G Model
CIRP-1324; No. of Pages 4

ARTICLE IN PRESS

CIRP Annals - Manufacturing Technology xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

High speed end milling of a zirconium alloy

Richard Hood [a], Sein Leung Soo (2)[a,*], Colin Sage [b], Phill Carcass [c]

[a] *Machining Research Group, School of Mechanical Engineering, University of Birmingham, Edgbaston, Birmingham, UK*
[b] *Rolls-Royce plc, Bristol, UK*
[c] *Rolls-Royce plc, Derby, UK*

ARTICLE INFO

Keywords:
Surface integrity
Milling
Zirconium

ABSTRACT

The paper details a comprehensive investigation into the machinability and surface integrity of Zircaloy-4 following end milling. Tool wear after machining for ~30 min at a cutting speed of 320 m/min was low, with surface roughness (Ra) values typically <0.6 μm. No evidence of thermal damage was detected on any of the surface/subsurface cross-sections analysed, although adhesion/re-deposition and smeared material with a width of ~50 μm was prevalent on the workpiece surface, particularly when operating at higher cutting speeds (320 m/min) and depths of cut (0.6 mm). Surface residual stresses were compressive up to a value of 120 MPa.

1. Introduction

Notwithstanding issues relating to safety risk management and mitigation, nuclear fission based energy generation is widely regarded as a sustainable alternative to fossil fuel driven systems. In a recent white paper [1] and technical report [2], the UK Government outlined that planned global investment in new nuclear power plants is estimated to be in the order of £930 billion. The UK's proposed construction of 16 civil nuclear power stations (projected total cost of £60 billion) over the next 25 years will provide ~16 GW of electricity generating capacity. However, since the last new reactor commenced operations in 1995, related manufacturing research activities have predominantly focused on the decommissioning of older nuclear facilities rather than new build capability development. This has caused a critical technological void and skills shortage that requires urgent attention [2]. Zirconium alloys are widely used as cladding for fuel rods in nuclear reactors and comprise solid solutions of Zr combined with other metals such as Sn, Nb, Fe, Cr or Ni. They are characterised by very low thermal neutron absorption cross-sections, high ductility along with excellent thermal and corrosion resistance. Nuclear-grade zirconium alloys typically have in excess of 95% (weight) Zr, with varying amounts of alloying elements added to improve overall mechanical and physical properties. Such materials are generally non-toxic but are classed as pyrophoric, where the accumulation of small/fine particles such as machined swarf can be prone to spontaneously combust after reacting with oxygen, resulting in corresponding release of hydrogen.

Published research relating to the machinability of Zr alloys is extremely scarce. In 1959, Schmidt and Roubik [3] reported an investigation into the milling of Zircaloy-2, however only the paper's abstract is currently available (despite an extended search via The British Library etc.). The authors recommended the use of sharp tools with large relief angles (approximately 10°) as well as the application of emulsion fluid for machining zirconium alloys, in order to reduce the risk of fire and material adhesion on the cutter flank. Similar cutting conditions were advocated by ATI (a specialty materials supplier) [4], who also noted that climb milling was preferred to penetrate the workpiece at the maximum approach angle and depth of cut while avoiding the work-hardened area. Furthermore, tool lead angles should vary between +15 and +30°, together with positive axial and radial rake angles. Unfortunately, no data regarding suggested operating parameters to achieve specific workpiece surface roughness or integrity was found. Trent [5] states that the machining behaviour of commercially pure zirconium is comparable to that of titanium. The contact area on the tool rake face is generally short, while the associated shear plane angle is high and resulting chips are thin. Additionally, the temperature gradients produced on the cutting tools were approximately equivalent. Given the stringent surface integrity and functional performance requirements of components utilised in nuclear related applications, the lack of detailed information on the effects of machining operations is a growing concern. The present paper details results from an in-depth experimental study on the machinability of zirconium alloys when end milling to assess the influence of varying operating parameters on tool life, workpiece surface roughness and surface/subsurface integrity.

