UNIVERSITY OF BIRMINGHAM

University of Birmingham Research at Birmingham

Cutting temperatures when ball nose end milling - TiAl intermetallic alloys

Aspinwall, D.K.; Mantle, A.L.; Chan, W.K.; Hood, R.; Soo, S.L.

DOI:
10.1016/j.cirp.2013.03.007

Citation for published version (Harvard):
Aspinwall, DK, Mantle, AL, Chan, WK, Hood, R & Soo, SL 2013, 'Cutting temperatures when ball nose end milling -TiAl intermetallic alloys', *CIRP Annals - Manufacturing Technology*, vol. 62, no. 1, pp. 75-78. https://doi.org/10.1016/j.cirp.2013.03.007

CIRP Annals - Manufacturing Technology 62 (2013) 75–78

Contents lists available at SciVerse ScienceDirect

CIRP Annals - Manufacturing Technology

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

Cutting temperatures when ball nose end milling γ-TiAl intermetallic alloys

David K. Aspinwall (1)[a,*], Andrew L. Mantle (3)[b], Wai Kok Chan[a], Richard Hood[a], Sein Leung Soo (2)[a]

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

ARTICLE INFO

Keywords:
Temperature
Titanium
Milling

ABSTRACT

Experimental results are presented for Ti–45Al–2Mn–2Nb + 0.8 vol% TiB_2XD and Ti–45Al–8Nb–0.2C alloys. Three approaches were employed involving a constantan-workpiece thermocouple arrangement, implanted K-type thermocouples and IR thermography. New and worn (~300 μm flank wear) coated carbide tools were used under dry conditions when down milling at 50–345 m/min, with workpieces mounted horizontally and at 45°. Despite slight variation in ancillary finishing parameters there was generally good agreement between data sets for the different evaluation techniques employed and for both alloys. Higher temperatures were measured with the workpiece at 45°, with constantan-workpiece thermocouple temperatures of 375 °C and 413 °C for new and worn tools respectively at 345 m/min.

1. Introduction

The link between high cutting temperature and poor machinability and the consequent limitations on productivity, tool life and workpiece integrity is well known. Thermal effects are particularly relevant when machining ferrous components or materials designed for aerospace applications such as nickel based superalloys and advanced titanium alloys [1,2]. Non metallic materials in general pose less of a problem however thermal degradation of both the tool and workpiece can be significant when machining advanced composites such as carbon fibre reinforced plastics (CFRP) [3]. While in general the guiding tenet to improved machinabilty is low temperature operation, for some applications notably hard part machining and grind hardening, elevated tool/workpiece interface temperatures can be used to advantage.

From a cutting temperature standpoint, the machining of titanium alloys is more critical than for most workpiece materials, both in relation to the magnitude for a given operating regime and location of the thermal load at or near the cutting edge due to the typically small contact area on the tool rake face. The poor thermal conductivity of titanium alloys as compared to steel (~7 W/mK for Ti–6Al–4V and ~50 W/mK for steel) adds to the problem [4,5]. With Ti based intermetallic alloys such as gamma titanium aluminide (γ-TiAl) which typically contain ~45 at% Al, their thermal conductivity is substantially higher (~22 W/mK) but temperature induced wear effects are no less significant or their adverse impact on workpiece integrity [6,7].

Gamma TiAl alloys are seen as potential replacement materials for nickel based superalloy compressor and turbine blades in future aeroengines [8,9] due to the material's weight advantage (density typically 50% that of nickel superalloy), however producing parts with 'acceptable' workpiece integrity is inherently more difficult than with conventional titanium alloys, not least due to their low room temperature ductility which is typically quoted as <2%. With such materials, use of high speed operating regimes to soften the workpiece in the shear zone has proved counterproductive, producing surface cracking, hardened layers and tensile residual stresses [6]. Even when using optimised operating strategies/conditions, only a limited number of processes have been shown to produce crack free surfaces, amongst them ball end milling [10], where the interrupted nature produces lower average temperatures than for say continuous turning. For any tool-workpiece system, knowledge of operating temperature regimes provides insight and potential control strategies for tool wear and workpiece quality. There are several established techniques for cutting temperature evaluation, details of which can be found in the comprehensive review by Davies et al. [11] and the paper by Le Coz et al. [12] dealing specifically with rotary processes (drilling and milling). Whereas temperature data when milling alloys such as Ti–6Al–4V have been reported previously, information for γ-TiAl in the literature is minimal. The current paper details results from experiments made over several years to assess machining temperatures measured using different methods when ball end milling of γ-TiAl.

