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Suitable clamping method for milling of thin-walled Ti6Al4V components

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Abstract

The use of Titanium alloys is becoming more widespread in the aerospace, automotive and medical industries due to its favourable mechanical and thermal characteristics. Reducing the number of defective parts will increase the overall efficiency of the machining operation and thereby contribute to a more sustainable manufacturing process. An industry problem where a thin-walled titanium alloy aerospace component has deformed during machining has been identified. The effects of clamping methods during the machining process on the accuracy of titanium parts will be investigated through FEM analysis and experiments.

Keywords: Ti6Al4V; Milling; FEM; Clamping; Deformation

1. Introduction

Currently, the global aerospace industry is characterised by a major drive towards sustainability. This includes reduced waste, manufacturing time and cost [1]. However, this is in direct contrast with the manufacturing requirements of aerospace components. One of the main drivers in aerospace manufacturing is weight reduction as this has a significant influence on the fuel efficiency over the lifespan of the aircraft. Weight saving features such as pockets and thin walls introduce high material removal rates (and therefore waste) and long machining times. In combination with light-weight alloys such as titanium, additional machining challenges are introduced such as

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elevated tool wear rates, vibrations, high cutting temperatures, and deflection of the workpiece during machining [2].

Much research has been done to address these challenges. Innovative cutting strategies are used to reduce tool wear and extend tool life [3]. Adapted geometric designs of cutting tools reduce vibration during cutting and allow effective cooling and lubrication at the cutting interface [4]. Smart clamping systems improve support and reduce deflections during machining [5].

Although extensive progress has been made with the respective technologies on various metals, they have not thoroughly addressed the specific effect of thin walled clamping for milling titanium components. Being high-value components, the effect of defective parts on production time, cost and waste have a significant influence on the performance of the manufacturing process. Improving the manufacturing process efficiency, in terms of reduced waste from rejected parts, will lead to higher production outputs without necessarily increasing the inputs. This efficiency in production will result in a sustainable production future. In order to improve sustainability, an investigation on the effect of clamping and resulting forces on final part accuracy of a simplified, thin-walled Ti6Al4V component, shown in Figure 1, is presented in this paper.

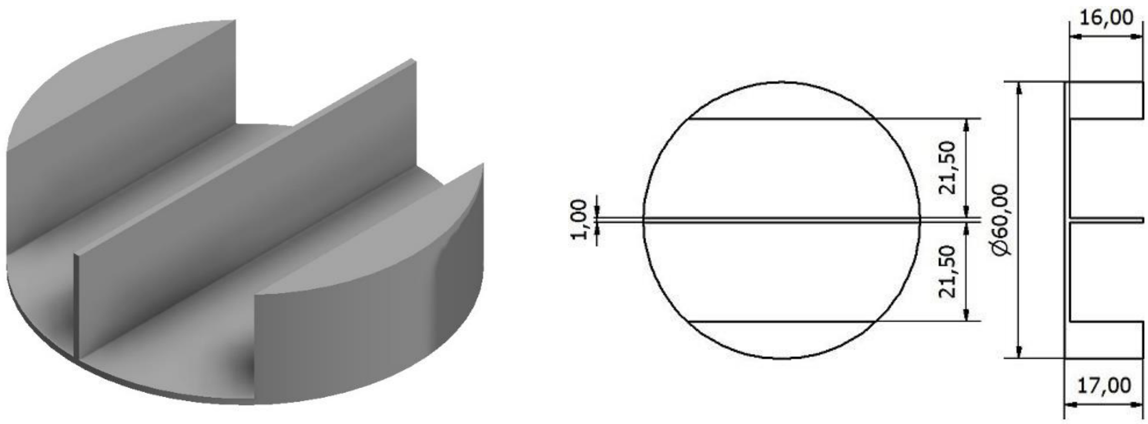

Figure 1. Thin-walled Ti6Al4V component under investigation.