2. Experimental work

The milling experiments were performed on a Matsuura LX-1 vertical machining centre with a rotational speed range of 200–60,000 rpm and maximum spindle power of 5 kW. The workpiece material was a commercial zirconium alloy commonly known as

---

* Corresponding author.
E-mail address: s.l.soo@bham.ac.uk (S.L. Soo).

http://dx.doi.org/10.1016/j.cirp.2015.04.057
0007-8506/© 2015 CIRP.

Please cite this article in press as: Hood R, et al. High speed end milling of a zirconium alloy. CIRP Annals - Manufacturing Technology (2015), http://dx.doi.org/10.1016/j.cirp.2015.04.057

Zircaloy-4 (Zr–1.5%Sn–0.2%Fe–0.1%Cr) and supplied in the form of blocks measuring 260 mm × 110 mm × 24 mm, with a nominal bulk hardness of ~250 HV_{30}. Tool flank wear was measured using a toolmakers microscope equipped with digital micrometre heads giving a resolution of 0.001 mm. Micrographs of tool wear scars were captured using a digital camera attached to a PC running image processing software. Surface roughness measurements based on a cut-off and evaluation length of 0.8 and 4.0 mm respectively, were taken using a Taylor Hobson Form Talysurf unit having a vertical resolution of 10 nm, a stylus angle of 60° and corresponding tip radius of 2 μm. Selected specimens for surface integrity assessment were sectioned, hot mounted in bakelite and ground using SiC paper with a diamond suspension. Samples were then polished and swab etched in a solution comprising 60% water, 35% HNO_3 and 5% HF for ~5 s. Machined workpiece surfaces and subsurface cross-sections were assessed using a Leica optical microscope running Buehler Optimet software or a JEOL 6060 scanning electron microscope (SEM).

Microhardness investigation was carried out using a Mitutoyo HM124 hardness tester with a Knoop indenter applied under a 25 g load for 15 s. Depth profile residual stress measurements were undertaken using the blind hole drilling technique. Target sites were prepared by thorough degreasing with acetone. Strain gauge rosettes type CEA-06-062UL-120 (Vishay Precision), were bonded to the workpiece surface using Loctite 407 adhesive. Each rosette was drilled using a PC-controlled 3-axis drilling machine. The tool datum depth was detected using an iterative command in the control software, which advanced the rotating drill bur in 2 μm increments. A small amount of fluid was applied when drilling to minimise the risk of zirconium chips catching fire. Fig. 1 shows the experimental setup and strain gauges mounted in position. Depth increments were set at 32 μm (four times), 64 μm (four times) and 128 μm (eight times), providing a completed hole depth of 1.41 mm for the determination of stresses up to 1024 μm below the machined surface.

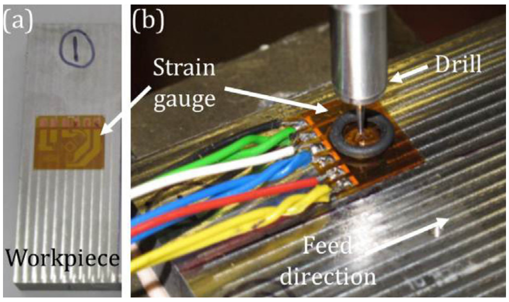

Fig. 1. Residual stress measurement showing; (a) workpieces with strain gauges attached; (b) drilling setup.

