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A Review on Cryogenic Machining of Super alloys Used in Aerospace Industry

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Abstract

The present work reviews the work done on cryogenic machining of super alloys around the four continents i.e. North America, Europe Asia and Australia. Cryogenic machining has emerged as one of the most effective procedure among the advanced machining techniques for machining super alloys. Along with that, the coating on the tool also plays a crucial role in cryogenic machining. It is found that, North American research focuses on cryogenic machining of innovative materials like shape memory alloys and ceramics. European research focuses on application of cryogenic as well as MQL techniques and studying the different types of wears and surface integrity. Several authors have also presented innovative nozzle geometries which increases cooling efficiency in cryogenic machining. Whereas Asian research focuses on tribological performance of cryogenic coolants using advanced manufacturing techniques like WEDM and using several types of coatings on tools. Australian Research focuses on tool wear and surface roughness of machined surface. More specifically, special attention is given to the main findings obtained over the last couple of years from the various authors collaborative research on cryogenic machining of super alloys, through the experimental investigations.

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Keywords: Super alloys; Cryogen; Cryogenic machining; Tribological behavior

1. Introduction

Aerospace industry is one of the pioneers in development of super alloys because if the jet engine is able to withstand higher temperature, it will lead to more powerful and more efficient engine [1-2]. Many problems caused during machining super alloys are due to the heat generation and the subsequent high temperatures associated with it. The heat generation is more concentrated at the tool chip interface [3]. Moreover, it intensifies because the super

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alloys have very low thermal conductivities; hence, it is necessary to reduce the temperature at the tool face in order to reduce the surface roughness in the workpiece [4]. Hence, focus has been laid on advance techniques to machine such super-alloy. Super alloys are broadly classified into four categories depending upon the major constituent present in them namely Nickel based, Titanium based, Cobalt based and Iron based (Figure1). Since the last couple of decades, a considerable research work has been done on super alloys which has resulted into process innovation for machining them. Table 1 shows the recent studies conducted on nickel alloys with cryogenic machining. Cryogenic cooling is an efficient way of maintaining the temperature at the cutting interface, well below the softening temperature of the cutting tool material [5].

In this research work, the cryogenic machining technique is studied from different points of view, namely cutting tool coating and workpiece material. The overall objective of this research is to advance the state-of-the art in cryogenic machining for the super alloys and thus complement already available limited literature. In a nutshell, this paper will review the main results of the cryogenic machining research that have been obtained in the last couple of years.

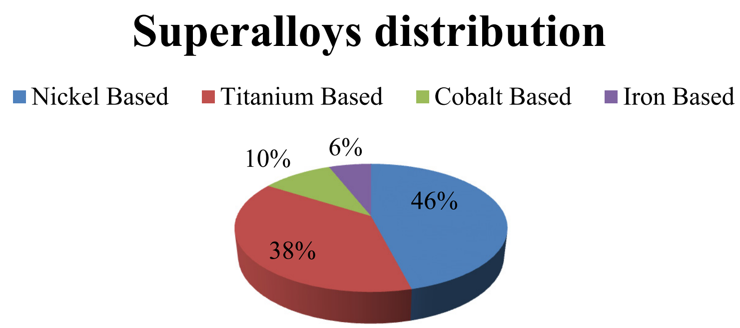

Figure 1. Distribution of types of super alloys used in present review

Table 1. Recent studies on cryogenic machining of nickel based super alloys.

