İmalat Teknolojileri ve Uygulamaları
Cilt: 2, No: 2, 2021 (10-29)
Derleme Makale
e-ISSN: 2717-7475

Manufacturing Technologies and Applications
Vol: 2, Issue: 2, 2021 (10-29)
Review Article
e-ISSN: 2717-7475

An Evaluation on Machinability of Titanium Alloy and Nickel Based Superalloys Used in Aerospace Industry

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ARTICLE INFO

Received: *20.05.2021*
Accepted: *17.08.2021*

Keywords:
Aerospace
Titanium
Superalloys
Machinability
Cutting tool
Surface integrity

ABSTRACT

Superalloys are a group of materials that are commonly used in aerospace applications and are also called high temperature materials, as they have superior wear and corrosion resistance. Ni-based superalloys are used more often than Ti alloys in the aerospace industry as they have mechanical and physical properties such as superior temperature resistance and toughness, high corrosion resistance, excellent fatigue and creep resistance. Ti alloys, on the other hand, have the highest strength / weight ratio among metals, increasing their preference in these industries continuously. Casting, forging, powder metallurgy and machining methods are used in the process of shaping machine parts used in the aviation industry from superalloys. However, many components are mostly manufactured using machining methods due to the part geometry, desired size and surface quality requirements. In this context, in the production of parts from Ti alloys and Ni-based superalloys, which are difficult to process, the correct selection or optimization of processing parameters is very important in terms of minimization of processing costs and therefore sustainable manufacturing. In this study, factors such as cutting tool quality and cooling/lubrication technology were evaluated for criteria such as tool life, surface integrity and cutting forces, which have an important place in the machinability of titanium and nickel-based superalloys.

Havacılık ve Uzay Endüstrisinde Kullanılan Titanyum Alaşımları ve Nikel Esaslı Süperalaşımların İşlenebilirliği Üzerine Bir Değerlendirme

MAKALE BİLGİSİ

Alınma: *20.05.2021*
Kabul: *17.08.2021*

Anahtar Kelimeler:
Havacılık
Titanyum
Süperalaşımlar
İşlenebilirlik
Kesici takım
Yüzey bütünlüğü

ÖZET

Süperalaşımlar, üstün aşınma ve korozyon direnci gibi özelliklere sahip olduklarından havacılık ve uzay uygulamalarında sıkça kullanılan ve yüksek sıcaklık malzemeleri olarak da isimlendirilen malzeme grubudur. Ni esaslı süperalaşımlar, üstün sıcaklık mukavemeti ve tokluk, yüksek korozyon direnci, mükemmel yorulma ve sürünme dayanımı gibi mekanik ve fiziksel özelliklere sahip olduğundan havacılık ve uzay endüstrisinde Ti alaşımlarından daha sık kullanılmaktadır. Ti alaşımları ise metaller içerisinde en yüksek dayanım/ağırlık oranına sahip olması nedeniyle bu endüstrilerde tercih edilme grafiğini sürekli yukarıya taşımaktadır. Havacılık sektöründe kullanılan makine parçalarının süperalaşımlardan şekillendirilmesi sürecinde döküm, dövme, toz metalurjisi ve talaşlı imalat yöntemleri kullanılır. Bununla birlikte, parça geometrisi, istenilen ölçü ve yüzey kalitesi gereksinimlerinden dolayı birçok bileşen çoğunlukla talaşlı imalat yöntemleri kullanılarak imal edilmektedir. Bu bağlamda, işlenebilirliği zor olan Ti alaşımları ve Ni esaslı süperalaşımlardan parça üretiminde, işleme parametrelerinin doğru seçimi veya optimizasyonu işleme maliyetlerinin minimizasyonu ve dolayısıyla sürdürülebilir imalat açısından çok önemlidir. Bu çalışmada, titanyum ve nikel esaslı süperalaşımların işlenebilirliğinde önemli bir yeri olan takım ömrü, yüzey bütünlüğü ve kesme kuvvetleri gibi ölçütler için kesici takım kalitesi ve soğutma/yağlama teknolojisi gibi faktörler değerlendirilmiştir.

