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Energy Consideration in Machining Titanium Alloys with a Low Carbon Manufacturing Requirements: A Critical Review

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Abstract. Machining of titanium alloys poses a serious challenge for the industry, due to its tendency to work harden during the machining process, high cutting temperatures, high cutting pressures, chatter, and its reactivity with tool materials over 500°C. In conjunction with its low thermal conductivity and low modulus of elasticity, these factors impede the machinability of titanium. This work presents an overview on machining the Titanium Alloy by considering the energy involved in the manufacturing processes to have a low carbon manufacturing requirements by evaluating carbon emission in the manufacturing process plan.

1.0 Titanium Alloys

Due to the good properties of titanium alloys such as high strength to density ratio, low thermal conductivity, high heat capacity conduction and high chemical reactivity coupled with excellent corrosion resistance even at elevated temperatures make them ideal for aerospace applications. Moreover, the biocompatibility of titanium also enables its widespread use in the biomedical and food processing industries. However, the difficulty in machining titanium and its alloys along with the high cost of its extraction from ore form presents a major economic constraint. In the context of machining economics, the wear map approach is very useful in identifying the most suitable machining parameters over a feed rate–cutting velocity plane.

Titanium (Symbol Ti, melting point 1670°C, density 4.5 g/cm3) is the fourth most abundant structural metal in the earth's crust [18, 50 &56]. However, prior to the development of improved extraction techniques in the late 1940s, its economic exploitation had not been realized. Although unalloyed titanium is soft and does not exhibit a notably high strength, its alloys like Ti-6Al-4V demonstrate remarkable mechanical properties including high strength and hardness as shown in Table 1 [23].

The additional properties such as high strength and low density to its excellent corrosion resistance make titanium alloys attractive for a variety of industrial applications. These titanium-based alloys exhibit excellent properties at elevated temperatures like nickel-based alloys; they have densities tending more towards aluminium (2.8 g/cm3) than nickel (8.8 g/cm3). Also, they demonstrate good fatigue resistance that comes despite its low density, quite unlike aluminium. Usually its endurance limit is defined as 40–60% of the tensile strength [18].

Many use of titanium alloys for aircraft parts or structures and load bearing components is thus likely to increase service life of airplanes. Titanium is also resistant to attack by a wide range of challenging environments, both natural as well as chemical. It has extremely high resistance to pitting and stress corrosion cracking. This property is retained even at temperatures around 100°C for most agents, including acetic acid, hydrochloric acid, brine, and molten sulphur [24]. Its application however is limited to temperatures below 400°C, since titanium can catch fire and may cause severe damage in situations where it rubs against other metals at high temperatures.

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Industrial applications for titanium alloys include aircraft, aero-engines, biomedical devices, and components in chemical processing equipment [32]. It had been established that Alloys of Titanium are widely used in aeronautics that demands a good combination of high strength, good corrosion resistance and low mass, but the mechanical properties associated lead to challenges in machining operations, such as high process temperature as well as rapidly increasing tool wear (Polini and Turchetta, 2014).

Table 1: Properties of aerospace alloys at room temperature.

Property	Material					
	Titanium	Ti-6Al-4V	Ti-6Al-6V-2Sn	Ti-10V-2Fe-3Al	Inconel 718	Al 7075-T6
Density (g/cm3)	4.5	4.43	4.54	4.65	8.22	2.81
Hardness (HRc)	10-12 (equiv.)	30–36	38	32	38–44	~7(equiv.)
Ultimate Tensile Strength(MPa)	220	950	1050	970	1350	572
Yield Strength (MPa)	140	880	980	900	1170	503
Modulus of Elasticity (GPa)	116	113.8	110	110	200	71.7
Ductility (%)	54	14	14	9	16	11
Fracture Toughness (MPa m1/2)	70	75	60	-	96.4	20–29
Thermal conductivity (W/mK)	17	6.7	6.6	7.8	11.4	130
Max. Operating Temperature (°C)	150	315	315	315	650	-

Also, titanium alloys are used extensively around the gas turbine engines for components such as compressor blades, disks, casings, bypass ducts, engine cowlings, and exhaust shrouds [18], in their research, it was made known that structural forgings, fasteners, hot-air ducts, heat shields, and hot area skinning in the airframe were also made from titanium based materials. Titanium is also suitable for marine applications owing to its corrosion resistance. Furthermore, titanium is also used for biomedical applications such as replacement for diseased bone and cartilage. [19] had made known that titanium metal exhibit allotropic transformation from α phase, characterized by a close packed hexagonal structure, to the body centered β phase, in their research, they characterized the alloying elements as α-stabilizers and β-stabilizers, which respectively raise and reduce the transformation temperature. [33] estimated the use of Ti-6Al-4V alloy to be 60% of all titanium-based alloys in the industry.

2.1 Sustainability in Manufacturing

The three pillars of sustainability have been defined by the United Nations World Commission on Environment and Development as economy, environment and social sustainability [36]. It is very important to strike a synergy among the sustainability pillars as shown in Figure 1 [36]. A forecast on environmental sustainability in manufacturing was used as a view to ensure that products are designed for their whole life cycle i.e. production, distribution, usage and disposal with acceptable influence on the environment [2].

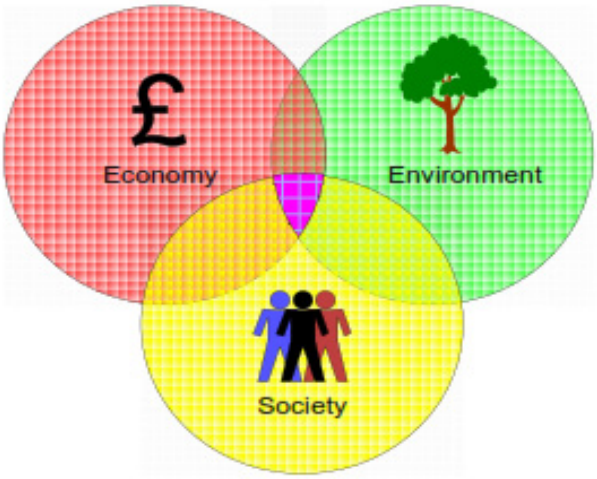


Figure 1: Sustainability Pillars.