2. Experimental work

All machining was carried out on a Matsuura FX-5 high speed machining centre equipped with a 20,000 rpm spindle. The workpiece material was principally a Ti–45Al–2Mn–2Nb + 0.8% vol TiB_2XD (45-2-2-0.8) γ-TiAl, however for infrared measurement tests an alternative gamma alloy Ti–45Al–8Nb–0.2C (45-8-0.2) was also evaluated. The former was a grain refined (50–100 μm), fully lamellar alloy which was investment cast and HIPped at 1260 °C/170 MPa for 4 h followed by heat treatment at 1010 °C for 50 h. This gave a bulk hardness of ~320–400$HV_{0.025}$. The latter material was produced as a cast billet, which was HIPped at 1260 °C/150 MPa for 4 h, resulting in a bulk hardness of ~365HV_{30}.

* Corresponding author.
E-mail address: d.k.aspinwall@bham.ac.uk (D.K. Aspinwall).

0007-8506/$ – see front matter © 2013 CIRP.
http://dx.doi.org/10.1016/j.cirp.2013.03.007

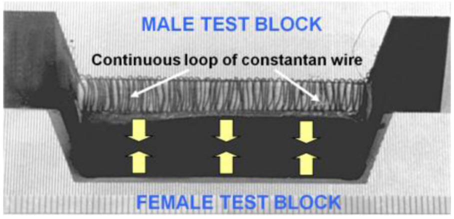

Fig. 1. Looped constantan wire thermocouple arrangement.

The majority of tests involved experiments using a continuous looped arrangement of Teflon insulated constantan wire (0.075 mm diameter core with an outer diameter of 0.19 mm), sandwiched between 2 blocks (male–female) of γ-TiAl (84 mm × 55 mm × 20 mm) to form a thermocouple. The wire loops were approximately 10 mm high with 1 mm protruding from the block surfaces and were stuck to the male workpiece block using adhesive tape. During the cutting process, the insulated constantan wire is locally stripped and the necessary circuit contact made forming an instantaneous hot junction between the wire and workpiece material. The arrangement had previously been used to assess cutting temperatures when high speed machining hardened AISI H13 mould/die steel [13] and is shown in Fig. 1.

Calibration of the thermocouple system involved production of a stepped γ-TiAl calibration bar to which was attached constantan thermocouple wires and standard K-type thermocouples (stainless steel sheathed). The equipment and procedure mirrored that reported by Dewes et al. [13], with the reference junction submerged in ice water and the measuring junction heated using an oxy-acetylene torch up to 1200 °C. Four sets of calibration results were evaluated to produce a response equation used to determine cutting temperature with appropriate compensation for the workpiece ambient temperature during machining trials. The brittle nature of γ-TiAl made it imperative to minimise the gap when the block assembly was clamped since edge fracture during machining compromised circuit contact. Consequently the gap between the male–female blocks was such that when assembled in the insulated machine vice, it was no larger than 0.1 mm (vice tightened using a torque wrench to ensure load consistency, ~25 N). A schematic of the complete test block and thermocouple assemblage is shown in Fig. 2. Under test conditions, recorded temperature was the mean of the 20 highest readings collected over several machining passes.