Two different types of 6 mm diameter, TiAlN coated, solid tungsten carbide (WC) end mills supplied by Sandvik Coromant were evaluated. The first was a high feed tool (R215.H4-0650BAC03P 1620) with no centre cutting capability, while the second was a radius end mill (R216.24-08050CCC13P 1620) capable of roughing/semi finishing and centre cutting. Both cutters were four fluted with a corner radius of 1 mm, a helix angle of 50°, a straight 45–55% core and a rake angle of 9–12°. The tools were selected based on the target application as well as recommendations from the tooling supplier. For all experiments, cutters were held in HSK shrink fit tool holders with an overhang of 28 mm while runout was <5 μm. Table 1 details the experimental matrix and operating parameter levels. Initial cutting conditions (Experiment 1) were chosen based on parameters suitable for machining titanium alloys (as Zr and Ti are in the same group of the periodic table). However, due to limited visible tool wear, the cutting speed, feed rate and depth of cut were subsequently increased to improve the material removal rate in Experiments (Exp.) 2–7. Feed rate was kept constant at 0.12 mm/tooth. All trials commenced by machining a slot in the centre of the workpiece followed by subsequent passes at the specified stepover in a down milling direction. Similar to tool selection, this strategy was applied due to requirements of the target industrial application (commercial restrictions prevent full disclosure). High pressure (HP) cutting fluid at 70 bar delivered through twin 0.7 mm diameter nozzles was employed in all of the experiments. The tool life criterion was a maximum flank wear of 200 μm (on any cutting edge) or a machining duration of ~33 min. The sole exception was Exp. 7, where the remaining supply of workpiece material was only sufficient for ~9 min cut time. Due to cost constraints, residual stress measurements were only conducted on samples from Experiments 1, 2, 4 and 5 (different cutting speeds) at trial cessation (worn tools).

Table 1
Experimental matrix with operating parameter levels.

Experiment	Tool type	Cutting speed (m/min)	Radial depth of cut (mm)	Axial depth of cut (mm)
1	High feed	80	2.0	0.3
2	High feed	160	2.0	0.3
3	High feed	80	4.0	0.3
4	High feed	240	2.0	0.3
5	High feed	320	2.0	0.3
6	Radius	320	2.0	0.3
7	Radius	320	2.0	0.6

3. Results and discussion

3.1. Tool wear

Adhered workpiece material was prevalent on all of the cutters particularly at the flank location, which complicated the measurement of 'actual' wear on the tool. The maximum flank wear (which encompassed the height of visible adhered material) for all experiments irrespective of cutting speed or tool type did not exceed ~90 μm even after machining for ~33 min, with none of the end mills reaching the end of life criterion. This implied that further machining or use of higher cutting speeds was possible. Sparks consisting of ignited zirconium however were often seen during machining in all experiments despite copious fluid supply, illustrating the reactive nature of the material.

All of the high feed end mills utilised in Experiments 1–5 showed comparable wear scar/edge profiles after cutting for ~33 min regardless of operating conditions, see example optical micrographs in Fig. 2(a) and (b). Tool wear/adhered material distribution was usually consistent/uniform over all four cutting edges, with no significant built up edge (BUE) formation or any apparent signs of chipping/notching. Similar wear patterns were observed on the radius end mills used in Exp. 6 and 7, see Fig. 2(c) and (d), with marginally increased levels of adhered material. Additionally, workpiece adhesion extended to the secondary relief face when machining at the higher depth of cut of 0.6 mm, see Fig. 2(d).

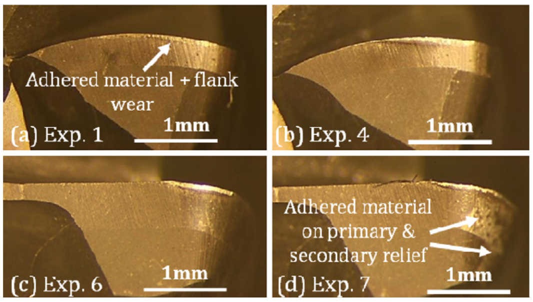

Fig. 2. Optical micrographs of tool wear patterns at experiment cessation.

Fig. 3(a–c) details high resolution SEM images of a sample cutting edge clearly showing adhered material on both the tool flank and rake faces, although there appeared to be minimal loss/delamination of coating or attrition of the carbide substrate. The presence of zirconium in the adhered material layer was confirmed by energy dispersive X-ray (EDX) spectroscopy analysis;

Please cite this article in press as: Hood R, et al. High speed end milling of a zirconium alloy. CIRP Annals - Manufacturing Technology (2015), http://dx.doi.org/10.1016/j.cirp.2015.04.057