The increase in the world population creates demand for manufactured products. The question that arose is how industries can cope with this demand and at the same time supporting environmental sustainable manufacturing. One of the answers lies on the efficient use of energy consumption in the manufacturing process. Energy consumption during manufacturing operations is one of the key parameters that play an important role towards environmental burden.

The link between manufacturing and its operations to the natural environment is gradually becoming recognized. Progress, profitability, productivity and environmental stewardship are now seen as needing consideration by manufacturing organizations [38] & [40]. Improving environmental stewardship and sustainability, while maintaining profitability and productivity, are increasingly viewed as strategic goals of manufacturing companies.

It is very important to study the relationship among sustainability pillars very well. For instance, health problems affect worker productivity and health insurance costs, and poor water quality prior to use in a process that requires clean water necessitates the extra expense and reduced profits associated with water treatment. Many traditional indicators are not holistic, like gross domestic product (GDP), which measures the amount of money being spent in a country. GDP is generally regarded as a measure of a country's economic well-being, under the presumption that the more money spent, the higher the GDP and the better the economic well-being, although this indicator reflects only the amount of economic activity, regardless of how that activity affects the community social and environmental welfare [38] & [40]. [38] & [40] established that the effective indicators for sustainability and other purposes must have the following common characteristics:

- Reliability: Provision of a good trustworthy information
- Relevance: Relevant and necessary information about a system or process
- Understandability: The experts and the non-experts must have adequate knowledge and understanding
- Accessibility and availability of data.

The relations among the social, environmental and economic parts of sustainability and some of the factors that comprise them were further discussed in the Figure 2 [38] & [40].

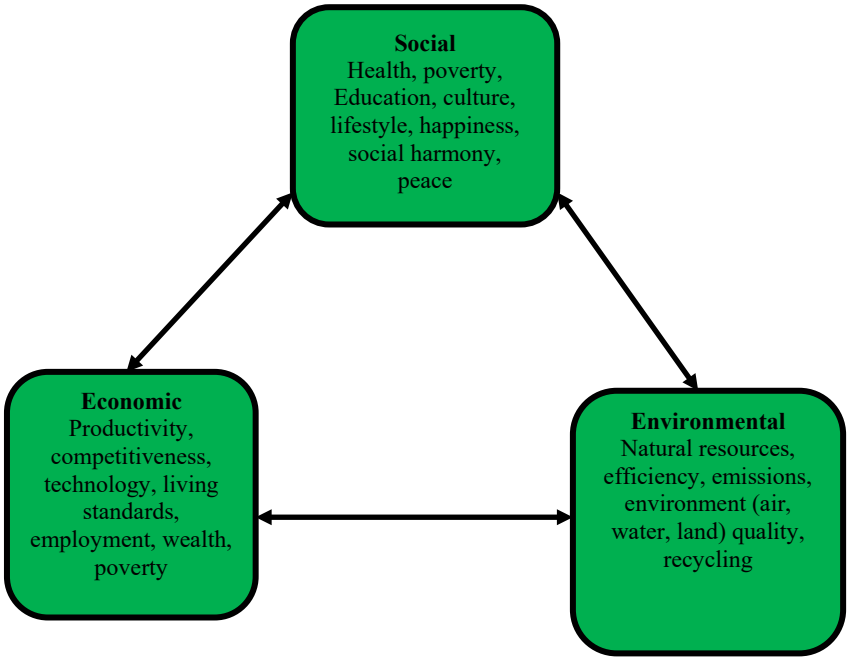


Figure 2: The Relations among social, environmental and economic parts of sustainability, and some of the factors that comprise them.

[38] highlighted the importance of integrating sustainability with manufacturing and design along with the need to utilize appropriate tools, like design for environment and life cycle assessment. They suggested that sustainability culture within companies and sustainability focus should be adopted by the manufacturing decision makers to enhance the design and manufacturing sustainability. The environmental stewardship and sustainability must be improved for advancing manufacturing operations and technologies in the future for the possibility of competitiveness, profitability and productivity. The main contributors to sustainable manufacturing are highlighted in the Figure 3 [38].

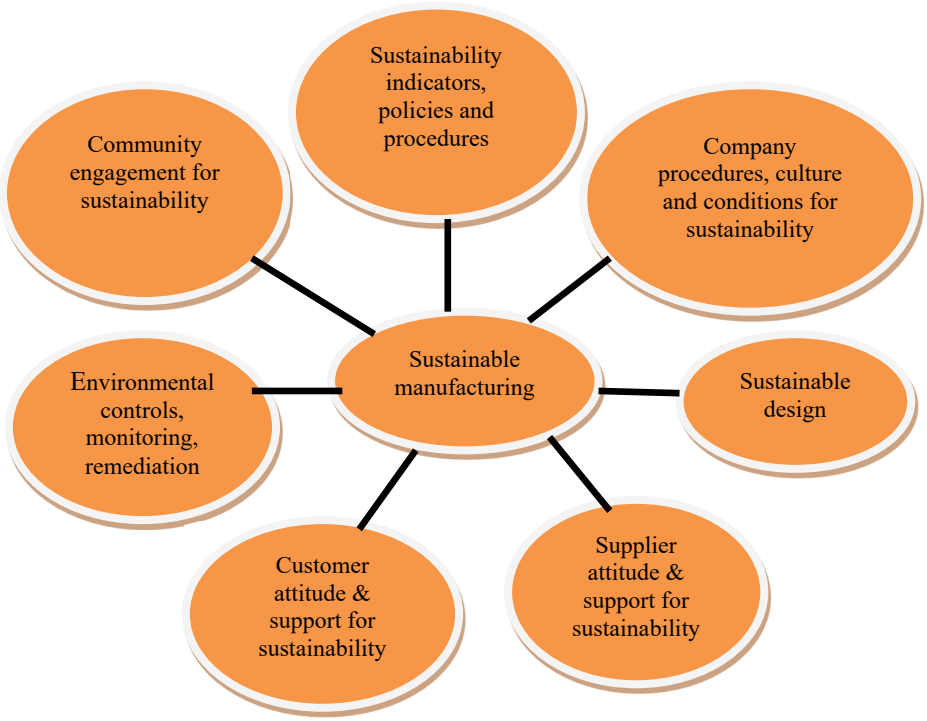


Figure 3: Key contributors to sustainable manufacturing.