Test details using this arrangement are shown in Table 1. The tooling was 6 mm diameter TiCN coated (PVD) solid carbide ball nose end mills with either 2 or 4 flutes (30° helix angle). These were collet mounted with an overhang of ≤30 mm. In all cases feed rate was 0.12 mm/tooth and except for T9, programmed operation involved down milling. Variable factors evaluated included the influence of tool condition (new or worn to 0.3 mm flank wear), workpiece orientation (horizontally or at 45°) together with cutting speed. Axial and radial depth of cut was the same in all tests except for T1. Additionally, T1 and T2 evaluated cutting temperatures over the life of the tool (flank wear criterion of 0.3 mm) in contrast to other trials.

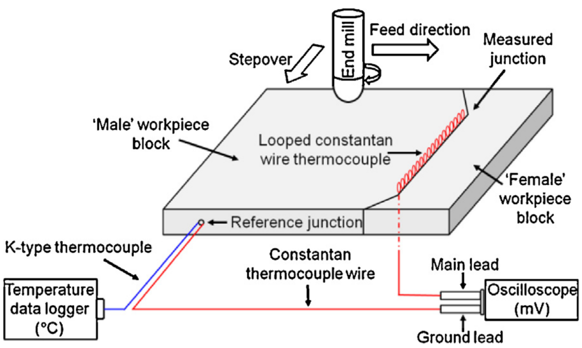

Fig. 2. Schematic of test blocks, tooling and measurement arrangement.

Table 1
Test details when using constantan-workpiece thermocouple system.

Test	Workpiece angle (°)	No. of flutes	Cutting speed (m/min)	Axial depth of cut (mm)	Radial depth of cut (mm)	Tool condition
T1[b]	0	2	70	0.5	0.5	New to worn
T2[b]	0	2	120	0.2	0.2	New to worn
T8[b]	45	4	120	0.2	0.2	New
T9[a]	45	4	120	0.2	0.2	New
T10	45	2	120	0.2	0.2	New
T13	0	2	50	0.2	0.2	New
T14	0	2	70	0.2	0.2	New
T15	0	2	135	0.2	0.2	New
T16	0	2	50	0.2	0.2	Worn
T17	0	2	70	0.2	0.2	Worn
T18	0	2	135	0.2	0.2	Worn
T19	45	2	50	0.2	0.2	New
T20	45	2	70	0.2	0.2	New
T21	45	2	135	0.2	0.2	New
T22	45	2	240	0.2	0.2	New
T23	45	2	345	0.2	0.2	New
T24	45	2	50	0.2	0.2	Worn
T25	45	2	70	0.2	0.2	Worn
T26	45	2	135	0.2	0.2	Worn
T27	45	2	240	0.2	0.2	Worn
T28	45	2	345	0.2	0.2	Worn

[a] Test performed using up milling.
[b] IR measurements also made.

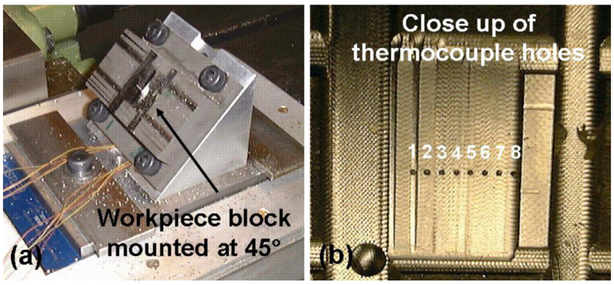

Fig. 3. Implanted thermocouple test block.

Complementary work involving implanted thermocouple wires utilised a rectangular block of material inclined at 45° to the cutter axis on an aluminium fixture mounted on a force dynamometer, see Fig. 3(a). Eight holes 0.59 mm diameter (produced using a 0.50 mm diameter electrode) were electrical discharge machined in the workpiece in order to allow thermocouple location/insertion, see Fig. 3(b).