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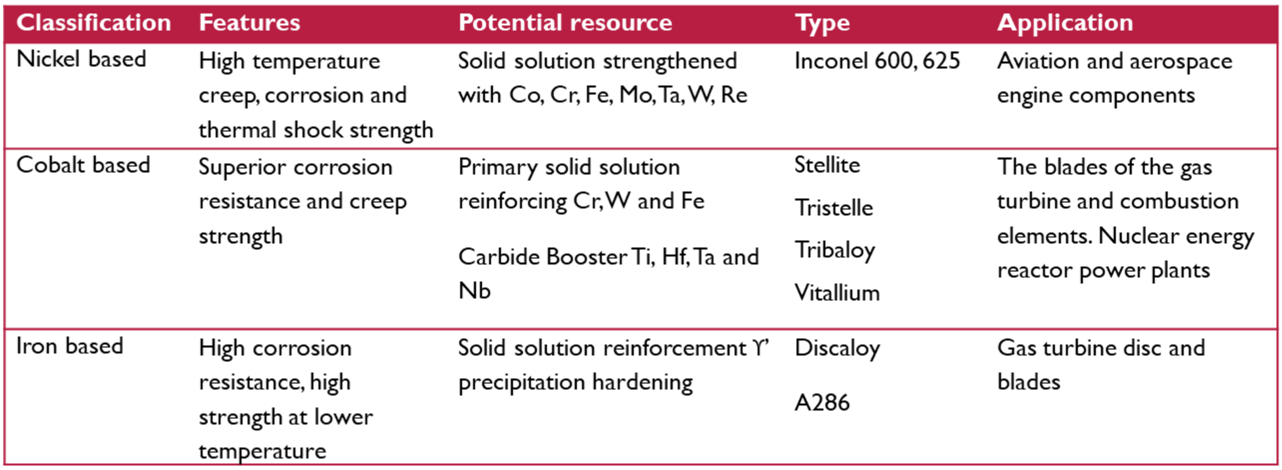
https://doi.org/10.52795/mateca.940261

1. INTRODUCTION (GİRİŞ)

The quick growth in the aviation industry has laid the groundwork for the development of materials used in aircraft construction. The main factor is the reduction in weight and increased service life of aircraft components, resulting in lower costs. Therefore, a lot of research was done for improving materials by optimized properties to reduce weight, increase damage tolerance, fatigue and corrosion resistance. The main purpose of the continuous development of new materials in aviation applications is to increase fuel efficiency and performance, and to reduce costs. Since the selection of engineering materials for aerospace applications affects both economic and environmental topics, these materials are expected to have superior properties. Superalloys were first developed for military gas turbines during in the early 1950s. Since then, superalloys have been in continuous development and numerous new materials have been produced in this area. At the same time, superalloys are an valuable class of high temperature materials used in the strongest parts of jet and rocket engines where temperatures get to 1200-1400 °C [1].

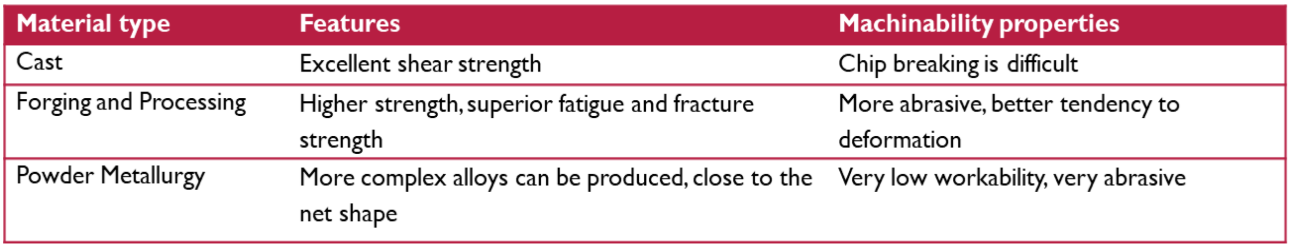
On the other hand, high strength, hardness and toughness make it difficult to process these materials with traditional processing methods. These materials are used for a widespread variety of applications for instance power generation, high-tech automotive parts, especially in the aerospace industry [2]. Al, Ti, Mg and Ni-based alloys have become developable alloys for the aerospace industry thanks to their superior advantages [3]. Figure 1 shows the application areas of some superalloys. High temperature resistant alloys are the main resources used in the production of aviation-engine parts. These exotic superalloys are classified at four main categories: Nickel-based alloys, cobalt-based alloys, iron-based alloys, and titanium alloys. Iron-based superalloys contain significant amounts of Cr, Ni and very small amounts of Mo or W in addition to Fe. Fe-based superalloys and solid solution reinforced alloys are the weakest of superalloys owing to their low strength at high temperatures.