2.2 Energy Consume

Environment is substantially stressed because of significant amounts of energy consumed by the manufacturing [16]. The increase in demand for electrical energy consumption has a significant impact on the energy costs [3] & [29]. Due to the soaring energy price and growing production demands, the energy cost of manufacturers increases considerably, thereby motivating a growing emphasis on the energy efficiency of machine tools. Also, the drive-in energy generation by energy consumption demand resulted to substantial part of carbon dioxide emissions and climate change [29] & [37]. Therefore, there is a need to minimize the energy consumption of manufacturing processes as to reduce the cost of the production and improve the environmental performance.

It had been discussed by many researchers that an accurate energy consumption model could improve the energy forecasting in the use phase of machine tools or in early design stages of a particular product, and that makes it possible to select the most energy efficient option. They established that the energy consumption model is useful for companies wanting to establish energy labelling of machine tools and products. [1] & [29] described a method for life cycle inventory analysis of production processes using theoretic equations to estimate the energy and resource consumption as well as waste and process emissions. [14] & [29] used a modelling framework for tool machine energy consumption forecasting based on a statistical discrete event formulation. The total energy for a machined product by the turning process was modelled and optimised to derive an economic tool-life that satisfies the minimum energy footprint requirement [29] & [36]. They evaluated the energy in single pass turning operation from the energy consumed by the machine during setup and cutting operations while implementing a tool change and the energy embodied in the process to produce a cutting tool. A web-based tool was created to estimate the energy consumption of machine tools, which is based on the relationship between machining time and energy consumption [13] & [29].

2.3 Carbon Emission

There is a strong view that the level of Green House Gases (GHG) in the atmosphere partly resulting from industrial processes is rising. Energy consumption by industries is one of the dominant factors contributing to the increase in the GHG. There is a need for the optimization of energy requirements for a given machining operation so that, the production cost and carbon dioxide (CO2) emissions can be reduced. Considering that carbon emissions are directly related to energy production, some eminent works modelling and analysing energy consumption of manufacturing processes have been done by many researchers. It was pointed out that an effectiveness approach might change the process chain entirely and causes a dramatically smaller amount of the energy consumption and carbon emission generation [17]. To evaluate and analyse the carbon emission of manufacturing process plans, a method was established to aggregate the unit process to form a combined model and then quantifies the amount of carbon emissions from individual processes [51].

2.4 Aluminium Alloys

The use of materials with low specific weight is an effective way of reducing the weight of structures. Aluminium alloys are among the most commonly used lightweight metallic materials as they offer many different interesting mechanical and thermal properties. In addition, they are relatively easy to shape metals, especially in material removal processes, such as machining. In fact, aluminium alloys as a class are considered as the family of materials offering the highest levels of machinability, as compared to other families of lightweight metals such as titanium and magnesium alloys. This machinability quantifies the machining performance, and may be defined for a specific application by various criteria, such as tool life, surface finish, chip evacuation, material removal rate and machine-tool power. It has been shown that chemical composition, structural defects and alloying elements significantly influence machinability [44].

2.5 Surface Finishing

The surface finish of a mechanical part plays an important role as it determines the part's field performance. The machining parameters and conditions governing the part surface finish also impact on the other machining process performance indicators such as tool wear, tool life, cycle time, machining cost, and undesirable emissions of aerosols and metallic particles. In today's metal cutting industry, a major concern is the occupational safety and health hazard associated with cutting fluids usage and metallic particle emission. It is therefore necessary to determine machining conditions that could improve the part surface finish while maintaining low the aerosol emission [29].

[25] described the surface roughness and surface finish as quantitative parameters that are opposite to each other. Surface roughness can be expressed in units of length after its measurement. Measurement of finely spaced deviations of actual surface from nominal surface (datum) in the units of length (μm) is the measurement of surface roughness. Lesser the value of surface roughness better the surface finish is said. There are two popular methods of expressing measured value of surface roughness.

2.6 Machining of Titanium Alloys

Machining of titanium alloys had been reported as a serious challenge for the industry, due to its tendency to work harden during the machining process, high cutting temperatures, high cutting pressures, chatter, and its reactivity with tool materials over 500°C [19]. Almost all titanium alloys are regarded as difficult alloys to cut due to their low thermal-conductivity and high chemical activity which can lead to low surface integrity, high temperature, and fast tool wear in their machining process [10], [31] & [52.

The literature review showed that many researchers had done a lot work to reveal their cutting mechanisms and enhance their machinability and efficiency [43] & [47]. Ti6Al4V has been the most common titanium alloy material in the aviation fields, but it posed a very complicated machining process with high-strain, high-temperature, and high-strain ratio. [39] & [55] conducted to study material removal mechanisms of Ti6Al4V. And milling is a complex process widely used in machining of Ti6Al4V. The milling process of titanium was experimentally investigated by [28] & [46].

To solve the problem imposed in machining titanium alloy material, the Finite Element Method was introduced to draw more and more attention; it is a powerful tool to study the complex milling mechanisms [45], [53] & [54]. Further studies on milling simulation and experiments were also carried out by introducing two milling processes under up-milling and down-milling simulated by an orthogonal cutting finite element model [52].

3.1 High Speed Machining of Titanium Alloys and Cutting Innovations

High Speed Machining (HSM) is usually associated with the Computer Numeric Controlled (CNC) Machine Tools. This machining process is an idea by taking small depths of cut and chip loads at high feed rates and cutting velocities so that, the small chip loads and high cutting velocities are expected to promote lower surface roughness. The high-speed machining process provides high metal removal rates, improved surface finish, and reduced cutting forces [20] & [24].

The guidelines for operation at high speed machining were produced, which suggested the limit or level for the high cutting speeds typical of HSM operation for aluminium or steel alloys as shown in the Figure 4 [24] & [42].

