki so imeli vršni kot 90°, 118°, 130° in 140°. Preizkusi so bili izvršeni pri hitrostih rezanja (12,5, 18,75 in 25) m/min in podajanju (0,05, 0,1 in 0,15) mm/r, brez uporabe hladilne tekočine. Rezultati so pokazali, da pri povečevanju podajanja in večanju vršnega kota svedra narašča tudi hrapavost površine, vendar pa se pri povečevanju hitrosti rezanja zmanjšuje hrapavost površine. Če se povečujeta podajanje in velikost vršnega kota, se zmanjšuje višina zarobka. Po drugi strani povečanje hitrosti rezanja poveča višino zarobka. Na splošno velja, da povečanje podajanja in povečanje vršnega kota svedra povečujeta premer izvrtine. Premeri izvrtin so bili blizu nazivni velikosti, če se je povečala hitrost rezanja.

Ključne besede: Ti-6Al-4V, hrapavost površine, izvrtek, vrtanje, višina zarobka, premer izvrtine

1 INTRODUCTION

Titanium and its alloys are widely used in many fields, especially in aircraft engines and automotive parts because they are light, exhibiting quite a good performance, high resistance to corrosion and high strength and being appropriate for high-temperature applications.[1,2] To give the final shape to these materials produced by casting, forging and powder metallurgy, various manufacturing methods are utilized.[3] The drilling process is one of the main manufacturing methods for obtaining the final shape of a material.[4] Nowadays, the drilling of Ti and its alloys within the desired tolerance is required. However, the drilling of these materials is very difficult because of their superior features.[5] During drilling, the chip welds to the cutting tools. In addition, the temperature of the tools and materials increase due to a low thermal conductivity of the HSS versus the Ti-Al-V alloys.[6] These factors negatively affect the tool wear, chip type, burr formation, surface roughness and geometric quality.[7] A correct selection of the cutting parameters and cutting conditions is important to minimize these problems and determine the ideal cutting conditions.[8,9] When literature studies are examined, it can be seen that there are not many studies related to this topic. Some studies performed on titanium alloys are given below.

Rahim and Sasahara[10] measured the tool wear, the temperature of the workpiece and the cutting forces occurring at various cutting parameters and different cooling types at high-speed drilling of Ti-6Al-4V. They found that the maximum temperature of the workpiece occurred when it was cooled with an air blower, being lower when using minimum quantity lubrication palm oil (MQLPO) and minimum quantity lubrication synthetic ester (MQLSE) and the lowest when using water. However, they reported that MQLSE led to a higher thrust force than MQLPO affecting the material during the cutting process. Park et al.[11] measured the thrust force and investigated the wear of tungsten carbide (WC) and polycrystalline diamond (PCD) during the drilling of titanium- and carbon-fibre-reinforced plastics. They determined that PCD drills showed a lower titanium adhesion when compared to WC drills. They also observed a higher spindle speed, causing a significant increase in the tool wear due to a higher temperature. Pujana et al.[12] applied ultrasonic vibrations on workpiece samples while drilling the Ti-6Al-4V alloy. They investigated the temperature, the chip formation and the feed force on the drill tip by means of an infrared radiation thermometer. They observed that a higher force was required for cutting because of a high-temperature occurrence when the vibration amplitude was increased. Shyha et al.[13] drilled titanium/carbon-fiber-reinforced plastic (CFRP)/aluminum stacks at different cutting parameters with a coated (a CVD diamond and a hard metal) tungsten-carbide drill. Due to out of roundness, they measured the hole size, cylindricity, burr height, hole-edge quality, average surface roughness (R_a), microhardness (of the metallic elements) and swarf morphology. The burr height was observed to be larger at the hole exit (Al 7050) compared to hole entry (Ti 6–4), while the delamination was significantly reduced by wen machining the CFRP in the stack configuration as opposed to the stand-alone configuration. However, the chip formation occurring while drilling Al 7050 was obtained using a similar cutting fluid and low cutting parameters of the titanium alloy. Isbilir and Ghassemieh[14] investigated the drilling of the Ti-6Al-4V alloy using the 3D Lagrange finite-element software. By analysing the materials, they reported that the thrust force, stresses and burr height of the drilled materials increased when the feed rate was increased. Guu et al.[15] analyzed the stresses in the micro-drilling of Ti and its alloy using finite-element methods. Kıvak and Şeker[16] investigated the effect of the cutting parameters on the cutting forces in drilling the Ti-6Al-4V alloy with coated and uncoated drills under dry and wet cutting conditions. At the end of the experimental study, they found that the coating materials provided about a 17 % decrease in the cutting forces. It was seen that the feed rate had a bigger effect than the cutting speed on the change in the cutting forces.