1.1. Clamping challenges

Deformation during machining remains a key challenge investigated by many researchers. Doing a comprehensive literature analysis Brinksmeier and Sölter [6] summarised the major causes for geometric deviations during machining as:

- Non-uniform material removal rate resulting from static, dynamic and external process forces [7, 8]
- Thermal strains due to generation of heat during cutting process [9, 10]
- Phase transformations resulting from process temperatures and forces altering the material density [11]
- Formation of a subsurface layer of plastically deformed material, acting as a source of residual stresses [12]
- Removal of material disrupting the residual stress equilibrium through reducing cross-sectional areas of the workpiece and removing plastic deformed layers [6]

To address these, several authors have looked at the effect of clamping and its control during machining operations. Ye et al. [13] used the basis of an adaptive mechanism to design a dual-sphere fixture allowing the part to be clamped under an unstressed state and enables the release of stress at any time during machining. Wang et al. [14] investigated the use of a special fixture using low-shrinkage of low-melting-point alloy to clamp and support thin-walled parts. Recycling and re-melting of the alloy reduced additional costs associated with clamping. Meshreki et al. [15] introduced a novel concept to optimise fixturing capability by designing a model that predicts the dynamics of complex thin-walled aerospace structures under sinusoidal impact and machining loads.

Deneka et al. [16] investigated the influence of process induced temperatures and deflections for a peripheral milling process on surface error generation of thin-walled structural parts. Yang et al. [17] reported on the effect of initial residual stresses together with cutting forces and temperatures on the effect of part distortion on a thin-walled part for titanium and aluminium. Li and Melkote [18] presented a method to determine the optimum clamping forces for a multiple clamp fixture subjected to quasi-static machining forces to reduce the impact on workpiece accuracy. Li et al. [19] proposed an approach to optimise the profile and magnitude of residual stress by analysing the effects of depth of cut on the redistribution of residual stresses. De Meter et al. [20] presented the formulation and execution of a linear clamp preload (LCPL) model to determine the minimum clamping pre-loads required to keep a workpiece from slipping while not causing force induced part deviations. Lastly, several authors investigated the use of finite element analysis and the finite difference method to determine and predict possible surface deviations of thin-walled components. Comparison to experimental results has shown these analyses to be in good agreement with the actual outcomes and have therefore proven to be an effective tool for clamping/fixturing analyses [6, 21, 22].

1.2. Finite Element Analysis (FEA)

Finite element analysis allows for effective analysis of structural problems in a virtual space. In the case of planning for a fixture, this can be a helpful tool in predicting the fixture/component interface before the fixture is produced. This eliminates the need for a physical, iterative means of evaluating a suitable clamping method and therefore reduces the time, material and energy requirements associated with "trial and error" processes.

2. Research methodology

A problem with an aerospace component manufactured by an industrial partner was addressed. The problem was that a thin-walled structural component of an aircraft distorts during machining. The distortion was enough for the component to be out of tolerance. The conclusion was that the distortion can be a result of three main issues:

- Fixture and clamping of the part
- Cutting strategy used
- Cutting tools used

A new manufacturing process, which addresses these issues was designed which made it possible for the components to be manufactured within the specified tolerances.

This problem was further addressed through an investigation into the effects of varying wall thicknesses as well as cutting speeds on the part distortion. Parts from 3 mm to 1 mm wall thicknesses were machined with cutting speeds from 299 m/min to 426.7 m/min. It was found that the cutting speed had no real effects on the part distortion, but significant distortion was noticed for the 1 mm wall thickness. It was suggested that further investigations be made with the 1 mm wall thickness and further investigations into the correct fixture and clamping methods be made.

The components with 1 mm wall thickness showed signs of being deformed by the clamping method itself. Experimental parts warped as if being bent at the clamp-workpiece interface. It is unclear whether this distortion is the result of residual stresses from the machining process or the clamping method. The following question can, therefore, be asked:

Does the clamping of the 1 mm wall thickness part result in stresses on the part which exceed the yield strength of Ti6Al4V sufficiently enough to deform the part by more than the 0.3 mm as observed in the previous study?

The proposed approach for investigating this problem is illustrated in Figure 2.