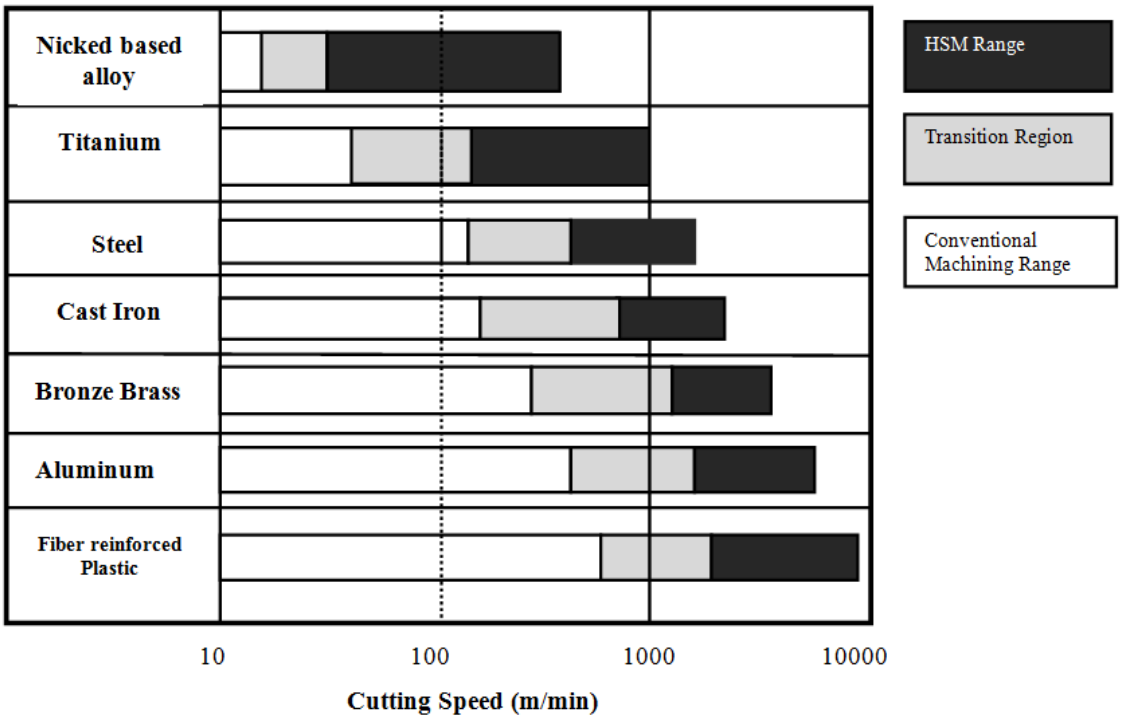


Figure 4: Cutting speed ranges for machining of various materials.

The current upper limit for HSM of titanium alloys is limited by rapid tool wear. In the industry, higher material removal rate for titanium alloys is achieved by using higher feed rates and depths of cut, as well as copious amounts of cutting fluids. This strategy is adopted since tool wear is most sensitive to increase in cutting speed as compared to feed or depth of cut. In machining operations, the use of coolants cannot be overlooked, for the optimum performance and efficiency of the cutting tools and effective cooling of the cutting zone, coolant must be used as to suppress thermally induced wear modes. There is always being an improvement in the performance of the tool and good surface finish of the workpiece when the coolant is used.

In machining titanium alloys, the use of rotary tools is also important. Rotary tools were described as tools in the form of a disk that rotate about its axis, whereby a fresh cutting edge is available at the cutting area thus reducing heat concentration at the cutting edge, it was described as a promising option for machining aerospace alloys [24] & [27]. Also, coolants must be used especially while machining titanium alloys in the range of 60–120 m/min as to reduce the tool wear. The six different lubrication techniques recommended for the cooling were; Flood Cooling, Dry Machining, Vegetable Oil MQL Machining, Cooled Air Lubrication, Cryogenic Machining (with liquid Nitrogen), Vegetable Oil + Cooled Air / MQCL machining [11]

3.2 Tooling and Cutting Conditions

Previously, the determination of wear rate for the machining of Ti-6Al-4V alloy was based on average flank wear or crater wear depending on which of these two wear mechanisms determine the end of tool life. For most machining operations, flank wear is usually considered because it affects component accuracy, surface finish, and integrity and is usually dominant in industrial machining. However, this approach was not suitable because it does not consider the amount of material removed or the material removal rate [24].

A new approach was introduced which normalized the effect by taking a ratio of the flank wear (length amount of material removed on the flank) and then divide it by the actual length of pass for material removed [24]. They assumed that the width of the flank wear land will be the same as the width of the cut pass length. The wear rate parameter R was calculated by taking the logarithm of the ratio of the flank wear land (VB) to the actual length of cut ls (spiral length in turning) as shown in the equation (1)

$$R = \log\left[\frac{VB}{l_s}\right] \quad = \quad \left[\frac{VB}{1000tV_c}\right] \tag{1}$$

Where:

The actual cutting time t (in minutes) in turning or the duration of active tool engagement can be expressed as

$$t = \frac{\pi Dl}{10000fV_c} \tag{2}$$

Where:

VB = the flank wear (mm)
D = the workpiece diameter (mm)
l = linear length (mm)
ls = spiral length of cut (mm)
f = feed rate (mm/rev),
Vc = cutting speed (m/min.)

In actual practice, since the cutting tool is designed to be harder than the workpiece, the wear rate parameter R is expected to be negative. Hence, a higher negative numerical value of R depicts lower flank wear and therefore better tool performance. The authenticity of wear rate parameter R approach was confirmed to be accurate with experimental results from previous researchers [24].

However, ability to choose an appropriate carbide tools in turning Ti-6Al-4V alloy plays important role in preventing the increase in tool wear that usually occurs at higher federates. It was reported that selecting inappropriate carbide tools in turning Ti-6Al-4V alloy, will cause increasing the feed rate thereby, leading to increasing in wear rate R [23]. It was noted that most of the researchers utilize K20 carbide tools instead of K10 due reduction in wear performance for K20 carbide tools [24].

The summary of the wear performance for K20 carbide tools under different coolant/lubrication and cutting variables is shown in Table 2 [24] & [48]. The effect of cooling and lubrication has long been of immense interest among researchers investigating the machining of titanium alloys. The Table 2 shows the comparison of tool wear rate under dry, wet, and cryogenic conditions. There is an improvement in performance, with the tool demonstrating best performance under cryogenic cooling, this was confirmed where liquid nitrogen was used as the coolant under cryogenic cooling, the growth of flank wear was effectively reduced [24] & [48].

However, [48] confirmed that at higher cutting speeds, this phenomenon was not as dominant and this could be attributed to ineffective fluid penetration into the tool–chip interface.