The main objective of metal cutting is to provide the surface quality and the burr height along with the geometric and dimensional completeness of the workpiece to be produced economically and within the desired limits. Nowadays, drilling the Ti-6Al-4V alloys that are used widely is very difficult because of their excellent properties such as high resistance to corrosion, high strength and high-temperature resistance. Therefore, in this study, the effects of the cutting parameters, together with different point angles of HSS drills, on the surface roughness, hole-diameter deviation, burr height, cutting temperature and structure of the chip formation were investigated during drilling a Ti-6Al-4V alloy at various combinations of the feed rates and cutting speeds.

Table 1: Chemical composition of the Ti-6Al-4V alloy (*w*/%)
Tabela 1: Kemijska sestava zlitine Ti-6Al-4V (*w*/%)

Ti	Al	V	Fe	C	N	H	O
89.52	6.1	4.1	0.056	0.019	0.025	0.08	0.1

Table 2: Cutting parameters and their values
Tabela 2: Parametri rezanja in njihove vrednosti

Parameters	Values
Cutting speed (m/min)	12.5, 18.75 and 25
Feed rate (mm/r)	0.05, 0.10 and 0.15

2 MATERIALS AND METHODS

2.1 Experimental study

For the experimental study, the Ti-6Al-4V alloy was provided by Sincemat Co. Ltd. The nominal chemical composition of the Ti-6Al-4V alloy with the size of 100 mm × 150 mm × 10 mm is given in **Table 1**.

In the experiments, a HUMMER VMC-1000 CNC vertical machining centre with the maximum speed of 8000 r/min and the spindle power of 15 kW was used.

The experiments were performed using 10 mm diameter HSS drills with the helix angle of 35°, with the point angles of 90°, 118°, 130° and 140°. For the experiments where no cutting fluids were used, the cutting parameters are given in **Table 2**.

2.2 Measurement of the surface roughness

A measurement of the surface roughness is quite important to see the effects of the cutting parameters on the material of a machined surface. With this regard, the surface-roughness measurements of the drilled alloy were performed for different cutting parameters using Taylor-Hobson's Surtonic 3 and a surface-roughness measuring device in accordance with ISO standards. The measurement sampling length was chosen as 5.6 mm. The measurement process was carried out parallel to the axis hole. Four surface roughness values (R_a) for the machined surfaces were obtained and then averaged.

2.3 Determining the burr height and the hole-diameter deviation

To determine the burr height and the hole-diameter deviation, a three-dimensional coordinate measuring device of the SIDIO XR brand, with a 1.4 megapixel IDIO Neo sensor, 340 mm scan area and Manfrotto Studio Tripod was used. Before scanning with this device, a non-destructive testing spray (BT 70) was sprayed on the surface of the Ti-6Al-4V alloy, where the drilling process would be applied, in order to make a better measurement and determine the reference points that were affixed to certain portions of the alloy to be drilled. For the determination of the burr height and the hole-diameter deviation, the Ti-6Al-4V alloy was scanned with a 3-D optical scanning system. For the determination of the effects of different cutting parameters and point angles of the drills on the burr height, the Ti-6Al-4V alloy scanned with the three-dimensional coordinate measuring device was transferred to the PolyWorks program. This program automatically gives minimum, mid and maximum values of the burr height at a hole exit. The burr height was determined by taking the arithmetic means of these values.

