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Study On The Effect Of Titanium (Ti) Alloys On Machining

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Abstract: The three main pillars of sustainability are the society, the environment, and the economy (people, planet, and profit). The key drivers that sustain these three pillars are energy and resource efficiency, a clean and 'green' environment that incorporates effective waste reduction and management, and finally cost-effective production. Sustainable manufacturing implies technologies and/or techniques that target these key drivers during product manufacture. Because of the effort and costs involved in the machining of titanium and its alloys, there is significant scope for improved sustainable manufacturing of these materials. Titanium and its alloys are extensively used for specialized applications in aerospace, medical, and general industry because of their superior strength-to-weight ratio and corrosion resistance. They are, however, generally regarded as difficult-to-machine materials. This article presents an overview of previous and current work and trends as regards to sustainable machining of titanium and its alloys. This article focuses on reviewing previous work to improve the sustainable machining of titanium and its alloys with specific reference to the selection of optimum machining conditions, effect of tool materials and geometry, implementing advanced lubrication and/or cooling techniques, and employing advanced and hybrid machining strategies. The main motivation is to present an overview of the current state of the art to discuss the challenges and to suggest economic and environment-friendly ways for improving the machinability of titanium and its alloys.

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Introduction

The invited review paper to accompany this special issue, authored by Williams and Boyer [1], provides a comprehensive historical appraisal for the application of titanium alloys in engineering components, a description of the current "state of the art" and a view to the future for titanium alloys within the aerospace sector in particular. Given their considerable commercial experience in the gas turbine and airframe industries respectively, the authors are fully cognisant of the financial barriers placed on the selection of titanium alloys for engineering applications. However, this perception of titanium as a high cost material can often be countered by the excellent fatigue strength, corrosion resistance and weight saving characteristics on offer, particularly when considered for components within high-performance gas turbines and rocket engines. A wide range of titanium processing techniques are introduced within the paper, including traditional melt/cast and wrought technologies, super plastic forming and the more recent employment of powder-based additive manufacturing. The control of the two basic allotropic and phases and the subsequent classification into five major classes of conventional alloy is described before introducing the field of intermetallic titanium systems. The latter offer opportunities to replace relatively dense nickel-based components for hot section applications above 700 C; however, their relatively low ductility at room temperature is recognised as a limiting factor. In conclusion, this paper should be considered as a seminal literature review of titanium alloy development and application.