In machining materials, the selection of carbide grades influences wear performance [24], different carbide grades (883 and 999) with identical geometry as shown in the Table 3 [24]. The results showed that selection of carbide grades influences wear performance. Innovative tools like self-propelled rotary tools are also worth consideration as evident from results given in the same table where self-propelled rotary tools revealed significant improvement in tool life. It was reported that inherent geometry of such tools may render them unsuitable for intricate features. Nevertheless, these tools may provide a breakthrough in simple high speed machining operations like straight turning and face milling [24].

3.3 Energy Efficiency at Process Level

[4, 15 & 16] indicated that the percentage of energy spent at the process itself is typically a small percentage of the total energy spent; they made the following findings from the study of the processes:

- The study of the processes provides the deeper possible understanding of the energy transformations that take place during the manufacturing process.
- Simple analytical models that lead to qualitative and quantitative results, adaptable to wide range of applications may be applied.

- Although the energy spent at the process level is minor, an appropriate selection of process parameters may also alter the consumption of machine peripherals that correspond to larger percentage of energy consumption. An example is that of the dependence of the consumption of a cooling unit on the processing speed.
- Processing time is a function of the process parameters. Thus, the selection of appropriate process parameters has consequences for both the machine peripherals consumptions (machine level) and the production planning (line and factory levels).
- Non-conventional processes, allowing space for significant energy gains at process level, have not been adequately studied.

They found out that a complete analysis that will address the problem of energy efficiency maximization requires process modeling that will describe the energy consumption at process level as function of the process parameters, and other aspects of the process, such as the processing time.

3.3.1. Conventional processes

Material removing processes are an important class of manufacturing processes for several industrial sectors that require high accuracy and flexibility in processing different kinds of materials [4 & 9]. They presented turning and milling processes as case study, the energy efficiency for material removal processes was defined as the ratio of the volume of the removed material to the energy spent.

$$Eef_p = \frac{V_{removed}}{E_{spent}} \tag{3}$$

Index p is the process level.

With relationship between the cutting forces with chip thickness and length, the consumed power and the material removal rate are related to the process parameters, resulting in the energy efficiency equation indicated in the equation 4 [4 & 41].

$$\mathbf{Eef} = \frac{\pi(\mathbf{d.a}-\mathbf{a^2})\mathbf{S}}{\mathbf{b}\left\{\mathbf{k_p h_e}^{1-\mathbf{m_p}}\frac{\mathbf{S}}{\mathbf{u_c}}+\mathbf{k_c h_c}^{1-\mathbf{m_c}}+\mu_\mathbf{k}\mathbf{k_n h_e}^{1-\mathbf{m_n}}\right\}\mathbf{u_c}} \tag{4}$$

Where:

kp	=	specific machining pressures of the passive force
kc	=	specific machining pressures of the cutting force
kn	=	specific machining pressures of the normal force
mp	=	Kienzle constants of the passive force
mc	=	Kienzle constants of the cutting force
mn	=	Kienzle constants of the normal force
uc	=	the cutting speed and the coefficient of kinetic friction,
S	=	the feed rate velocity, b is the chip length,
h	=	the chip thickness
a	=	the depth of cut
d	=	the starting piece diameter.

The energy efficiency versus the feed rate velocity for some typical values of the material and the process parameters were illustrated in the Figure 5 [4]. The illustration served as evidence that the faster the process, the more energy efficient would be. This is a general trend that appears in several conventional processes.

Table 2: Summary for tooling, cutting parameters, and wear rates for K20 tools.

Reference	Cutting Tool	Process	V [cm/min]	f [mm/rev]	a_p [mm]	Wear Rate $\log\left[\frac{VB}{1000tV_c}\right]$
[23]	RCHT 12T3MO-KL K20	Wet turning	120 120	0.25 0.4	0.25 0.25	-7.14[a] -6.82[a]
[23]	SNMG 120408-23 K20		60 60	0.3 0.4	2 2	-6.89[a] -6.60[a]
[23]	CNMG 120408–23 K20 RCHT 1204M0-KL K20		60 60 60	0.3 0.3 0.4	2 2 2	-6.33[a] -7.44 -6.68
[48]	SNMA 120408 K20	Dry turning Wet turning Cryogenic turning	70 70 70	0.2 0.2 0.2	2 2 2	-6.09 -6.44 -6.67
	SNMA 120408 K20	Dry turning Wet turning Cryogenic turning	70 70 70	0.2 0.2 0.2	2 2 2	-5.84[b] -6.32[b] -6.59[b]
	SNMA 120408 K20	Dry turning Wet turning Cryogenic turning	100 100 100	0.2 0.2 0.2	2 2 2	-5.98 -6.05 -6.25
	SNMA 120408 K20	Dry turning Wet turning Cryogenic turning	100 100 100	0.2 0.2 0.2	2 2 2	-5.81[b] -6.00[b] -6.10[b]
	SNMA 120408 K20	Dry turning Wet turning Cryogenic turning	117 117 117	0.2 0.2 0.2	2 2 2	-5.75 -5.81 6.07
	SNMA 120408 K20	Dry turning Wet turning Cryogenic turning	117 117 117	0.2 0.2 0.2	2 2 2	-5.66[b] -5.60[b] -5.79[b]

Where:
a = average value based on data provided in the publication
b = based on maximum tool wear criterion

Table 3: Summary for tooling, cutting parameters and wear rates for other carbides.