3 RESULTS AND DISCUSSION

3.1 Surface roughness

The surface roughness of the holes occurring as a result of drilling the Ti-6Al-4V alloy is given in **Figures 1** and **2**. As seen in these figures, the surface roughness increased when the feed rate was increased and it decreased when the cutting speed was increased. In addition, it was observed that the surface roughness increased with an increase in the point angle. While the lowest surface roughness was obtained with the 90° point-angle drills, 0.05 mm/r feed rate and 25 m/min cutting speed, the largest surface roughness was obtained with the 140° point-angle drills, 0.15 mm/r feed rate and 12.5 m/min cutting speed. Similar results were found by Kim et al.[17] and Sharif and Rahim.[18]

During the machining at a high cutting speed, the cutting temperature increases due a small contact length between the tool and the workpiece. This could be due to a decrease in the value of the coefficient of friction, resulting in a low friction at the tool-workpiece interface. These factors could contribute to an improvement in the surface-roughness values.[19] In addition, as the cutting speed increases, more heat is generated, thus softening the workpiece material, which, in turn, improves the surface roughness. However, a low cutting speed may lead to the formation of a built-up edge and, hence, deteriorates the machined surface. The investigation revealed that at a high feed rate the surface roughness is poor, probably due to distinct feed marks produced at the high feed rate.[10]

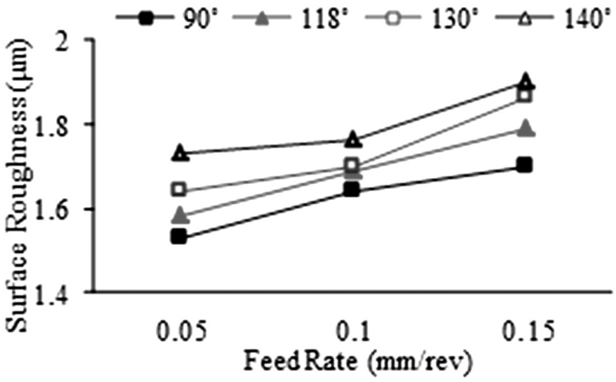

Figure 1: Effect of the feed rate on the surface roughness
Slika 1: Vpliv hitrosti podajanja na hrapavost površine

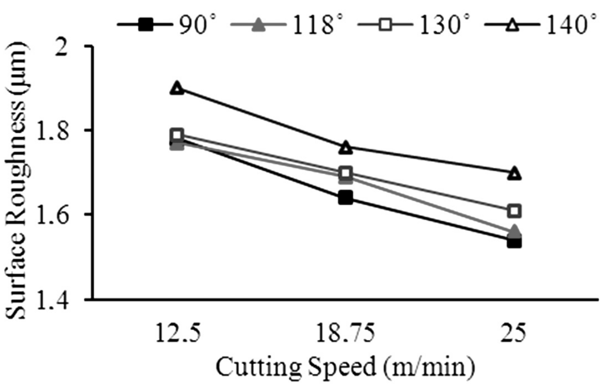

Figure 2: Effect of the cutting speed on the surface roughness
Slika 2: Vpliv hitrosti rezanja na hrapavost površine