Classification	Features	Potential resource	Type	Application
Nickel based	High temperature creep, corrosion and thermal shock strength	Solid solution strengthened with Co, Cr, Fe, Mo, Ta, W, Re	Inconel 600, 625	Aviation and aerospace engine components
Cobalt based	Superior corrosion resistance and creep strength	Primary solid solution reinforcing Cr, W and Fe Carbide Booster Ti, Hf, Ta and Nb	Stellite Tristelle Tribaloy Vitallium	The blades of the gas turbine and combustion elements. Nuclear energy reactor power plants
Iron based	High corrosion resistance, high strength at lower temperature	Solid solution reinforcement ϒ' precipitation hardening	Discaloy A286	Gas turbine disc and blades

Figure 1. Classification and application of superalloys (Süper alaşımların sınıflandırılması ve uygulanması) [4]

The biggest advantage of these alloys is that their price is more economical than other superalloys. They are also the easiest to process superalloys because they cannot maintain their strength at high temperatures, and contain higher amounts of nickel and chromium than stainless steels. Cobalt-based superalloys contain Co as the main element, with significant amounts of Ni, Cr, W and small amounts of Mo, Nb, Ta, Ti. At high temperatures, they show higher strength and thermal fatigue resistance compared to Fe and Ni-based superalloys, and excellent hot corrosion resistance with high Cr addition. Alternatively, Co-based superalloys are the most demanding type of superalloys in machining as they tend to have high hot hardness at high shear temperatures. It appears that two out of three of aircraft production is occupied by the aviation industry, especially for the production of aircraft engines, turbines, jet engines and related parts [5]. Aerospace superalloys are usually found in cast, machined, forged and sinter forms (Figure 2). Parts generated by casting methods display excellent shear strength together with toughness. These properties produce machinability troubles thanks to low chip slicing. Forged and machined parts usually have high strength, superior fatigue and fracture resistance. More complex and almost net shaped parts are manufactured using powder metallurgy method. Parts in this production method present extremely low machinability and are very abrasive. In this review study, it is aimed to make a detailed evaluation on important machinability criteria such as superalloys that are critical in aerospace industry and insert materials, tool life, cutting environment and surface integrity, which are important for sustainable manufacturing.

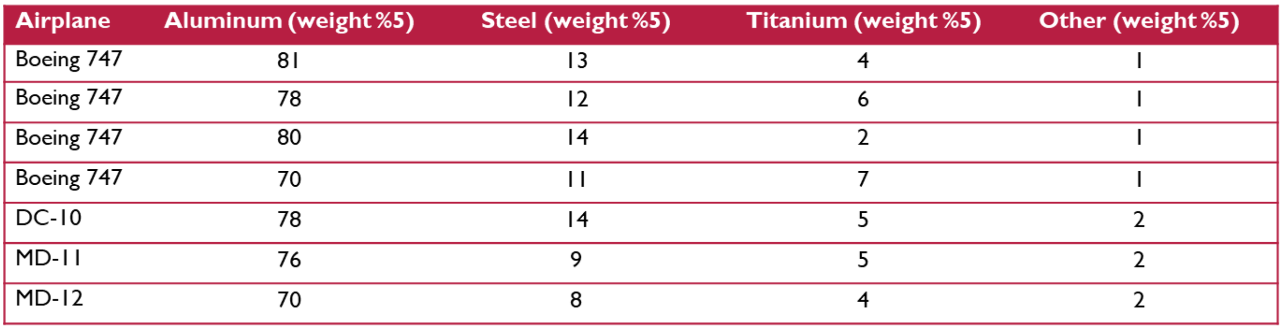


Material type	Features	Machinability properties
Cast	Excellent shear strength	Chip breaking is difficult
Forging and Processing	Higher strength, superior fatigue and fracture strength	More abrasive, better tendency to deformation
Powder Metallurgy	More complex alloys can be produced, close to the net shape	Very low workability, very abrasive

Figure 2. Industrial processing techniques and properties of superalloys (Endüstriyel işleme teknikleri ve süper alaşımların özellikleri) [5]