Elements of fundamental metallurgy and microstructural evolution are described for highly specialised titanium-based laser welded joints, shape memory alloys, additive manufactured parts and biomedical Ti-Ni alloys (Abdollahi et al. [2], Huang et al. [3], Panin et al. [4], Cascadan and Grandini [5], respectively). Choe et al. [6] describe grain boundary TiFe precipitation in a + alloy and the employment of isothermal aging as a mechanism for controlling subsequent strength. Reliant on high quality empirical study, all of these papers emphasise the relationship between mechanical properties, development of distinct microstructures and the role of interstitial elements. In selected cases they also serve as a reminder of the wider applications for titanium beyond the aerospace sector. Various papers specifically focus on the fundamental mechanisms controlling the "cold dwell" response of near alloys [7]. These publications are highly pertinent given the current interest around a recent in-service dwell-related failure of a Ti 6/4 fan disc [8]. The development of textured microstructures and the relationship to fatigue crack initiation via quasi-cleavage faceting is described by Germain et al. [9]. The formation of inhomogeneous microstructures through highly localised variant selection during the forging process is highlighted as a subsequent driver for stress redistribution during loading between “weak” and “strong” regions of the material. Their alloy of interest, Ti 6242, has long been noted as a “dwell sensitive” variant, with a comprehensive study documenting many aspects of cold dwell performance published by Ghosh et al. [10]. It is interesting to note that Ti 6/4, being a popular choice for fan and compressor applications since the 1960s, has developed a longstanding reputation as a dwell “insensitive” alloy. However, the recognition that “microstructurally textured regions” (MTRs) or “macrozones” can also be retained in Ti 6/4 forgings and go on to promote an associated dwell debit [11] has highlighted a need to revisit this perception. Computer modelling of such adverse microstructures is included in this special volume by Ma and Truster [12]. Based on crystal plasticity, the success of the models are (somewhat naturally) shown to be sensitive to the description of representative microstructures. Regardless, the stress redistribution process and control from crystallographic orientations relative to loading is clearly predicted. Fundamental mechanical properties under cyclic and dwell loading configurations are considered by Bache et al. [13], concentrating on low and high cycle fatigue scenarios for a novel near alloy. Ti 407 was developed for containment applications due to a high inherent ductility; however, it also serves as a model for dwell behaviour. Emphasis was placed on crack initiation and faceting mechanisms. At the opposite end of the fatigue process, the paper from Renon et al.[14] concentrates upon the damage tolerant characteristics of conventional forms of Ti 6/4 and Ti 6/4 ELI (extra low interstitial variant) subjected to various heat treatments. A comprehensive database is presented to describe constitutive behaviour and continuum fatigue crack growth. Optical fractography and 3D profilometry are used to good effect to illustrate the complex, tortuous fracture path taken by cracks generated in relatively large grained lamellar microstructural forms. Su et al. [15] also concentrated upon crack propagation behaviour, on this occasion under dwell waveforms in commercially pure titanium as a function of temperature, performing their test matrix up to 300 C. The concept of “dwell” effects under this scenario is slightly different to that described above relating to life to first crack and fatigue strength. Focusing solely on damage tolerance, i.e., Stage II or “Paris” crack growth, the imposition of dwell under these circumstances controls time dependent creep mechanisms at the crack tip together with environmental enhancement on crack growth rates through oxidation.

Figure 1.
Sustainability basic dimensions.

Problem related with conventional machining

Difficult-to-machine materials are heat resistant; therefore, in machining of such materials, huge amount of cutting tools and coolants is used. The cost of a machined part mainly involves the cost of tools used, electrical energy and coolant cost. In conventional methodology, the parts are machined using mineral-based cool ants. These coolants have disadvantages in worker's health and environment where it is disposed of. Titanium alloys and other nickel-based alloys are difficult-to machine, and therefore a number of cutting tools are wasted in their machining increasing the overall cost of the product. Conventionally used coolants have many problems associated with the health of workers and environmental impact. The problem becomes more critical when machining the difficult-to-machine materials where high temperatures are built at the tool-chip interface. Using of conventional mineral-based coolant to reduce the temperatures and frictions is creating other environmental problems because disposition of these lubricants is not only harmful for human life but also creating issues for aquatic organisms. Social impact of conventional lubricant and coolants is increasing health and safety problems of workers due to exposure to toxic chemicals. The working environments are being polluted increasing both the mist and noise levels. Industrial setups are required to adopt the sustainability principles in order to avoid increasing cost and environmental and safety issues. Alternative coolants are in exploration phase to replace with the conventional mineral-based coolants.