The thermocouples used were insulated K-type; nickel–chromium and nickel–aluminium with a wire diameter of 0.079 mm. The sum of the wire and insulation diameter was approximately 0.28 mm. The positive and negative thermocouple wires were held together by a protective sheath giving an overall diameter of 0.63 mm. The sheath was carefully removed before inserting the thermocouples into the workpiece holes. The junction of each thermocouple was made by twisting a non insulated length of approximately 0.5 mm and then soft soldering. The thermocouples were held in place using high temperature insulating cement. The location/position of the thermocouple in the workpiece relative to the surface to be machined was such that no more than 2 passes with a ball end cutter was feasible. The signal from the thermocouples was sent to an amplifier with cold junction compensation (giving 10 mV/°C) and then to an oscilloscope using a 10% pre-trigger, typically at the 50 °C level. The setup was checked at both 0 °C and 100 °C.

Assessment involving the implanted thermocouples centred on the evaluation of two different 6 mm diameter ball end cutters, one with a TiCN coating employing a 13° rake angle (Tool A), the other a TiAlN coating with a 0° to 3° rake angle (Tool B). These were tested at 120 m/min. Further comparative testing was then carried out at 70 m/min using the TiCN coated tool. Each tool had 4 flutes and was used in the new condition. Fixed operating parameters included a feed rate of 0.12 mm/tooth with radial and axial depths of cut of 0.2 mm respectively. Down milling was employed with the tool traversing in a vertical upwards cutter path direction. As in the previous constantan-workpiece thermocouple experiments, testing was performed dry. The configuration of the workpiece and block ensured that for the specified operating parameters (V_c and a_p), the peripheral cutting speed varied over the arc of contact and for the 120 m/min trials, the corresponding minimum speed was 93 m/min. Maximum temperatures were recorded from results of replicated tests.

In a final series of experiments, testing on 45-2-2-0.8 material utilised an AGEMA Thermovision 900 infrared camera system operating with a wavelength of 8–12 μm over the infrared spectrum and sensitivity of 0.1 °C at 30 °C. The temperature range settings used were 0–250 °C and 100–600 °C with a measurement accuracy of ±1% and repeatability of ±0.5%. Measurements were carried out in accordance with test conditions previously shown in Table 1 for T1, T2 and T8, with assessment of temperature in T1 and T2 involving worn tools. Subsequent research on 45-8-0.2 alloy employed a FLIR Thermacam SC3000 IR unit having a temperature range of −20 to 2000 °C with an accuracy of ±1% or 1 °C for measurements up to 150 °C and ±2% or 2 °C above this limit. The thermal sensitivity was rated at 20 mK at 30 °C with a corresponding spectral range of 8–9 μm. Three trials were performed to evaluate the effect of varying cutting speeds of 160, 250 and 340 m/min at a constant feed rate of 0.06 mm/tooth with axial and radial depths of cut of 0.25 mm using 4 fluted, 8 mm diameter, AlTiN coated ball nose end mills. Both new and worn tools (0.3 mm flank wear) were tested. An emissivity value of 0.81 was employed, derived in accordance with the procedure outlined by Mantle and Aspinwall [14].

3. Results and discussion

Constantan-workpiece thermocouple results are shown in Figs. 4–7. Although not plotted, comparative temperature data for tools employing 2 and 4 flutes showed no significant difference (277 °C for T10 and 291 °C for T8). Similarly the effect of milling direction when using new tools produced only minimum variation, however higher temperatures were observed with up milling in T9 (313 °C) compared to the down milling operation in T8 (291 °C). Typically higher cutting temperatures due to increased rubbing

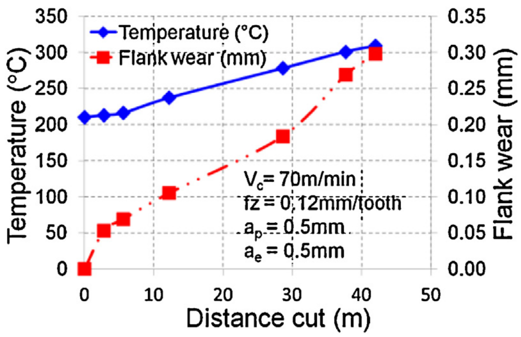

Fig. 4. Temperature and flank wear progression for T1.