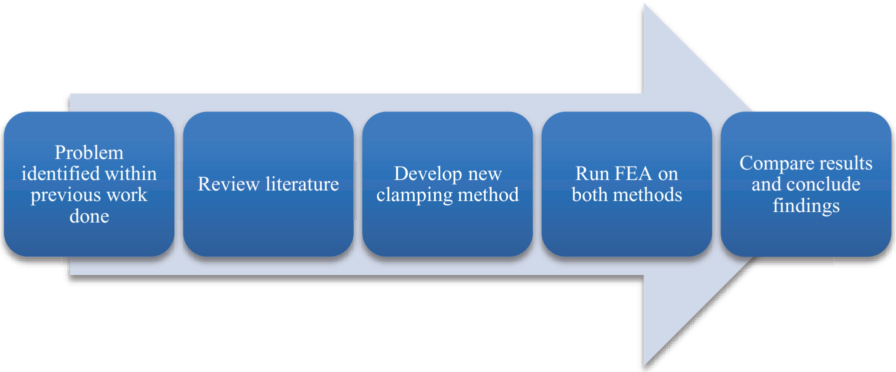

Figure 2. Research Methodology process steps

2.1. Original Clamping method

The original clamping method consisted of a two-piece step clamp method on either side of the part. This method is shown in Figure 3 (a). The interface between the triangular upright (the step block) and the clamps is a stepped surface with acute angles to prevent slipping between the two parts.

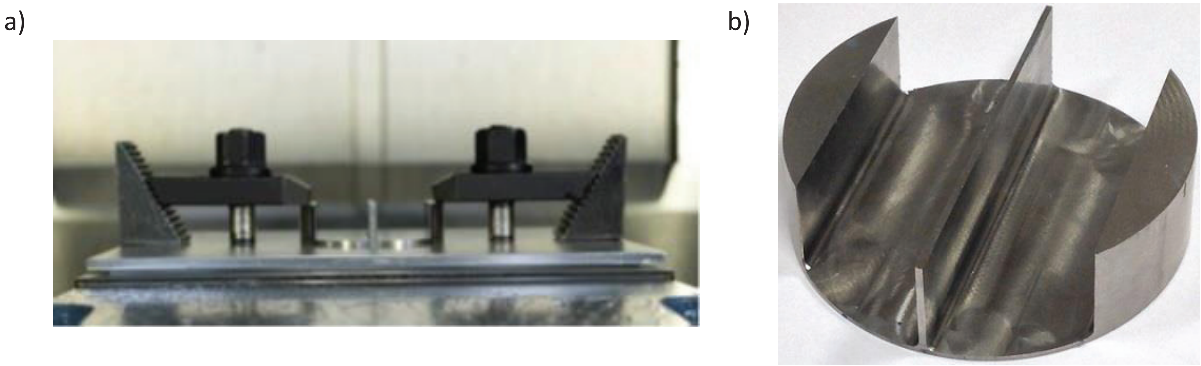

Figure 3. (a) Original method of clamping component; (b) actual thin-walled component to be produced

It can also be seen in Figure 3 that the clamp may cause a sideways force on the component if clamped too close to the edge of the component. This clamping error would be unlikely when the mounting of the workpiece is carried out by a skilled machine operator.

2.2. New Clamping method

The new fixture design consists of a one-piece clamp on either side of the workpiece as shown in Figure 4. This eliminates the possibility of slip between the triangular part and clamp completely. The clamp is also designed with a recess to fit around the workpiece. This eliminates the possibility of incorrect interfacing between the workpiece and the clamp. The possibility of the clamping error mentioned in Section 2.1 is eliminated with this fixture design.