2. SUPERALLOYS (SÜPERALAŞIMLAR)

In the aerospace industries, many models of superalloys, especially nickel and titanium, are used, which vary according to their usage areas. The main purpose of the alloying process is to optimize the material strength, its machinability properties and its strength at high temperatures. In aerospace practices, components must have a certain fault tolerance in both static and/or dynamic loads. To achieve this, existing traditional materials for instance steel and aluminum are being formed for the aviation industry. When developing new alloys, the goal is to increase endurance to crack expansion, environmental damage, creep stress and high temperature yield stress. The composition of current alloys and specific alloys widely used in aviation applications is shown in Figure 3 [6].



Airplane	Aluminum (weight %5)	Steel (weight %5)	Titanium (weight %5)	Other (weight %5)
Boeing 747	81	13	4	1
Boeing 747	78	12	6	1
Boeing 747	80	14	2	1
Boeing 747	70	11	7	1
DC-10	78	14	5	2
MD-11	76	9	5	2
MD-12	70	8	4	2

Figure 3. Current alloys for aircraft (Uçaklar için mevcut alaşımlar)

2.1. Titanium Alloys (Titanyum Alaşımları)

Ti alloys are structural materials widely utilized in the aviation industry, shipbuilding and chemical industries, turbo machines, machine and tool making, and medicine [7]. In addition to pure titanium, the alloys are widely used in medical products and implant production. These alloys are known to exhibit features such as superior biocompatibility, osseointegration, high wear and corrosion strength and superior compressive strength within the body [8]. The low thermal conductivity of the materials causes high temperatures in the cutting region. This temperature in the cutting region is high average 2.2 as much from AISI 1045 processing [9]. Demand for titanium is steadily improving in the aerospace industry, due to its outstanding weight-to-strength ratio and the increasing need for electrochemical compatibility with composites in the field of aerospace. This alloys have superior mechanical properties, but they are hard-to-work materials with high chemical reactivity, low thermal conductivity, modulus of elasticity and production rates, as well as higher tool wear [10]. Modern aircraft designers, who widely use composite materials, also use certain proportions of titanium. Contrasted to aluminum, titanium is more consistent with composites in airplane designs / assemblies [11]. Titanium is resistant to flaking, stress corrosion and other alloy forms, from aluminum alloys, steels, etc. Titanium also resists corrosion factors by forming oxide in the surface layer in application environments. Titanium alloys are also frequently used in airframe subjected to air-kinetic heating due to its thermal stability [12]. In Figure 4, the application areas of the materials usually used in the sector and the modifications of the alloy are given by classifying them according to α, α + β, β type.