Author	Tool	Operation	Workpiece	Area of study
Gangopadhyay et. al. 2016	CVD bilayer (TiCN/Al2O3) and PVD multilayer (TiAlN/TiN) coated cemented carbide tools	Turning	Nimonic C-263	Surface Roughness, Cutting Temperatures, Cutting Forces, Tool Wear, Tool life.
Kaynak 2014	Uncoated WC	Turning	Inconel 718 AMS 5663M	Cutting Force, Tool Life, Chip formation, Surface Integrity.
Courbon et. al. 2013	PVD TiN coated WC and uncoated WC	Tribological behavior	Ti-6Al-4V and Inconel 718	Heat transfer, Material transfer, friction coefficient.
Iturbe et. al. 2016	CVD coated carbide inserts	Turning	Inconel 718	Cutting forces, tool wear, surface integrity.
Kaynak et. al. 2013	PVD TiB2 coated KC5410 graded	Turning	Ni-Ti shape memory alloy	Tool Wear, Cutting Forces, Chip Thickness.
Musfirah et. al. 2015	PVD multilayer coated WC inserts	High Speed Milling	Inconel 718	Interface Temperature, Cutting Forces, and

				Surface roughness.
Fernandez et. al. 2014	PVD coated Carbide tool	Turning	Solution annealed Inconel 718	Tool wear, surface roughness.
Sun et. al. 2010	CNMX1204A2-SMH13A type tool	Turning	Ti-6Al-4V	Chip temperature, Cutting force, Chip formation.

2. Recent advances in research on cryogenic machining of super alloys

2.1. North American Research

Jawahir et. al. [6] analysed the tool-wear behavior and cutting forces in machining of Ni-Ti shape memory alloys under various machining conditions like dry, preheated, and cryogenic cooling. They concluded that cryogenic cooling plays a significant role in reducing notch wear at higher cutting speeds compared to the machining under dry and preheated conditions. They also found that, cryogenic cooling decreases the amount of cutting force required as compared with machining under dry and preheated conditions. Ulutan and Ozel [7] reviewed the machining induced surface integrity in titanium and nickel alloys. They provided experimental and empirical studies on various parameters like tool geometry, feed rate, depth of cut, cutting speed and preparation, tool wear, that affect the surface integrity. Rajurkar and Wang [8] presented a technique for machining of advanced ceramics using liquid nitrogen LN2 cooled polycrystalline cubic boron nitride tool, Inconel alloys, titanium alloys and tantalum with cemented carbide tools. They found that due to cryogenic cooling the temperature in the cutting zone is significantly reduced, therefore, the strength and hardness of the tool at elevated temperatures remains high, and the temperature-dependent tool wear reduces to a greater extent under all machining conditions. They also concluded that the surface roughness gets significantly reduced while using cryogenic coolant. Hong [9] studied how the temperature affects Ti-6Al-4V properties, and compared different cryogenic cooling strategies. Moreover, based on the findings they proposed a new economical cryogenic cooling approach using a minimum amount of liquid nitrogen (LN2), with innovative specially designed micro-nozzle. They observed that the combination of two micro-nozzles provides the best effective cooling while using the least LN2 flow rate. They stated that the performance is significantly enhanced by the position of the nozzle and chip breaker. They claimed that their cooling approach increases the tool life up to five times compared to emulsion cooling.

2.2. European Research

Klocke et. al. [10] provided an overview on current technological capabilities of abrasive machining of advanced aerospace super alloys. They suggested the use of abrasive tools having grits with cutting edges for abrasive machining of Ti-alloys. Pusavec et. al. [11] investigated effects of cryogenic cooling on machining Ti-6Al-4V and Inconel 718 using carbide tools and the lubrication capabilities of a nitrogen jet under extreme contact conditions using a tribometer. They found that both liquid nitrogen and nitrogen gas were not effective in reducing friction co-efficient and adhesion on Ti-6Al-4V, whereas liquid nitrogen shows significant reduction in friction co-efficient for machining Inconel 718. Arrazala et. al. [12] discussed practicality of replacing conventional cutting fluids by liquid nitrogen cooling combined with MQL for finishing operations in industry by carrying out turning operation on Inconel 718. They reported that the combination of cryogenic and MQL machining positively impacts the machining performance for short machining periods in comparison with dry and MQL machining, but the combination is not effective for long machining periods. Sarıkaya and Gullu [13] experimentally investigated the tool wear patterns while machining cobalt based super-alloy Haynes 25 under cryogenic cooling conditions using uncoated carbide tools. They stated that using cryogenic cooling, maximum flank wear was approximately 60% lower than tool wear values obtained from dry cutting. Using ANOVA analysis, they found that cutting speed is the most dominant parameter for cryogenic cooling. Kaynak [14] presented experimental data on force components, various tool wear parameters, cutting temperature, chip morphology, and surface roughness during cryogenic machining of Inconel 718 and compared the results with dry machining and MQL machining. He stated that cryogenic machining offers improved machining performance by providing reduced tool wear, cutting temperature, and improved surface quality results. He also found that the number of nozzles play a vital role in controlling cutting forces and power consumption in cryogenic machining of Inconel 718. Shokrani et. al. [15] reviewed issues and solutions for difficult-to-machine materials under dry, cryogenic, MQL and chilled air machining.