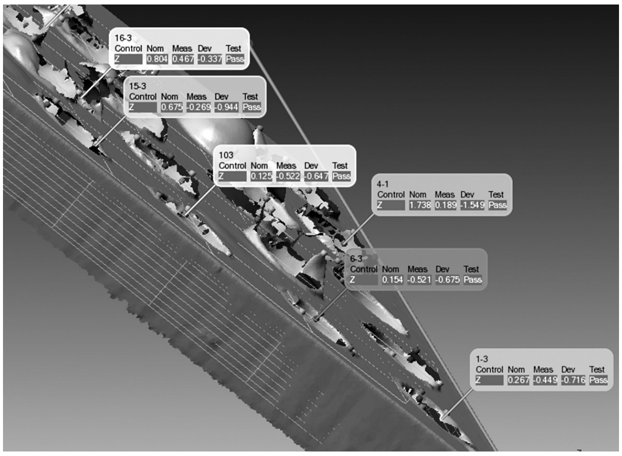

Figure 3: PolyWork burr measurement
Slika 3: Merjenje zarobka s PolyWork-om

3.2 Burr height

In **Figure 3**, the burr heights obtained with the PolyWork program for the alloy scanned with the three-dimensional coordinate measuring device are shown. In addition, the burr heights obtained depending on feed rates, cutting speeds and point angles are given in **Figures 4** and **5**.

The burr height occurring at the hole exit at the low feed rate was found to be larger than the burr height occurring at the hole exit at the high feed rate. However, when the cutting speed was increased, the burr height at the hole exit also increased. For this reason, the biggest burr height was obtained at the high cutting speed and low feed rate. The burr that occurred in the drilling process carried out with large point-angle drills was found to be smaller. Similar results were found by Kim et al.[20] and Dornfeld et al.[21]

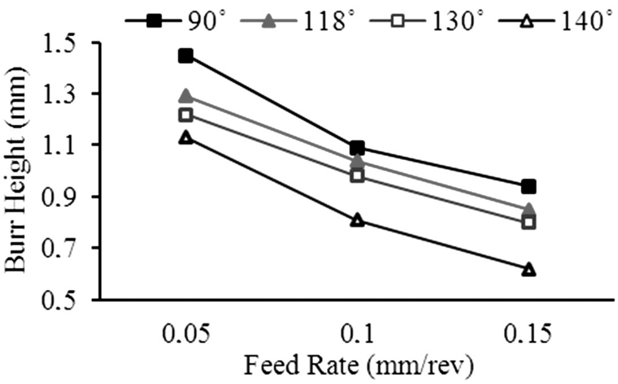

Figure 4: Effect of the feed rate on the burr height
Slika 4: Vpliv hitrosti podajanja na višino zarobka

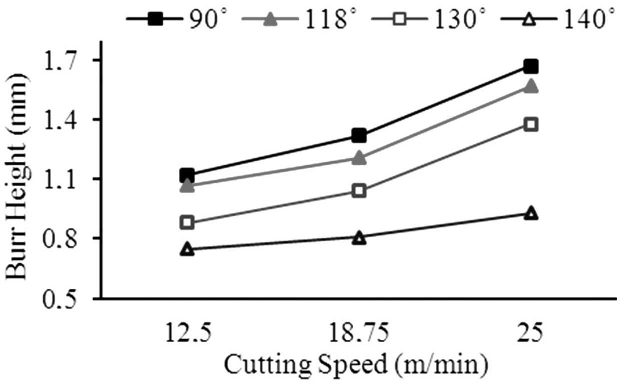

Figure 5: Effect of the cutting speed on the burr height
Slika 5: Vpliv hitrosti rezanja na višino zarobka

The cutting tool, processed materials, cutting parameters and the cooling fluid affect the burr formation.[22,23] Especially the drilling of metal materials causes the formation of burrs, resulting from the plastic deformation of workpiece materials both at the entrance and the exit of a hole.[7] ISO 13715 standards define the burr dimensions that deviate from the ideal geometry. However, the measurement of chip characteristics is rather difficult and takes time.[24] Therefore, the easiest way of characterising chips is to measure their height and thickness.[25] The burr height and thickness are very important for deburring an unwanted formation off the workpiece. These unwanted burrs are harder than the workpiece. Therefore, deburring is quite costly forcing us to use extra tools. This causes the costs to rise by up to 30 %, especially for aircraft engines. For automobiles, on the other hand, the cost rise varies between 15 % and 20 %.[26]

3.3 Hole-diameter deviation

A hole-diameter deviation is usually a result of the effects such as deflection, vibration, wear and lack of