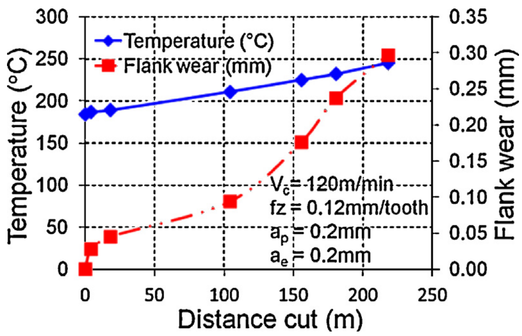

Fig. 5. Temperature and flank wear progression for T2.

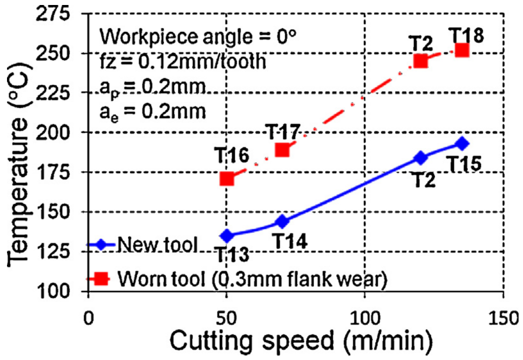

Fig. 6. Effect of cutting speed and tool condition on temperature at 0° workpiece angle.

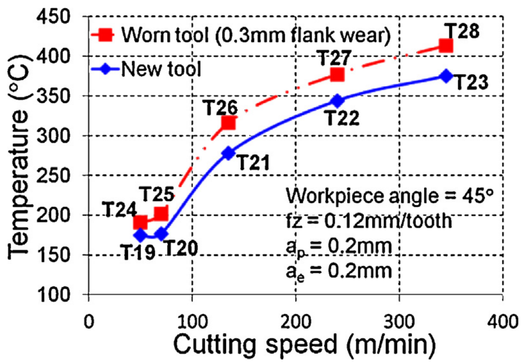

Fig. 7. Effect of cutting speed and tool condition on temperature at 45° workpiece angle.

and vibration/instability are associated with up milling, consequently down milling is generally preferred. The higher axial and radial depths of cut at 70 m/min used in T1 are associated with a semi-finishing operation while those in T2 reflect finishing conditions. Despite the higher cutting speed of 120 m/min in T2, substantially longer tool life was obtained compared with T1 (~5 fold increase) together with significantly lower temperatures at the end of life, see Figs. 4 and 5.

As anticipated, marked differences occurred in the temperature levels shown in Fig. 6 when employing new and worn tools (27–34%) over the range of speeds evaluated. Measured temperature shows a 43–47% increase as cutting speed varies from 50 to 135 m/min. With the workpiece tilted at 45° instead of 0°, substantially higher temperatures were recorded as shown in Fig. 7, which also details data for cutting speeds up to 345 m/min, resulting in temperatures of 413 °C with a worn tool. The trends correspond with published data for a range of workpiece materials including hardened steels [13], where increasing tilt angle produces higher average cutting speeds in the tool/workpiece contact region. Further evidence of this effect was shown by comparing results from T2 (0° workpiece) and T10 (45° workpiece), which gave ~50% higher temperatures for the latter (184 °C as against 277 °C with new tools). Despite lower values with 0° workpiece orientation, this scenario is unlikely in aerofoil machining and therefore higher cutting temperatures can be expected, but with reduced material ploughing/deformation as well as improved surface quality [10].

The implanted thermocouple technique proved problematic as difficulties encountered in ensuring sound joints and inserting/cementing the wires in place caused spurious signals and short circuits. Additionally, there was concern as to whether the thermocouples had an appropriate response time, which at 50 μs proved unwarranted. Consequently, several sets of thermocouples were implanted in the 8 holes shown in Fig. 3(b) and test replications performed. Fig. 8 shows a sample measurement trace from the oscilloscope with a corresponding micrograph of implanted thermocouple holes when cutting at 70 m/min. Results for the mean maximum temperatures together with range values

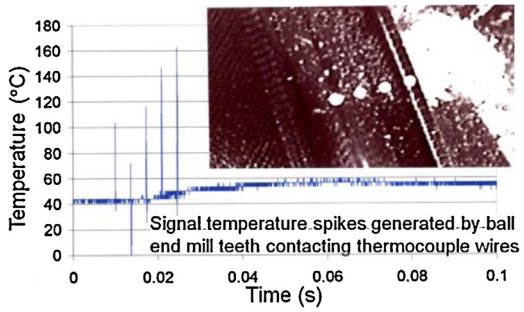

Fig. 8. Sample temperature trace from pass over 4th thermocouple.