2.3. Asian Research

Musfirah et. al. [16] studied tribological behavior of liquid nitrogen near the cutting zone of Inconel 718 in ball end milling process. They performed experiments using a multilayer TiAlN/AlCrN-coated carbide inserts under cryogenic and dry conditions and found that implementation of cryogenic coolant can significantly decrease the amount of heat transferred to the tool and substantially improve the surface roughness when compared to dry-machining. Gangopadhyay and Thakur [17] presented review on various surface integrity properties while machining of nickel-based super alloys. They critically explained the state-of-the-art influence of various cutting parameters, cutting conditions, coating, wear and edge geometry of cutting tools on various aspects of surface geometry. Mandal et. al. [18] investigated the influence of the WEDM process parameters on cutting rate, surface roughness, spark gap, and wire wear ratio during machining of Nimonic C-263 super alloy and presented an optimized setting for it. Kumar and Ravi [19] experimentally analysed the machinability of AISI H13 hardened tool steel using LN2 as coolant and concluded that reduction in cutting temperatures is significant at lower cutting speeds. Yuan et. al. [20] investigated different cooling strategies while milling of Ti-6Al-4V alloy. They stated that the MQL technique has the most favorable effects among the strategies involved but the chip hardness also increases as the temperature is lowered. Dhananchezian and Kumar [21] studied the effect of liquid nitrogen by spraying it through the holes made in cutting tool insert to the rake surface, and the main and auxiliary flank surfaces during the turning of the Ti–6Al–4V alloy. Ghosh et. al. [22] envisaged tool wear characteristics of PVD TiN coated carbide inserts during turning of Nimonic 90-Ni based alloy and Ti-6Al-4V using minimum quantity lubrication technique. They observed that due to high chip tool contact during machining of Nimonic 90, more intense nose wears were created over cutting inserts and the notch wear was more in Nimonic 90 compared to Ti-6Al-4V due to its high strength. The high penetration abilities of Ti-6Al-4V significantly reduced flank wear and rake wear. Akhtar et. al. [23] analyzed surface roughness, micro-hardness, and residual stresses while varying the cutting parameters. They found a substantial effect of each parameter on surface integrity of GH4169/Inconel 718. They stated that carbide inserts produced better surface integrity of the finished part, whereas ceramic inserts generated very high surface tensile stresses and poor surface finish due to back striking of the adhered metal chips. Thakur and Gangopadhyay [24] evaluated the tribological properties of the tools coated with chemical vapour deposition (CVD) and physical vapour deposition (PVD) with reference to the uncoated tools while machining Incoloy 825. They found that PVD coated tools were better than the others due to the excellent tribological properties of TiAlN/TiN multilayer coating.