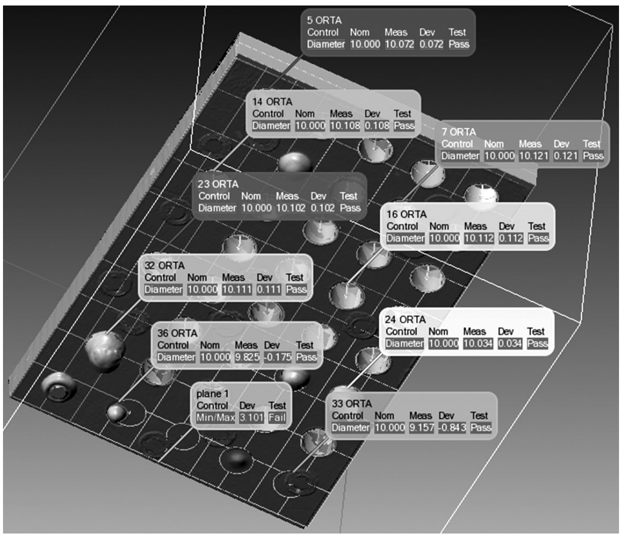

Figure 6: PolyWork hole-diameter deviation
Slika 6: Merjenje odmika premera izvrtine s PolyWork-om

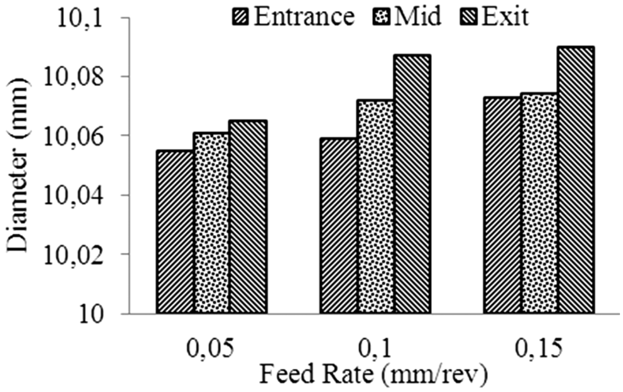

Figure 7: Effect of the feed rate on the hole diameter
Slika 7: Vpliv hitrosti podajanja na premer izvrtine

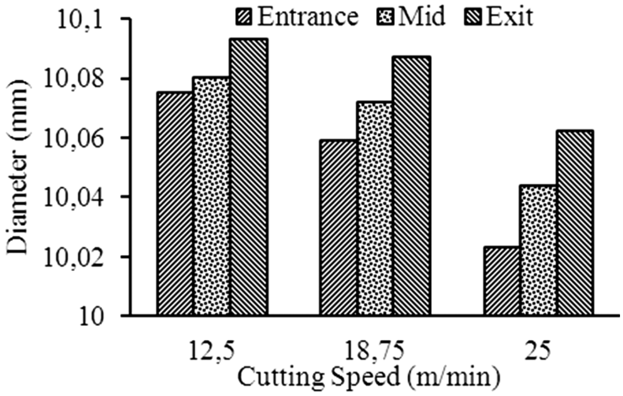

Figure 8: Effect of the cutting speed on the hole diameter
Slika 8: Vpliv hitrosti rezanja na premer izvrtine

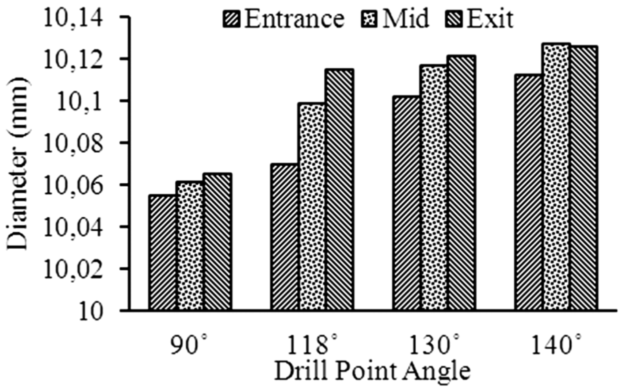

Figure 9: Effect of the drill-point angle on the hole diameter
Slika 9: Vpliv vršnega kota svedra na premer izvrtine