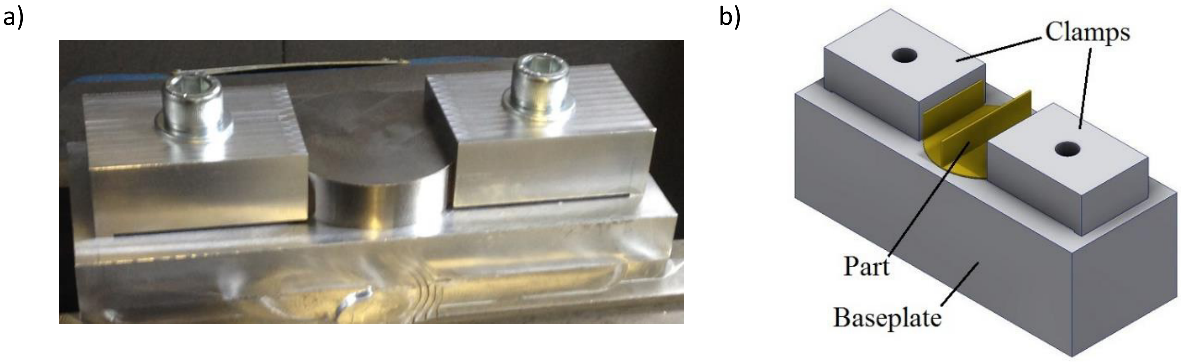

Figure 4. (a) Actual disc in new clamp; (b) CAD model of new clamp design with finished part in place

3. Experimental results

A static, structural finite element analysis using ANSYS software was conducted on both clamping methods. For all contact points between the components, the conditions were either set as bonded when no movement between components where desired, or frictional, with a frictional coefficient of 0.1, when movement in one plane was required. The tests were run with a 10 kN force in the middle of the clamps to simulate the bolt being tightened down.

3.1. Original Clamping method

The simplified model for the original clamping method with total deformation is shown in Figure 5. The interface between the clamp and triangular uprights was set as a bonded contact to simulate the hooked steps on the real part.

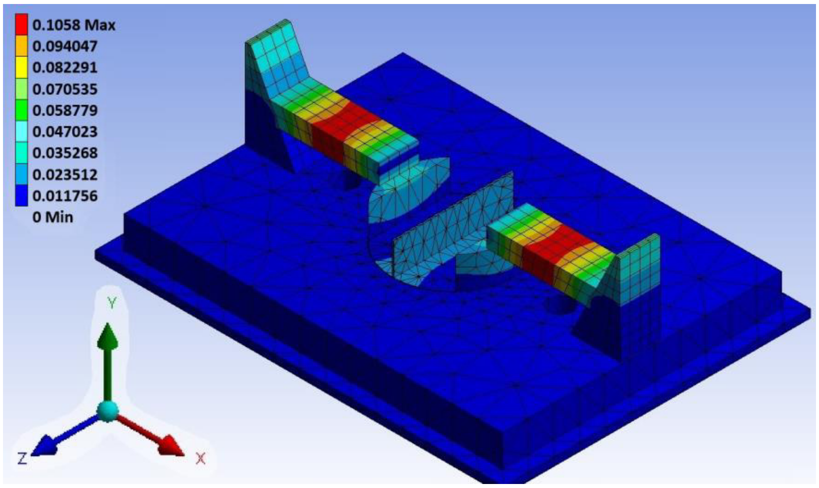

Figure 5. Total deformation for original clamping method

The results for the analysis of the original method is given in Table 1.

Table 1. Results for FEA on original method

Item	Largest Value	Location
Total deformation	0.10776 mm	Middle of clamp
Maximum principle stress	112.12 MPa	Middle of clamp
Equivalent stress	121.06 MPa	Bottom middle of clamp

The maximum for the total deformation of the workpiece itself was only 0.023 mm with a maximum principal stress of only 7.4109 MPa at that point. This is considerably less than the yield stress of Ti6Al4V. The deformation and stress from the original clamping method are therefore not enough to permanently deform the final component.

3.2. New Clamping method

The total deformation for the new clamping method is shown in Figure 6.
The key results of the analysis are given in Table 2.