Reference	Cutting Tool	Process	V [cm/min]	f [mm/rev]	a_p [mm]	Wear Rate $\log\left[\frac{VB}{1000tV_c}\right]$
[6]	CNMG 432-MR4 grade 883, uncoated carbide.	Dry turning	0.15	61	0.76	-7.22
	CNMG 432-MR4 grade 883, uncoated carbide	Dry turning	0.15	61	1.27	-6.70
[20]	Carboloy Tool SNG432 grade 883 (cl. angle 5°)	Wet turning	0.23	91.44	1.52	-4.81
	Carboloy tool SNG432 grade 999 (cl. angle 5°)	Wet turning	0.23	91.44	1.52	-5.83
	Carboloy tool SNG432 grade 999 (cl. angle 17°)	Wet turning	0.23	91.44	1.52	-6.01
[49]	Carboloy 883 SNG 433F	Dry turning	0.23	91.44	2.54	-5.86
[27]	Fixed tool (uncoated carbide)	Turning	0.3	105	0.2	-6.22
	Self-propelled rotary tool (uncoated carbide)	Turning	0.3	105	0.2	-6.80

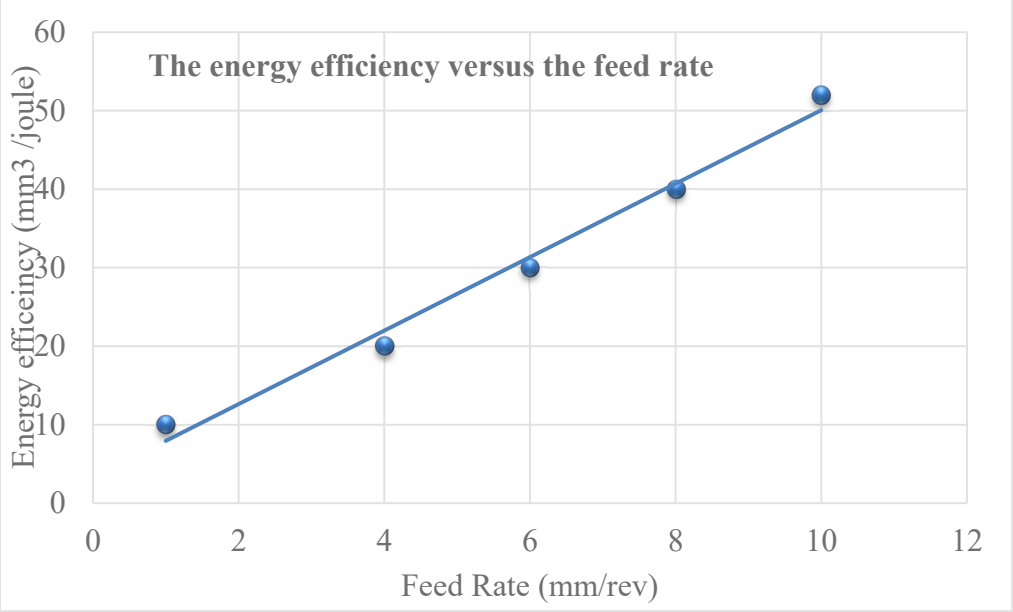


Figure 5: Energy efficiency as function of the feed rate.

3.3.2. Non-conventional processes

Due to the many applications of Lasers in manufacturing processes (such as cutting, welding etc.), energy efficiency for laser processes is considered as a typical example of non-conventional processes [4 & 8].. They adapted energy efficiency definition for laser drilling as a manufacturing process.

$$Eef_p = \frac{d_{hole}}{Espent} \quad (5)$$

Where:

*d*hole = the depth of the drilled hole (hole with specific depth).

When considering the case of laser welding, it is critical to decide whether the numerator of the energy efficiency definition should be the volume or the depth of the melt pool of metal, thus, the definition of energy efficiency, at process level, is often process dependent [4 & 8].
The reported that at process level, there are energy losses due to physical mechanisms related to the nature of the process. The energy loss at this manufacturing level is due to the following factors such as;

- Material reflectivity
- Laser beam defocusing
- Heat Conduction.

All these factors allow only a small percentage (of the order of 1%) of the laser beam energy to be converted into useful form e.g. latent heat of fusion in the case of drilling [4].

3.3.3. Energy consumption at machine level

The actual consumed energy required for machining processes is much exceeded by the energy demand of the related peripheral equipment that perform the auxiliary processes, such as coolant pumps, lubrication supply and technical air ventilation, not mentioning the indirect energy drawn by technical building services namely heating, air conditioning or air suction [21]. The studies revealed that less than 13% of energy expenditures have been utilized for productive operations, and all operating states of a given process vary in their mean power demand, timing and therefore also in their energy amounts [4 & 12].

Energy management was used to define the sum of all processes and measures to ensure minimal energy consumption by a given demand, including the implementation of organization, information structure, and tools [4 & 26]. The operations and possible improvement measures must be usually implemented at the single process level by integrating the calculation of energy efficiency into the bottom layer and then transfer to the upper levels throughout the IT systems [30]. The definition of energy efficiency at machine level is given in the equation 6 [4].

$$Eef_m = \frac{E_{provided\ to\ the\ process}}{E_{consumed\ by\ machine}} \quad (6)$$

Index m = the machine.

The overview of the energy consumption for the examined laser machine is displayed in the Figure 6 [4 & 5], the maximum energy requirement for the actual machining is only 5.7% of the total

3.4 Calculating Carbon Emission in Production Systems

The quantitative analysis of the carbon emission in manufacturing process plans is presented here. The unit process is aggregated to form a combined model and then quantifies the amount of carbon emissions from individual processes. The permits identification of opportunities is formed by this model to reduce the carbon emissions at the unit process level and driving the whole process towards low carbon emission based on an examination of the aggregated manufacturing process level mode. A manufacturing process plan of an axis production is presented to demonstrate how to apply the carbon emissions calculation method.

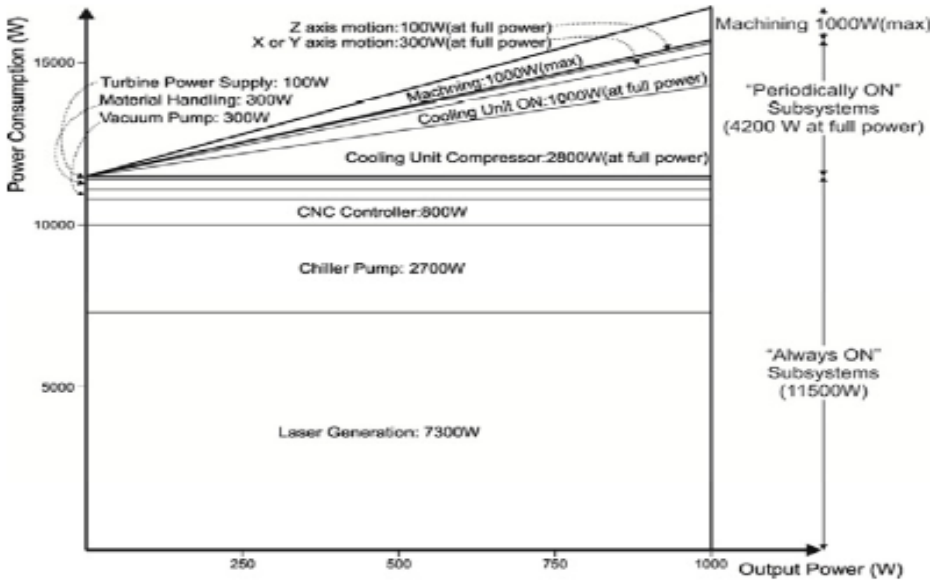


Figure 6: Energy used as a function of material removal rate for a laser machine.