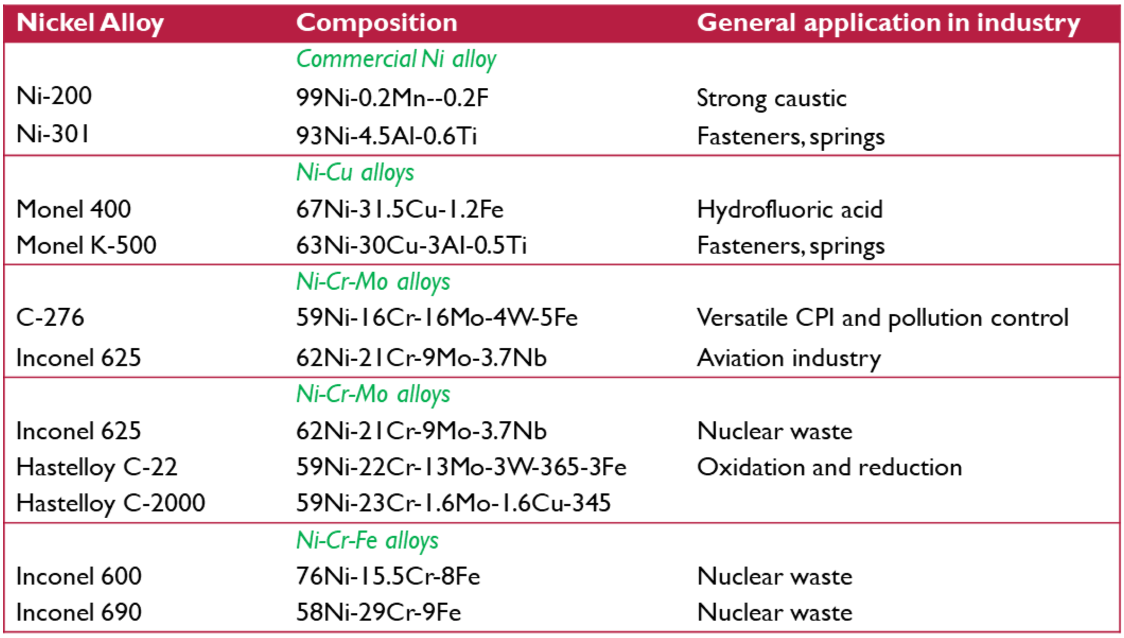
α titanium alloy	**Applications**
Ti-3Al-2.5V	When high pressure duct pipes of aircraft are produced with this alloy, they provide 40% weight savings compared to pipes made of steel. This alloy stands out with its acceptable corrosion strength, nice weldability and suitability to produce seamless hydraulic pipes.
Ti-5Al-2.5Sn [13]	Welded joints with good stability have oxidation resistance up to 1000 °F, making it suitable for manufacturing blades for aircraft and steam turbines. Its ability to maintain ductility and break toughness up to cryogenic temperatures allows this alloy to be used to store H2 in the turbo pump of spacecraft.
Ti-6-2-4-2, Ti-5.5A1-3.5Sn-3Zr-1Nb-0.25Mo-0.3Si	It is used to manufacture the RB211-535-E4 engine, spacers, blades and compressor discs of the Boeing 757 aircraft.
α + β titanium alloy	**Applications**
Ti-6Al-4V [13]	Approximately 80% of the total volume of Ti utilized in body parts (cladding panels, stiffeners, wing containers, spare parts, etc.) is produced of this alloy. It also has a large share by amount in jet engine components (60% of the total Ti) and aircraft bodies (80-90% of the total Ti). The impact resistance needed in cockpit glasses is supplied by this forged alloy. Forged alloy is widely used for rotor heads in helicopters of the BK117 and BK105.
β titanium alloy	**Applications**
Ti-15V-3Cr-3Al-3Sn [14]	Boeing 777 replaces the CP Ti material in conduit pipes, and the Boeing fuselage is significantly lighter Springs made of this alloy are less weight (up to 70%), less volume (up to 50%) and further corrosion strength than steel springs.

Figure 4. Titanium alloys and their application areas (Titanyum alaşımları ve uygulama alanları)

α titanium alloys: The amount of α-stabilizer elements in here separates into two classes as α-α alloys and super α alloys. The important reason for using α-Ti alloys in engine parts used in aircraft is that they can retain their strength during most heat treatments. α + β titanium alloys: Break toughness, superb shear strength, ductility of *α + β titanium alloys* are better to α-Ti alloys. The tensile and fatigue strength of these alloys are better to Ti-Ti alloys. *β titanium alloys:* Microstructural changes in the mechanical properties of β + Ti alloys through heat treatment allow the material to fit into the airframe parts, [13]. Especially Ti alloys in the α + β phase are widely utilized in the human body because of their non-toxic and low allergenic characteristics. These lead to a better level of biocompatibility. Super elasticity and shape memory have become progressively more valuable features not only in bio-applications but also in distinct industries for instance automotive and aerospace [14]. Compared to other materials [29], titanium-based superalloys produced by traditional methods are relatively limited in production due to their relatively high cost and poor machinability [30]. An increasing number of specialty materials are obtainable in additive manufacturing technologies, involving titanium. Ti6Al4V alloy is typically utilized in the production of additive manufacturing parts using EBM (electron beam melting) technology [15].