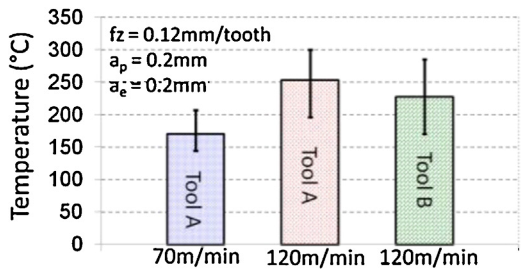

Fig. 9. Influence of tool geometry/coating and cutting speed on temperature measured using implanted K-type thermocouple method.

from tests carried out to determine the effect of tool geometry/coating and cutting speed are detailed in Fig. 9.

A *t*-test on the results for Tools A and B operating at 120 m/min indicated there was no statistically significant difference (at the 5% level). With ductile workpiece materials, higher positive rake angle tools generally produce a reduction in cutting forces and temperatures while with less positive/negative rake geometry, increased workpiece deformation and associated higher strain leads to greater cutting temperatures. With brittle materials however, chips are produced by a tensile fracture mechanism, very little deformation occurs and rake face contact is minimal. Due to the brittle nature of γ-TiAl, it was not surprising therefore that the differences in tool geometry/coating (when new) had minimal effect on temperature. Measured temperatures at 70 m/min were understandably lower by ~33% and while showing reasonable agreement with results obtained previously using the constantan-workpiece thermocouple, this latter approach gave in general higher temperatures (~5–15%), with possible discrepancies relating to the smaller gap involved in the arrangement and also the smaller size of the hot junction.

Infrared thermography results when milling the 45-2-2-0.8 alloy were in all cases lower compared to values obtained with the constantan-workpiece thermocouple technique by an average of ~28%. Differences/errors can be attributed to focussing difficulties, emissivity variation, chip flow effects and data averaging over the field of measurement [11]. When machining at 45° with a cutting speed of 120 m/min, axial and radial depths of cut of 0.2 mm, a feed of 0.12 mm/tooth and new tooling, the temperatures recorded for constantan-workpiece thermocouple,

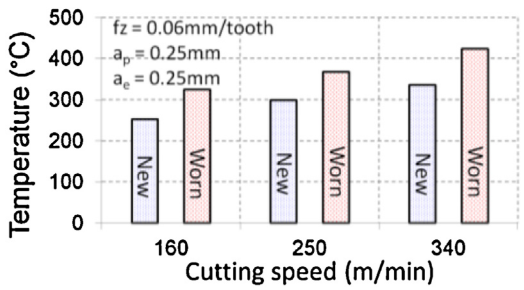

Fig. 10. Effect of cutting speed and tool condition on temperatures measured using IR thermography when machining 45-8-0.2 alloy.

implanted K-type thermocouple and IR thermography were 291 °C, 253 °C and 254 °C respectively. Data for 45-8-0.2 are shown in Fig. 10. Despite the minor differences in operating levels, the data bear favourable comparison with measurements using the constantan-workpiece thermocouple method.

Measured temperatures when ball end milling did not exceed 450 °C even when using worn tooling. As a result, the thermal effects on surface integrity are likely to be minor, particularly when finishing in the preferred cutting speed range typically <200 m/min. For material phase changes to occur, temperatures of ~1120 °C would be required. High cutting temperatures which cause a drop in plastic yield strength typically result in tensile residual stresses due to the surrounding workpiece constraining thermal expansion leading to plastic compression of the heated area and lattice mismatch. However the combination of low TiAl thermal expansion (~6.8×10^{-6}/°C) and high strength at elevated temperature (no major strength loss in TiAl below 700 °C) means that the likelihood of tensile residual stresses is low.