3.4.1 Carbon emission model of manufacturing process plans

The manufacturing process plan is the combination of diverse production processes (each process with its own attribute) and operations to turn the input resources into consumer products. The basic elements of process include the input/output resource and energy, resource and energy flow inside, intermediate products and auxiliary resource and energy, emissions, waste, production equipment, and the manufacturing environment in which the process is carried out [7 & 51]. A basic process model is illustrated in the Figure 7 [51].

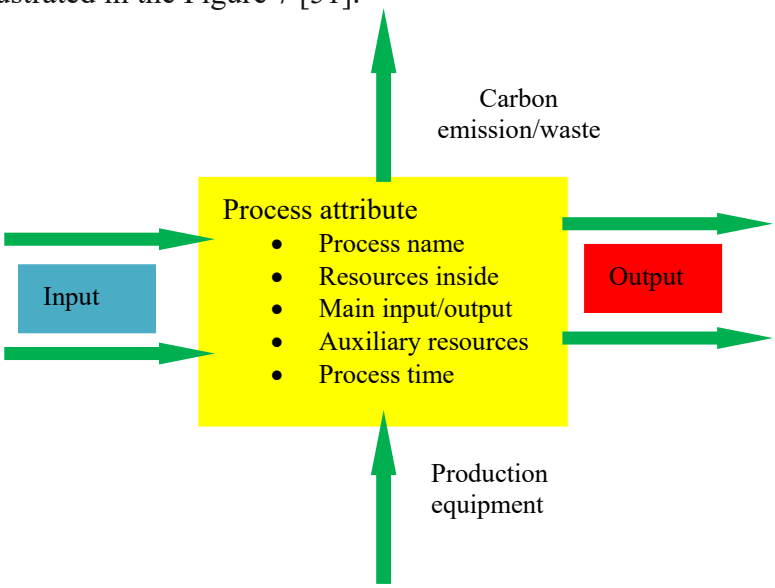


Figure 7: Basic process model.

During the transformation of material and energy flows into the products or semi-products through operations and manufacturing processes, there is carbon emissions associated [35]. A framework for carbon emission analysis is presented in the Figure 8 to account for the causes of carbon emissions [51].

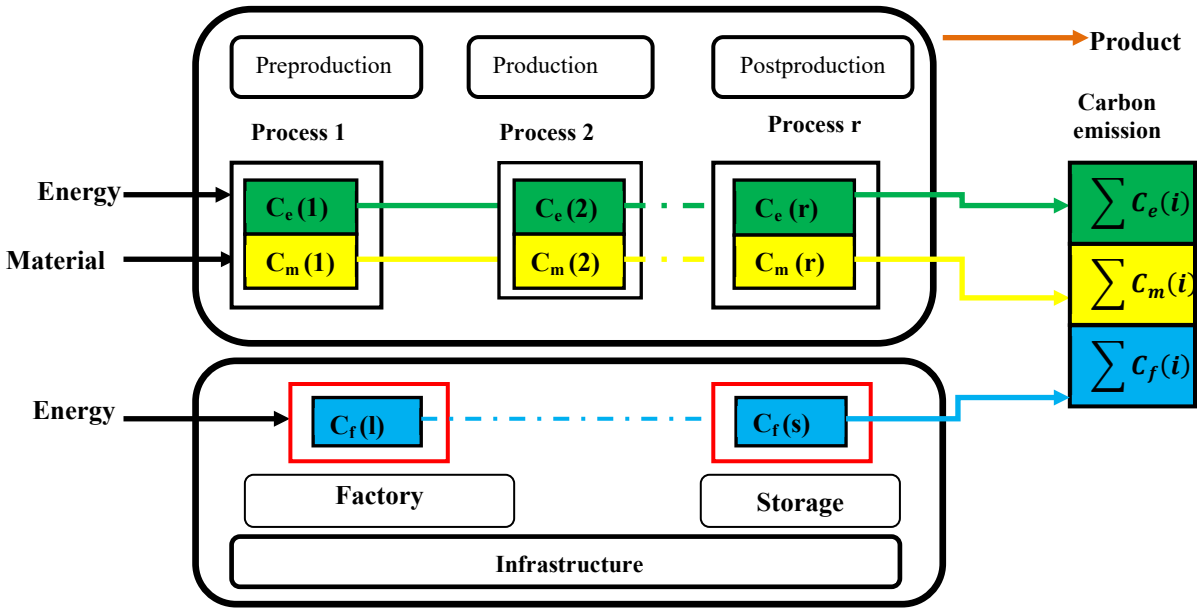


Figure 8: Carbon emission analysis framework for a product manufacturing

The occurrence of carbon emissions is usually accompanied with resource and energy consumption. The carbon emissions are categorized into direct emission and indirect emission depending on the different types of the input resources and energy type [51].

The direct carbon emission mainly refers to the emissions generated because of consumption of operational energy and material during the manufacturing process, while the indirect carbon emissions are the emissions emancipated during other non-operational phases in product manufacturing by power consumption which include hydraulic device, transmission device, and other electric devices.

The total carbon emission of a manufacturing process plan can be expressed as the sum of the carbon emissions generated from various processes in the equation 7 [51].

$$\boldsymbol{C_T} = \sum_{i=1}^{r}[\boldsymbol{C_e}(\boldsymbol{i}) + \boldsymbol{C_m}(\boldsymbol{i})] + \sum_{j=1}^{s}\boldsymbol{C_f}(\boldsymbol{j}) \quad (7)$$

Where:

$C_e(i)$ = directed energy-related carbon emission of the ith unit process in the process plan
$C_m(i)$ = material-related carbon emission of the ith unit process in the process plan
$C_f(j)$ = indirect energy-related carbon emission of jth zone in manufacturing plant.