2.2. Nickel-Based Superalloys (Nikel Esaslı Süper Alaşımlar)

The ability to retain high mechanical and chemical properties at elevated temperatures makes superalloys an excellent material for use in rotary and stationary components of jet engines. Components manufactured by superalloys are lighter than those produced from traditional steel. This means less fuel economy and a decline in pollution [16]. Approximately 50% by weight of aircraft engine alloys are nickel-based alloys [17]. These alloys present a higher strength / weight ratio than steel with higher density. The superalloys are an exceptional metal class with a combination of high temperature resistance, toughness and resistance to oxidizing environments [18]. Nickel-based superalloys are commonly applied in engine parts for instance engine compressor discs, turbine disc, bearing parts, housing, fins and other running parts [19–21]. In this context, advanced gas turbine engines are likely to achieve progressively upper levels of fuel budget, lower NOx emissions, lower noise and unit weight to meet the demand for life cycle costs in civil aeronautics. These challenges inevitably require that high pressure compressor and turbine disc rotors be made of materials that can withstand higher temperatures and stresses. High strength nickel-based superalloys are needed in the production of these critical parts, as the wrong material selection can threaten the safety of the passengers and the aircraft [22]. In terms of chemical composition, some nickel-based alloys can be classed as: (i) commercially pure Ni; (ii) Ni-Cu alloys; (iii) Ni-Mo alloys; (iv) Ni-Cr-Mo alloys and (v) Ni-Cr-Fe alloys. Proximate chemical structure and classic mechanical properties of the best known nickel-based alloys are given in Figure 5.



Nickel Alloy	Composition	General application in industry
	Commercial Ni alloy	
Ni-200	99Ni-0.2Mn--0.2F	Strong caustic
Ni-301	93Ni-4.5Al-0.6Ti	Fasteners, springs
	Ni-Cu alloys	
Monel 400	67Ni-31.5Cu-1.2Fe	Hydrofluoric acid
Monel K-500	63Ni-30Cu-3Al-0.5Ti	Fasteners, springs
	Ni-Cr-Mo alloys	
C-276	59Ni-16Cr-16Mo-4W-5Fe	Versatile CPI and pollution control
Inconel 625	62Ni-21Cr-9Mo-3.7Nb	Aviation industry
	Ni-Cr-Mo alloys	
Inconel 625	62Ni-21Cr-9Mo-3.7Nb	Nuclear waste
Hastelloy C-22	59Ni-22Cr-13Mo-3W-365-3Fe	Oxidation and reduction
Hastelloy C-2000	59Ni-23Cr-1.6Mo-1.6Cu-345	
	Ni-Cr-Fe alloys	
Inconel 600	76Ni-15.5Cr-8Fe	Nuclear waste
Inconel 690	58Ni-29Cr-9Fe	Nuclear waste

Figure 5. Approximate chemical compositions and applications of corrosion resistant nickel alloys (Korozyona dayanıklı nikel alaşımlarının yaklaşık kimyasal bileşimleri ve uygulamaları) [23]

50 percent of a plane engine is made by Inconel 718, which is the most commonly used Ni-Fe-Cr alloy [24]. It accounts for 25 and 45 percent of the yearly production volume for cast and machined nickel-based alloys, respectively [25]. Nickel-based superalloys cover 40-50 percent of engine weight in existing industrial aircraft and are used especially in the combustion and turbine segments in functioning temperatures surpass 1250 °C [26,27]. Commercially available and heavily used nickel-based alloys Inconel (587, 600, 625, 706, X750, etc.), Nimonic (75, 80A, 90, 263, PE 11, C-263, etc.), Rene (41, 95), Udimet (400, 500, 630, 700, etc.), Pyromet 860, Astroloy, Waspaloy, Unitemp AF2-IDA6, Cabot 214 and Haynes 230 [25]. Turbine wings and nozzle director blades are

formed by the complex casting method that can precisely control the grain boundary structure. Parts containing columnar grains manufactured by directional solidification (DS) casting generally have an operating temperature limit of about 25 °C higher than equivalent pieces. This is cause the grain boundaries of the DS fins are aligned near the main stretching path parallel to the size of the main foil [28]. Besides, adhesion, diffusion and oxidation wear of insert become more severe when machining nickel-based superalloys, and consequently tool life is shorter. For example, a one meter long nickel-based superalloy blade takes more than seven hours to rough and fine turning [29].