4. Conclusions

For the 3 measurement methods employed, the constantan-workpiece thermocouple proved the most reliable, however it entailed substantial fabrication. With the implanted K-type thermocouples, manufacturing constraints meant that the location holes were larger than ideal, with consequent effects on the temperature field and it is unclear what percentage of heat generated was due to shearing of the thermocouple rather than machining of the γ-TiAl workpiece. The correlated data however suggests ball end milling over the range of operating levels evaluated produced only moderate temperatures even at 45° workpiece angles with worn tools. For speeds < 200 m/min, maximum mean temperatures of up to ~350 °C were recorded.

Acknowledgements

We would like to thank the UK EPSRC, Rolls-Royce plc, Iscar Tools Ltd., Sandvik Coromant and Matsuura Machinery for both financial and technical support including Loan Pool equipment.

References

[1] Trent EM (1984) *Metal Cutting*, 2nd ed. Butterworths, London.
[2] Jawahir IS, Brinksmeier E, M'Saoubi R, Aspinwall DK, Outerio JC, Meyer D, Umbrello D, Jayal AD (2011) Surface integrity in material removal processes: recent advances. *CIRP Annals – Manufacturing Technology* 61(2):603–626.
[3] El-Hofy MH, Soo SL, Aspinwall DK, Sim WM, Pearson D, Harden P (2011) Factors affecting workpiece surface integrity in slotting of CFRP. *Procedia Engineering* 19:94–99.
[4] Kikuchi M (2009) The use of cutting temperature to evaluate the machinability of titanium alloys. *Acta Biomaterialia* 5:770–775.
[5] Armendia M, Garay A, Villalr A, Davies MA, Arrazola PJ (2010) High bandwith temperature measurement in interrupted cutting of difficult to machine materials. *CIRP Annals – Manufacturing Technology* 59(1):97–100.
[6] Aspinwall DK, Dewes RC, Mantle AL (2005) The machining of γ-TiAl intermetallic alloys. *CIRP Annals – Manufacturing Technology* 54(1):99–104.
[7] Priarone PC, Rizzuti S, Settineri L, Vergnano G (2012) Effects of cutting angle, edge preparation and nano-structured coating on milling performance of a gamma titanium aluminide. *Journal of Materials Processing Technology* 212:2619–2628.
[8] Rugg D (2003) The current status of titanium alloy use in aeroengines. *Proceedings of the 10th World Conference on Titanium, vol. V*, 13–18 July, Hamburg, Germany, Wiley-VCH, Weinheim 2727–2735.
[9] Voice WE, Henderson M, Shelton EFJ, Wu X (2005) Gamma titanium aluminide, TNB. *Intermetallics* 13:959–964.
[10] Mantle AL, Aspinwall DK (2001) Surface integrity of a high speed milled gamma titanium aluminide. *Journal of Materials Processing Technology* 118:143–150.
[11] Davies MA, Ueda T, M'Saoubi R, Mullaly B, Cooke AL (2007) On the measurement of temperature in material removal processes. *CIRP Annals – Manufacturing Technology* 56(2):581–604.
[12] Le Coz G, Marinescu M, Devillez A, Dudzinski D, Velnom L (2012) Measuring temperature of rotating cutting tools: application to MQL drilling and dry milling of aerospace alloys. *Applied Thermal Engineering* 36:434–441.
[13] Dewes RC, Ng E, Chua KS, Newton PG, Aspinwall DK (1999) Temperature measurement when high speed machining hardened mould/die steel. *Journal of Materials Processing Technology* 92-93:293–301.
[14] Mantle AL, Aspinwall DK (1996) Temperature measurement and tool wear when turning gamma titanium aluminide intermetallic. *Proceedings of the 13th Conference of the Irish Manufacturing Committee (IMC-13)*, 3–4 September, Limerick, Ireland, 427–436.