2.4 Australian Research

Bermingham et. al. [25] investigated the tool life and chip morphology while turning Ti-6Al-4V with constant cutting parameters and fixed coolant nozzle position using different cooling techniques. They found that high pressure water based emulsions provide marginally better tool life than cryogenic coolant. They stated that the most dominant parameter was coolant nozzle position. Goldberg et. al. [26] studied the tool wear, surface roughness and micro-structural alterations induced while machining of wrought and Selective Laser Melted (SLM) titanium alloy. They found that higher cutting speeds leads to rapid tool wear which damages the surface integrity. The main reason for poor surface integrity were deposition of chip on machined surface and increase in depth of plastic deformation of machined sub surface. Palanisamy et. al. [27] analyzed various tool wear mechanisms while using uncoated carbide cutting tools to machine Ti-6Al-4V titanium alloy under dry conditions. They stated that adhesion, diffusion, attrition and abrasion were the mechanisms responsible for cratering of rake surface of cutting tool. They described the formation of crater wear by presenting evidence of weakening of rake surface. Palanisamy et. al. [28] analyzed the effect of the application of cutting fluid at high pressure while machining titanium alloys. They also investigated the effect of coolant application pressure on the morphology of the machined chip. They observed a significant variation in the microstructure of the machined chip. Sun et. al. [29] used cryogenic compressed air while machining Ti-6Al-4V titanium alloy. They found that cryogenic machining produces thinner chips as compared to dry machining. They stated that the effect of cryogenic compressed air on the cutting force and chip formation reduces with increase in cutting speed and feed rate. Bermingham et. al. [30] characterised the tool life and wear mechanism for two uncoated carbide tools while turning Ti-6Al-4V at high speed. They observed that thermally assisted machining reduces the cutting forces. They found that the process has a damaging effect on tool life because the dominant wear mechanism associated with diffusion is worsened during thermally enhanced machining.

3. Conclusion

This paper has reviewed the use of cryogenic machining for machining super alloys used by Aerospace industry. The reviewer has attempted to classify the review with the parameter of work done in various continents in cryogenic machining of super alloys. It is evident that in majority of cases, cryogenic cooling and machining techniques have positively contributed in improving machinability of various super alloys in terms of surface integrity and tool life. Hence, cryogenic machining has emerged as one of the most effective procedure among the advanced machining techniques for machining super alloys. Along with that, the coating on the tool also plays a crucial role in cryogenic machining (Figure2).

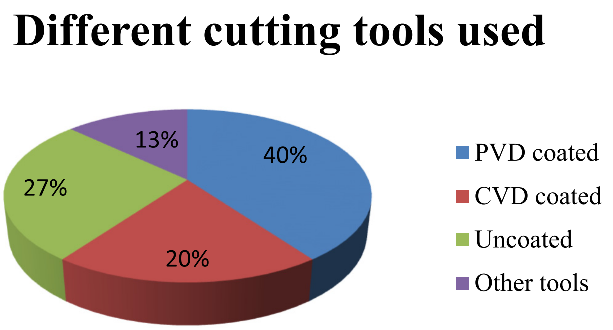

Figure 2. Distribution of type of cutting tools used in cryogenic machining of super alloys in present study

It is clear that the advancements in coating technology can improve the surface integrity and tool life. In order to get rid of surface defects, various pameters like cutting speed, tool geometry, coating materials must be properly selected. From the given study, it has been observed that North American research focuses on innovative materials like shape memory alloys and ceramics. European research focuses on application of cryogenic as well as MQL techniques and studying the different types of wears and surface integrity. Several authors have also presented innovative nozzle geometries which increases cooling efficiency in cryogenic machining. Asian research focuses on tribological performance of cryogenic coolants using advanced manufacturing techniques like WEDM and using several types of coatings on tools. Australian Research focuses mostly on tool wear and surface integrity of work piece material.