3.4.2. Calculation of directed energy-related carbon emissions of a unit process.

The total energy consumption for a unit process in the direct carbon emissions is given in the equation 8 (Zhao et al., 2012)

$$\boldsymbol{E_{total}}(\boldsymbol{i}) = \boldsymbol{E_{tip}}(\boldsymbol{i}) + \boldsymbol{E_{idle}}(\boldsymbol{i}) + \boldsymbol{E_{basic}} = \int_0^{\boldsymbol{T_{tip}}}[\boldsymbol{P_i d_t} + (\boldsymbol{P_{idle}} \times \boldsymbol{T_{idle}}) + (\boldsymbol{P_{basic}} \times \boldsymbol{T_{basic}})] \quad (8)$$

Where:

$E_{total}(i)$ = the total energy consumed
$E_{tip}(i)$ = the energy associated with the productive part of the operation
$E_{basic}(i)$ = the basic energy consumed by fundamental activities of the manufacturing equipment
(i) = idle energy consumed when there is no active processing
T_{tip} = the total processing time
P_{idle} = the total idle power, T_{idle} is the time in a state of idle
Pbasic = the basic power, and T_{basic} is the basic time
Pi = the total power during the process of cutting material, composed of standby power Pu, cutting power Pc, and additional load loss power Pa (the certain power loss generated by the load of workpieces) [22 & 51].

Thus, the total power during the process of cutting material can be represented in the equation 9.

$$\boldsymbol{P_i = P_u + P_c + P_a} \quad (9)$$

Consequently, the energy from each unit process can then be converted to a carbon emission using the equation 10**.**

$$\boldsymbol{C_e(i) = E_{total}(i) \times \alpha_{elect}} \quad (10)$$

Where:

$C_e(i)$ = the carbon emissions of the energy consumed in the ith unit process

α_{elec} = the conversion factor for electricity to carbon emissions.

However, α_{elec} varies considerably due to the differences in generating resources among utility service areas and seasonal variations. Many countries have data for the conversion factor for electricity to carbon emissions; example of this is the conversion factor shown in the Table 4 from the Department of National Development and Reform Commission in China [51]. Particularly, average of these grids' emission factors is taken as the αelec.

Table 4: Electricity carbon emission factors.

Name of Power Grid	**CEF_{elec} ($kgCO_2$/kwh)**
North China Power Grid	0.7802
Northeast China Power Grid	0.7242
East China Power Grid	0.66826
Middle China Power Grid	0.5802
Northeast China Power Grid	0.6433
South Power Grid	0.5722
The National Average	**0.6747**

3.4.3. Calculation of material-related carbon emissions of a unit process.

The carbon emissions in this unit process are determined by the w different types of material consumptions, and it can be calculated using equation 11 [51]

$$\boldsymbol{C_m(i) = \sum_{k=1}^{w} m_k(i)\alpha_k(i)} \quad (11)$$

Where:

$C_m(i)$ = the total carbon emissions of the material flows for the ith unit process in the process plan

$m_k(i)$ = the mass for the kth type of material used in the ith unit process

$\alpha_k(i)$ = the conversion factor for the kth type of material to carbon emission in the ith process.

The conversion factors for each of the w types of materials can be obtained either through an LCA software package or through published reports or papers.

3.4.4. Calculation of indirect energy-related carbon emissions of a unit process.

The manufacturing plant can be refined into a series of zones with similar indirect energy-related resource and energy consumptions [57]. In this approach, the carbon emissions attributed to a part in zone j (i.e., $C\ f(j)$) can be calculated by multiplying the total material energy consumed of zone j in the equation 11 with the conversion factor for energy to carbon emissions (i.e., α_{elect}) as expressed in the equation 12.

$$\mathbf{C_f(j) = E_f(j).\alpha_{elect}} \quad (12)$$

Therefore, the indirect energy-related carbon emissions of total Zones can be expressed in the equation 13.

$$\mathbf{\sum_{j=i}^{s} C_f(j).\alpha_{elect}} \quad (13)$$

3.5. Carbon emission evaluation based optimization strategy.

The identification of improvement opportunities to monitor the resource and energy consumptions during the entire process planning depends on determination of the quantitative values for each unit process and breakdown of carbon emission [51]. Each improvement opportunity has been linked to a positive effect on at least one previously identified carbon emission. It is necessary and beneficial to implement the improvement opportunity to enhance the carbon emission reduction and to meet other sustainability goals.

Considering the factors such manufacturing equipment selection, operational efficiency, and product specification, there are possibilities for reducing the resource consumption and carbon emission if the following factors are implemented [51]. They are;

- Process Technology Selection
- Machine Tool Selection
- Optimal resource consumption.

To select a manufacturing process plan with the least carbon emission, manufacturing process plans must be modified and optimized through a quantitative analysis of the carbon emission impact among the process technology, equipment, and operational parameter.

4.0 Future Outlooks of Titanium Alloys.

The processing of titanium alloys manufactured via advanced powder manufacturing routes such as additive layer manufacturing (or 3D printing) and metal injection moulding is clearly receiving increased attention and being adopted as alternative to machining and casting. This is because of the associated key advantages which include the design flexibility, reduced processing costs, reduced waste, energy efficiency and improved functionality as has been demonstrated in several of the above studies. Therefore, the advanced manufacturing routes collectively represent a significant opportunity to transform the medical device industry. It is possible that advanced manufacturing techniques could replace the machining or casting of metal alloys in the manufacture of devices because of associated advantages that include design flexibility, reduced processing costs, reduced waste, and the opportunity to more easily manufacture complex or custom-shaped implants. The emerging advanced manufacturing approaches of metal injection moulding and additive layer manufacturing are receiving attention from the implant fabrication industry because they could overcome some of the difficulties associated with traditional implant fabrication techniques such as titanium casting. Using advanced manufacturing, it is also possible to produce more complex porous structures with improved mechanical performance, potentially matching the modulus of elasticity of local bone.

5. Conclusion.

A review has been presented on machining Titanium Alloy by considering the energy involved in the manufacturing processes to have low carbon manufacturing requirements by evaluating carbon emission in the manufacturing process plan.

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