Table 2. Results for the FEA of the new method

Item	Largest Value	Location
Total deformation	0.0313 mm	Middle of clamp
Maximum principle stress	30.135 MPa	Bottom middle of clamp
Equivalent stress	58.06 MPa	Outer edge of workpiece at clamp interface

The maximum value of the total deformation of the part was at the outer edge at the workpiece – clamp interface. The value was 0.0174 mm and the maximum principal stress at this point was found to be 2.856 MPa. This results in a 24.3% decrease in the total deformation of the part, as well as a 61.5% reduction in the maximum principal stresses, on the part.

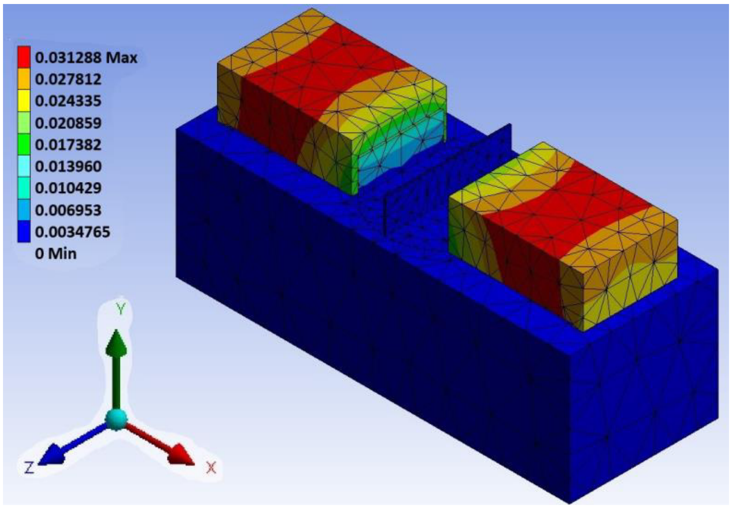

Figure 6. Total deformation of finished part method 2

4. Conclusion

Reduced part deformation leads to less scrap which greatly increases resource efficiency. Two different fixtures for machining a simplified, thin-walled Ti6Al4V component were examined using FEA. It was suspected that the original clamping method resulted in direct bending of the component. A new clamping method, which provides better support for the workpiece, was proposed and compared to the original clamping method. The new clamping method showed a reduction of total deformation of the component by 24.3% as well as a reduction in maximum principle stresses of 61.5%. The maximum principle stresses in both cases were significantly less than the yield strength of Ti6Al4V. It can thus be concluded that neither of the two methods will cause permanent bending of the component. Use of the new clamping method will reduce the chance of human error in the clamping process, which may lead to bending of the part, and is, therefore, the recommended method of clamping for future investigations.

References

[1] K. Gopalakrishnan, Y. Y. Yusuf, A. Musa, T. Abubakar and H. M. Ambursa, "Sustainable supply chain management: A case study of British Aerospace (BAe) Systems," International Journal of Production Economics, vol. 140, no. 1, pp. 193-203, 2012.

[2] G. Oosthuizen, G. Akdogan and N. Treurnicht, "The performance of PCD tools in high-speed milling of Ti6Al4V," International Journal of Advanced Manufacturing Technology, vol. 52, pp. 929-935, 2011.

[3] P. Conradie, G. Oosthuizen, D. Dimitrov and M. Saxer, "Effect of Milling Strategy and Tool Geometry on Machining Cost when Cutting Titanium Alloys," The South African Journal of Industrial Engineering, vol. 26, no. 3, pp. 137-151, 2015.

[4] R. M'Saoubi, D. Axinte, S. L. Soo, C. Nobel, H. Attia, G. Kappmeyer, S. Engin and W. M. Sim, "High performance cutting of advanced aerospace alloys and composite materials," CIRP Annals - Manufacturing Technology, vol. 64, pp. 557-580, 2015.

[5] W. Chen, L. Ni and J. Xue, "Deformation control through fixture layout design and clamping force optimization," International Journal of Advanced Manufacturing Technology, vol. 38, pp. 860-867, 2008.

[6] E. Brinksmeier and J. Sölter, "Prediction of shape deviations in machining," CIRP Annals-Manufacturing Technology, vol. 58, no. 1, pp. 507-510, 2009.