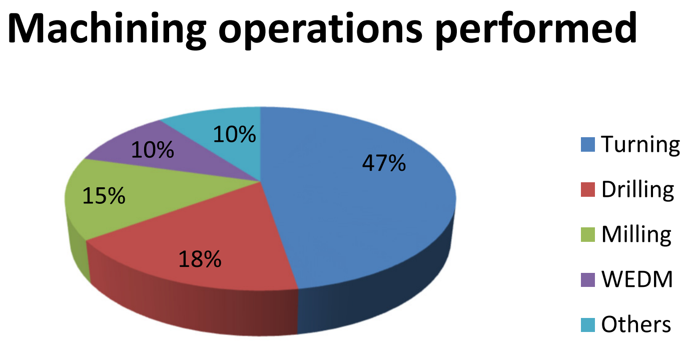

Figure 3: Distribution of machining operations performed in present study

It is apparent that most of the research, till date focuses on the turning operations only (Figure 3). Hence, a further research in cryogenic machining on operations like drilling, milling and grinding can be done using different tool geometries and coating materials. Moreover, the research done on iron based super alloys needs further enhancement and some detailed research. The use of cryogenic machining in advanced manufacturing techniques which will use innovative materials like shape memory alloys and ceramics must be critically analyzed.

References

[1] E.O. Ezugwu, "Key improvements in the machining of difficult-to-cut aerospace super alloys" International Journal of Machine Tools & Manufacture; 45; 1353–1367 (2005).
[2] I. S. Jawahir, T. Xia, Y Kaynak, C. Arvin " Cryogenic cooling-induced process performance and surface integrity in drilling CFRP composite material "-The International Journal of Advanced Manufacturing Technology; 82; 605-616 (2016).
[3] Franci Pusavec, Ashish Deshpande, Shu Yang, Rachid M' Saoubi, Janez Kopac, Oscar Wlliam Dillon, IS Jawahir, "Sustainable machining of high temperature Nickel alloy – Inconel 718: part 2 – chip breakability and optimization" Journal of Cleaner Production; 87; 941-952 (2015).
[4] YakupYildiz, Muammer Nalbant, "A review of cryogenic cooling in machining processes" International Journal of Machine Tools & Manufacture"; 48; 947–964 (2008).
[5] Patel and Ranjan," Advanced Techniques in Machining of Aerospace Super alloys: A Review"- International Journal of Advance Research in Engineering, Science &Technology (IJAREST); 2; 393-406 (2015).
[6] Y.Kaynak, H.E. Karaca, R.D. Noebe, I.S. Jawahir, "Analysis of Tool-wear and Cutting Force Components in Dry, Preheated, and Cryogenic Machining of Ni-Ti Shape Memory Alloys", 14th CIRP Conference on Modeling of Machining Operations, Procedia CIRP; 8; 498 – 503 (2013).
[7] Durul Ulutan, Tugrul Ozel," Machining induced surface integrity in titanium and nickel alloys: A review", International Journal of Machine Tools & Manufacture"; 51; 250–280 (2014).
[8] K. P. Rajurkar, Z. Y. Wang, " Cryogenic machining of hard to cut materials"- Wear; 239 ; 168–175(2000).
[9] Shane Y. Hong, Yucheng Ding, "Cooling Approaches and cutting temperatures in cryogenic machining"- International journal of machine tool and manufacture; 41; 1417-1437 (2013).
[10] Fritz Klocke , Sein Leung Soo, Bernhard Karpuschewski ,John A. Webster, DonkaNovovic , AmrElfizy , Dragos A. Axinte, Stefan,"Abrasive machining of advanced aerospace alloys and composites"- CIRP Annals - Manufacturing Technology; 64 ;581–604 (2015).
[11] C. Courbon, F. Pusavec, F. Dumont, J. Rech, J. Kopac," Tribological behaviour of Ti-6Al-4V and Inconel718 under dry and cryogenic conditions—Application to the context of machining with carbide tools"-Tribology International; 66; 72–82 (2013).
[12] A. Iturbe, E. Hormaetxe, A. Garay, P. Arrazola, "Surface Integrity Analysis when machining Inconel 718 with conventional and cryogenic cooling"- Procedia CIRP; 45; 67–70 (2016).
[13] Murat Sarıkaya and Abdulkadir Gullu," Examining of Tool Wear in Cryogenic Machining of Cobalt-Based Haynes 25
Super alloy"- International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering; 9; 8-14 (2015).
[14] Yusuf Kaynak, " Evaluation of machining performance in cryogenic machining of Inconel 718 and comparison with dry and MQL machining"- International Journal of Advanced Manufacturing Technology;72;919-933(2014).
[15] Shokrani, Alborz, Vimal Dhokia, and Stephen T. Newman. "Environmentally conscious machining of difficult-to-machine materials with regard to cutting fluids." International Journal of Machine Tools and Manufacture ;57;83-101 (2012).
[16] A. H. Musfirah, J. A. Ghani, C. H. CheHaron, M. S. Kasim," Effect of cutting parameters on cutting zone in cryogenic high speed milling of Inconel 718 alloy"- JurnalTeknologi (Science and Engineering);77;1-7 (2015).
[17] Thakur and Gangopadhyay, "State of the art in surface integrity in machining of nickel based super alloys"-International journal of machine tool and manufacturing; 100; 25-54 (2016).