lubrication. On the other hand, a deviation from the circularity represents the fluctuations on the surface, and it is defined as the difference between the largest and the smallest radius measured from the center point. However, there are various ways of determining the center of a hole. In this study, the hole diameter and the circularity were determined with the coordinates taken at different points. These measurements used in the evaluation of the hole diameter and circularity were transferred directly to the PolyWorks program (**Figure 6**). Thus, the hole-diameter deviation was detected at the entrance, the middle and the exit of a hole.

The evaluation of the hole diameter was performed by comparing the values obtained with the cutting tool depending on different cutting parameters. The diameters affected by the feed rate, the cutting speed and the point angle are given in **Figures 7** to **9**. With an increase in the feed rate and drill-point angle, the diameter also increased significantly at the entrance, middle and exit of a hole. On the other hand, the diameter deviation decreased with an increase in the cutting speed. In addition, it was found that the deviation at the entrance of a hole was smaller than that at the exit.

3.4 Cutting temperature

During the drilling process, 90 % of work is converted to heat as a result of the plastic deformation.[27] Therefore, a very high temperature occurs in the drilling zone. This temperature affects a specific region of the chip, tools and workpiece.[28] In connection with the thermal properties of the workpiece and cutting, either the cutting tool or the workpiece is affected by this. Since Ti and its alloys, which are about 1/6 of steels,[29] have low thermal properties, a great deal of heat, as much as 80 %, is absorbed by the tool.[30] 50 % to 60 % of the heat generated during the drilling of steel is absorbed by the tool.[31] When machining Ti and its alloys, the tool reaching a high temperature wears quickly because of the high cutting temperature and a strong adhesion between the tool and the workpiece; and the high stresses developed at the cutting edge of the tool may cause a plastic deformation and accelerate the tool wear.[32]

The images of the Ti-6Al-4V alloy taken by a thermal camera at various cutting parameters are given in **Figure 10**. As seen in this figure, a low cutting speed leads to a low temperature because of the interaction between the material and the tool.

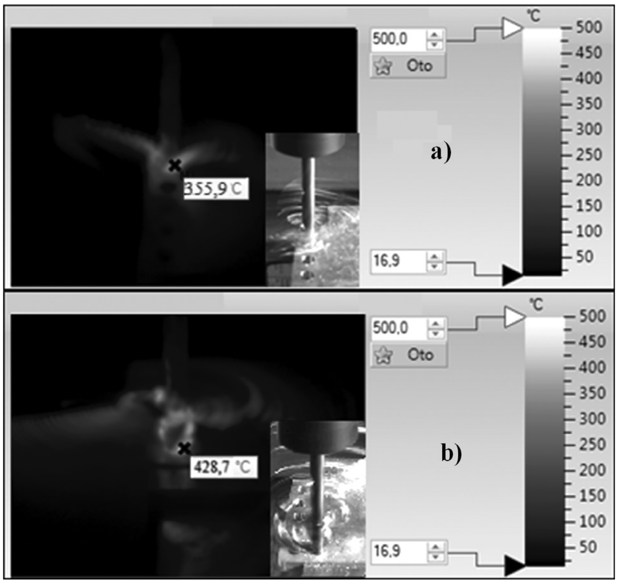

Figure 10: Temperature measurements with thermal cameras: a) low cutting speed, b) high cutting speed
Slika 10: Merjenje temperature s toplotno kamero: a) majhna hitrost rezanja, b) velika hitrost rezanja

3.5 Chip types

A chip formation of titanium alloys during the drilling process is quite difficult when compared with the other metals. There are three types of chip. These are the continuous chip, the continuous chip with a build-up edge, and the discontinuous chip.[33] When the feed rate was low, the Ti chip was long and continuous, and when the feed rate was increased, it became shorter and stiffer.[17] However, as the cutting speed was raised, the chip-serration frequency was enhanced.[34]