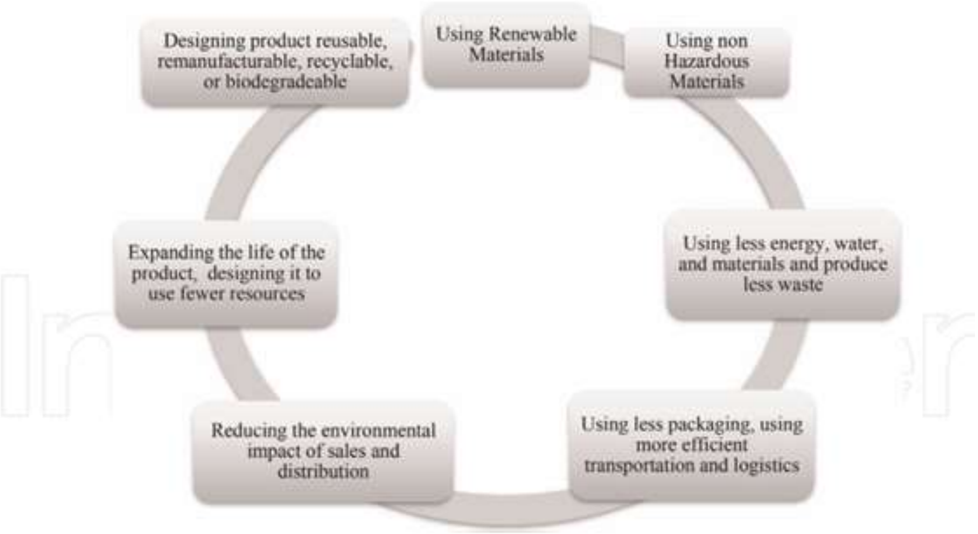

Figure 2.
Sustainable manufacturing aspects.

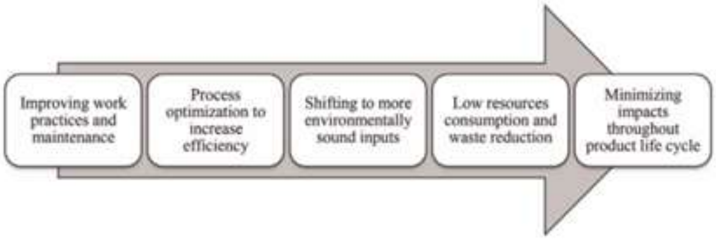

Figure 3.
Implementing sustainable manufacturing.

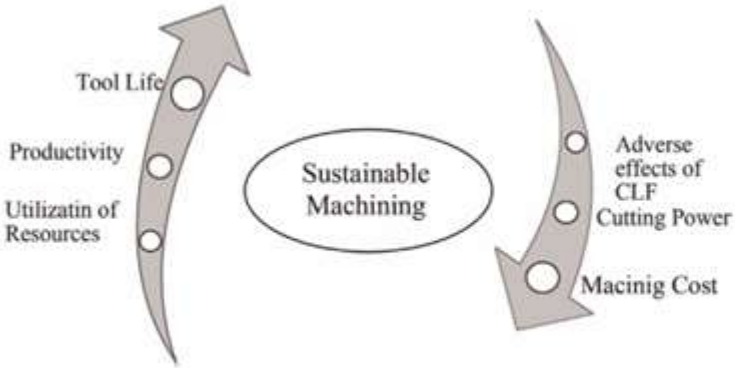

Figure 4.
Sustainable machining model.

Sustainable manufacturing

Sustainability is defined as the ability to preserve, to keep or to maintain some thing. When something is sustainable it means that it is able to be kept and contin ued [4]. The three dimensions of sustainability (Figure 1) are environmental, social and economic, sometimes adding technology as the fourth one [5]. Initially sustain able development defined by Brundtland is reported in 1987 as 'the way for improving the well-being and quality of life for the present and future generation'. More precisely it was defined as 'to meet the needs of the present without compromising the ability of future generations to meet their own needs' [6]. Manufacturing contributes by about 22% of Europe's GDP, while 70% of jobs in Europe are directly related with manufacturing [7]. Energy consumption is a major factor in manufacturing industry which is based on electrical energy and oil. According to the action plan for energy efficiency, industrial production is respon sible for about 18% of the total energy consumption of Europe [8]. Sustainable manufacturing is important for the manufacturing industry as it helps to cope with the increasing environmental regulations, meeting the customer requirements for better environmental performance, lowering the material and energy costs resulting to greener products. Sustainable manufacturing is the crea tion of products using such processes that minimize the environmental impacts, conserving natural resources and energy, are safe for the communities, employees and customers and are economically sound. It has become a business imperative as companies across the world are facing increased costs of energy and materials coupled with higher expectations of customers, communities and investors.