[18] Amitava Mandal, Amit Dixit, Alokkumar, Niladri Mandal, "Modeling and optimization of machining Nimonic c-263 super alloy using multicut stratergy in WEDM"- Materials and Manufacturing processes; 31; 860-868 (2016).
[19] Ravi and Kumar, "Experimental investigations on cryogenic cooling by liquid nitrogen in the end milling of hardened steel"- Cryogenics; 51(9); 509-515(2011).
[20] S.M. Yuan, L.T. Yan, W.D. Liu, Q. Liu," Effects of cooling air temperature on cryogenic machining of Ti–6Al–4V alloy"- Journal of Materials Processing Technology; 211; 356-362 (2011).
[21] Dhananchezian and Kumar, "Cryogenic turning of the Ti–6Al–4V alloy with modified cutting tool inserts"- Cryogenics; 51(1); 34-40 (2011).
[22] S. Ghosh, B. C. Behra, Chetan, "Wear Behavior of PVD TiN Coated carbide inserts during machining of Nimonic 90 and Ti-6Al-4V super alloys under dry and MQl conditions"-Ceramics International;42;14873-14885 (2016).
[23] Waseem Akhtar, Jianfei Sun, WuyiChen,"Effect of Machining Parameter on Surface integrity in High speed milling of super alloy Gh4169/Inconel 718"-Materials and Manufacturing Processes;31;761-773 (2014).
[24] A. Thakur, S. Gangopadhyay," Influence of tribological properties on the performance of uncoated, CVD and PVD coated tools in machining of Incoloy 825"-Tribolical International; 102; 198-212 (2016).
[25] Bermingham M. J., et al. "A comparison of cryogenic and high pressure emulsion cooling technologies on tool life and chip morphology in Ti–6Al–4V cutting." Journal of Materials Processing Technology; 212.4; 752-765 (2012).
[26] Shunmugavel, Manikandakumar, et al. "Tool Wear and Surface Integrity Analysis of Machined Heat Treated Selective Laser Melted Ti-6Al-4V." International Journal of Materials Forming and Machining Processes (IJMFMP); 3.2; 50-63 (2016).
[27] Palanisamy et. al. " Tool wear mechanisms involved in crater formation on uncoated carbide tool when machining Ti-6Al-4V titanium alloy" - The International Journal of Advanced Manufacturing technology;83;1457-1465 (2016).
[28] Palanisamy, Suresh, Stuart D. McDonald, and Matthew S. Dargusch. "Effects of coolant pressure on chip formation while turning Ti-6Al-4V alloy." International Journal of Machine Tools and Manufacture ;49.9 ;739-743 (2009).
[29] Sun, S., M. Brandt, and M. S. Dargusch "Machining Ti–6Al–4V alloy with cryogenic compressed air cooling." International Journal of Machine Tools and Manufacture 50.11 ;933-942 (2010).
[30] Bermingham, S. Palanisamy, and M. S. Dargusch. "Understanding the tool wear mechanism during thermally assisted machining Ti-6Al-4V." International Journal of Machine Tools and Manufacture ;62; 76-87 (2012).