[7] B. Denkena and C. Schmidt, "Experimental Investigation and Simulation of Machining Thin-walled Workpieces," Production Engineering Research and Development, vol. 1, no. 4, pp. 343-435, 2007.

[8] E. Brinksmeier, J. Sölter and C. Grote, "Distortion Engineering—Identification of Causes for Dimensional and Form Deviations of Bearing Rings," CIRP Annals-Manufacturing Technology, vol. 56, no. 1, pp. 109-112, 2007.

[9] S. Okuyama, T. Nishihara, S. Kawamura and S. Hanasaki, "Study on the geometrical accuracy in surface grinding—Thermal deformation of workpiece in traverse grinding," International journal of the Japan Society for Precision Engineering, vol. 28, no. 4, pp. 305-310, 1994.

[10] J. Fleischer, R. Pabst and S. Kelemen, "Heat flow simulation for dry machining of power train castings," CIRP Annals-Manufacturing Technology, vol. 56, no. 1, pp. 117-122, 2007.

[11] O. Keßler, C. Prinz, T. Sackmann, L. Nowag, H. F. F. Surm, T. Lübben and H.-W. Zoch, "Experimental Study of Distortion Phenomena in Manufacturing Lines," in Proc. 1st International Conference on Distortion Engineering, Bremen, Germany, 2005.

[12] E. Brinksmeier, J. T. Cammett, W. König, P. Leskovar, J. Peters and H. K. Tönshoff, "Residual stresses—measurement and causes in machining processes," CIRP Annals-Manufacturing Technology, vol. 31, no. 2, pp. 491-510, 1982.

[13] J. H. Yu, Z. T. Chen and Z. P. Jiang, "A control process for machining distortion by using an adaptive dual-sphere fixture," The International Journal of Advanced Manufacturing Technology, pp. 1-8, 2016.

[14] T. Wang, J. Zha, Q. Jia and Y. Chen, "Application of low-melting alloy in the fixture for machining aeronautical thin-walled component," The International Journal of Advanced Manufacturing Technology, pp. 1-11, 2016.

[15] M. Meshreki, J. Kövecses, H. Attia and N. Tounsi, "Dynamics modeling and analysis of thin-walled aerospace structures for fixture design in multiaxis milling," Journal of Manufacturing Science and Engineering, vol. 130, no. 3, pp. 1-12, 2008.

[16] B. Denkena, C. Schmidt and M. Krüger, "Experimental investigation and modeling of thermal and mechanical influences on shape deviations in machining structural parts," International Journal of Machine Tools and Manufacture, vol. 50, no. 11, pp. 1015-1021, 2010.

[17] Y. Yang, M. Li and K. R. Li, "Comparison and analysis of main effect elements of machining distortion for aluminum alloy and titanium alloy aircraft monolithic component.," The International Journal of Advanced Manufacturing Technology, vol. 70, no. 9-12, pp. 1803-1811, 2014.

[18] B. &. M. S. N. Li, "Fixture clamping force optimisation and its impact on workpiece location accuracy," The International Journal of Advanced Manufacturing Technology, vol. 17, no. 2, pp. 104-113, 2001.

[19] B. Li, X. Jiang, J. Yang and S. Y. Liang, "Effects of depth of cut on the redistribution of residual stress and distortion during the milling of thin-walled part," Journal of Materials Processing Technology, vol. 216, pp. 223-233, 2015.

[20] E. De Meter, S. Choudhuri and S. Vallapuzha, "Pre-Load Model with Respect to Milling Operations," in IEEUASME International Conference on Advanced Intelligent Mechatronics Proceedings, Corno, Italy, 2001.

[21] Q. Wu, D. P. Li, L. Ren and S. Mo, "Detecting milling deformation in 7075 aluminum alloy thin-walled plates using finite difference method," The International Journal of Advanced Manufacturing Technology, pp. 1-12, 2015.

[22] S. P. Siebenaler and S. N. Melkote, "Prediction of workpiece deformation in a fixture system using the finite element method," International Journal of Machine Tools and Manufacture, vol. 46, no. 1, pp. 51-58, 2006.