Cryogenic machining Cryogenic machining is much safer than the conventional lubrication and cool ants. Nitrogen gas has no hazards on life as about 79% of this already exist in air. Liquid nitrogen at cooling temperature is effective for cooling the cutting edge during machining of hard materials as cutting temperature exceeds 200°C [12]. It is a new technique of cooling the cutting zone and part during the machining at high speed and temperatures with cryogenic CLF. The coolant is nitrogen which is liquefied at 196°C and is safe, non-corrosive and non-combustible gas. This gas evaporates leaving no contaminates with part, operator, machine tool, and chips; thus disposal cost is eliminated. Mostly cryogenic CLFs are applied in the machining of superalloys. The cryogenic machining process is more beneficial and more sustainable in terms of safety, clean and environment-friendly machining. Due to minimization in changeover time, productivity also increases. Tool life is increased due to low abrasion rate and chemical wear. Improvement is observed in the surface quality without the degradation in its mechanical/chemical properties. For implementation of cryogenic machining at industrial level, investigations are required about the tool wear and tool life using cryogenic cooling [17]. Applica tion of cryogenic machining at shop-floor level will be transitioning towards the sustainable machining and will promote the development of optimization for cryo genic fluid delivery with mass flow and controlled pressure. In cryogenic machining the cryogenic fluid is directly applied on the cutting tip of the tool. This flow is manageable to be controlled against flow and pressure which makes it more economic than conventional fluids. N2 gas is used as a cooling medium in cryogenic machining and is harmless to the health. This process increases the tool life and helps in productivity improvement, surface integrity improvement, chip breakability enhancement, reduction in built-up edge and burr formation [19]. In comparison of cryogenic cooling with conventional cooling and lubrication process, it is clear that the cost of power required for pumping of cooling and lubrication fluid is eliminated. The cost of cleaning CLF from the machined part becomes zero. Alternates of cutting fluid like N2,O2 and CO2 have been used and compared to wet and dry machining and found that fine surface finish obtained with increased flow rates and pressure of gases [18]. Compressed air as coolant was used for machining of optical glass and found that low cutting forces are observed as compared with diamond drilling [19]. Experiments performed using liquid nitrogen in turning process of titanium alloy with modified tools resulted in improved tool life, surface finish and reduced.

Machining problems of difficult-to-machine materials

In machining of difficult-to-machine materials like Ti-6Al-4V, excessive tool wear and heat are produced making the surface quality poor [52]. Alternative solutions of dissipating the heat generated at chip-tool interface and cutting tool materials are in exploration since the last few years. The main reasons for rapid tool wear are building of high cutting temperatures. In machining of hard and difficult to-machine materials, the conventional CLF (oil-based) does not effectively decrease the cutting temperatures, and therefore tool life is not increased. It is due to the fact that the coolants do not access the chip-tool interface which is under high cutting temperature and vaporize close to the cutting edge. Due to this phenome non, the conventional CLF becomes ineffective for machining the materials with low thermal conductivity and high shear strength. Dry machining is not recommended at high-speed machining of difficult-to machine materials. Such materials are used in aerospace industry and are capable of bearing high operating temperature like in jet engines.

Conclusions

From the experimental results, it is concluded that cryogenic machining is recommended for Ti-6Al-4V. Results are satisfying sustainability for eco-friendly impact on the environment, reducing tooling and energy cost. Efforts can be made to switch from conventional machining to cryogenic machining which would be beneficial in reducing machining costs, health risks along with fine surface surface. The minimum value of surface finish can be obtained by the cryogenic machin ing using the coated carbide cutting tools. The cutting tool will not be damaged by cryogenic cooling ensuring both the sustainability and cost saving. Comparison of cutting power, cutting time, electricity cost, coolant cost, machine operating cost and material removal rate (Figure 7) for nearly identical response of surface finish shows that the cryogenic machining is more sustainable than others. The results of tool life describe that cutting tool will survive for longer time in cryogenic cutting conditions than dry and conventional, resulting low cost of tool for the machining processes. Similarly, the cost evaluation resulted in low machining cost for cryogenic cooling as compared to dry and conventional. Cryogenic machining is more affordable and economic as there is no cost of pumping coolant, very low cost for cutting tool inserts and labour.

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