A few chip samples were taken from each drilling process to detect the effects of the cutting parameters and drill-point angle on them. From these chips, it was observed that the chips were formed under difficult conditions and that high cutting force and temperature took place; depending on these factors, the shapes of the

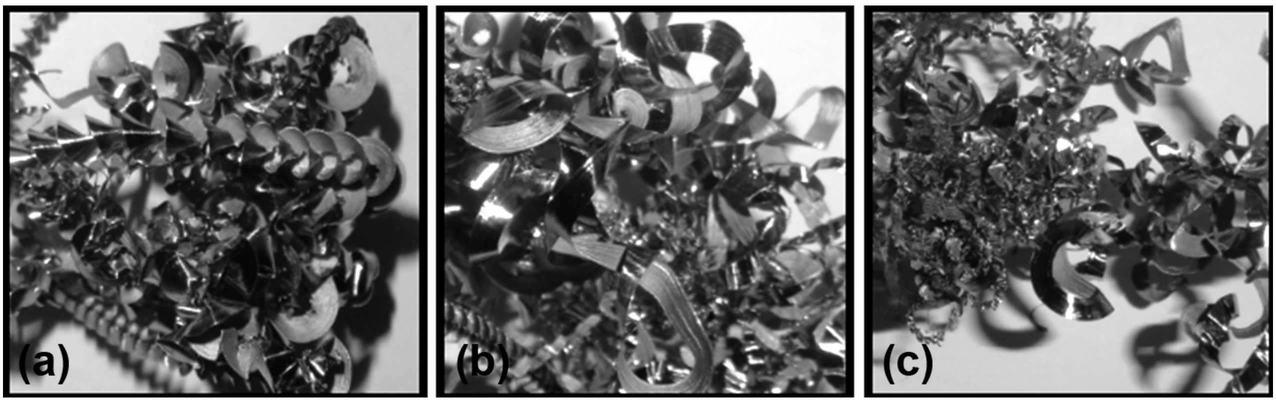

Figure 11: Some chip shapes: a) continuous chip, b) continuous chip with a build-up edge, c) discontinuous chip
Slika 11: Nekaj oblik izvrtkov: a) kontinuirni izvrtek, b) kontinuirni izvrtek s poudarjenim robom, c) razlomljeni izvrtek

chips were irregular. At a low cutting speed, feed rate and drill-point angle, the chip was observed to be ductile and continuous (**Figure 11a**). The chip was hardened and it became fragile with an increase in the cutting speed, feed rate and drill-point angle (**Figure 11b**). However, with an increase in the cutting speed, ridges appeared on the chip surface (**Figure 11c**).

The effect of the temperature on the chip hardening is very important due to the friction. Due to the temperature effect, the chip had a dark colour.

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4 CONCLUSION

In this study, the parameters such as surface roughness, burr height, hole-diameter deviation, cutting temperature and structure of a chip formation were investigated during the drilling of the Ti-6Al-4V alloy under different feed rates, cutting speeds and drill-point angles using HSS drills with 90°, 118°, 130 ° and 140° point angles and the following conclusions were reached:

- When the feed rate and drill-point angle were increased, the surface roughness increased as well; when the cutting speed increased, the surface roughness decreased.
- When the feed rate and drill-point angle were increased, the burr height decreased, but an increase in the cutting speed increased the burr height.
- Generally, when the feed rate and drill-point angle were increased, the hole diameter increased; when the cutting speed was increased, the diameter was close to the nominal value.
- For all the drill-point angles, the cutting speed and feed rate combinations, the diameters obtained were larger than the nominal values.
- For the low cutting speed and feed rate, the chip form was found to be more regular and ductile.
- With an increase in the cutting speed and feed rate, the chip formation displayed a shift from a ductile structure towards a more rigid and fragile form.
- An increase in the cutting speed caused the material to overheat due to the friction and the thermal properties of Ti-6Al-4V.

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