These alloys include the intermetallic combination Ni3 (Al, Ta) in a nickel matrix with chromium, tungsten and rhenium as solid solution reinforcement elements. Here, tantalum increases high temperature and oxidation resistance, and it is alloyed with titanium to lessen the alloy's temperature. Thus, turbine blades made of this material can work at temperatures up to 520 °C [17]. Usually, the structure of nickel-based alloys is 38-76% Ni, up to 27% Cr and 20% Co by weight. In addition, these technical properties can be improved by adding refractory elements namely W, Ta and Mo. The amount of elements for instance Si, P, S, oxygen and nitrogen added to the alloy is regulated by the melting process. Conventional parts produced by casting from the alloys are turbine fins and brake discs [30]. In this method, the process is carried out with the highest level of precision in order to keep the machining processes to the lowest. Vacuum induction melting improves casting quality by disconnecting most of the rare elements from the alloy. In this context, turbine blade faults are mostly caused by vertical forces at the grain boundaries to which the weakest points of the structure are subjected [31]. This defect can be reduced or minimized by directional solidification casting. Structures with grain boundaries in the lengthwise trend to the forces operated by DS casting can be created. In addition, better parts can be manufactured using single crystal technique. Manufactured by single crystal or DS processes, these parts can operate at plus 250 °C higher than traditional polycrystalline blades [17]. Forged nickel-based alloys include approximately 10-20 percent by weight of Cr, up to 8 percent Al and Ti conjugated, 5-15% Co and Fe [25]. This type alloys offers moderately high temperature strength and well resistance to stress aging cracking at the weld. Since they have high strength suitable for working with turbine discs, their main usage field is the manufacturing of these turbine discs [30].

3. MACHINABILITY OF TITANIUM ALLOYS AND NICKEL BASED SUPERALLOYS

(TİTANYUM ALAŞIMLARI VE NİKEL ESASLI SÜPERALAŞIMLARIN İŞLENEBİLİRLİĞİ)

Machinability is the simplicity or complexity wherein a material can be processed in a variety of cutting conditions involving cutting speed, feed rate, and cutting depth [30]. It can also be defined as response size of the material machined with a particular tool that provides a suitable tool life, fine surface quality, and appropriate functional properties. The degree of machinability varies according to tool life, surface quality and the power consumption in the machining process [32]. On the other hand, the machinability can be evaluated mainly by measuring surface integrity and cutting force components during a cutting process.

Precision casting, forging and other modern manufacturing technologies are applied to produce machine parts by nickel-based and titanium alloys. But complicated alloys / materials cannot be simply produced employing these methods. For this reason, machining methods are used to manufacture complex quality elements required material / component design at reasonable costs nowadays. However, superalloys are known to be hard to process materials [33] by reason of their elevated temperature resistance, fast strain hardening, minimal thermal conductivity, and the existence of abrasive deposits in the structure [4,34]. At this point, it required the advancement of tools (carbides, ceramics and CBN) with superior thermal and chemical constancy for improving the machinability of aerospace alloys. Poor machinability of aircraft engine alloys exposes the tool cutting edge to extreme thermal and mechanical pressures and these frequently cause rapid tool wear [30]. Usual cutting tool problems detected once machining air motor alloys are notching of the tip and / or cutting edge, side and crater wear, chipping, and breakage. Tools utilized to machine these alloys must have sufficient hot hardness to resist the high temperatures produced in higher speed [35]. High velocity machining of aircraft engine components is usually performed using coated carbide, ceramic and CBN / PCBN tools, but uncoated carbide are used in lower cutting velocity. Ceramic inserts exhibit low performances owing to their high wear amount by the high sense of titanium alloys with ceramic. For this reason, these types of insert are not preferred for processing titanium alloys [36,37].

When machining Ti alloys and Ni-based superalloys, fine and saw-tooth shaped chips are usually formed. Ni-based superalloys have an austenitic matrix and harden rapidly during machining like stainless steels. As a result, localization of the slip in the chip makes it difficult to remove the chip and generates abrasive saw-toothed sides [25]. These alloys also tend to link with the high temperature tool material produced during machining. The built-up edge (BUE) tendency in machining and the abrasive carbides in their structure undesirably influence machinability. These cause extreme temperatures and stresses in the cutting region and cause faster flank wear, cratering and chipping, dependent on the tool material and the cutting conditions [38]. Nickel-based superalloys harden by precipitation of a Ni3 (Ti, Al) type γ′ phase [39,40], titanium and aluminum can be used interchangeably. The machinability of these alloys is related to the chemical element content and heat treatment. Here, as the nickel content, which is the main element of nickel-based superalloys, the cutting temperature rises and the notch wear increases as the hardness increases, as shown in Figure 6. The chemical structure of superalloys should be related to hardness while deciding machining conditions [41], [42]. The hardness of Ni and Ti alloys rises considerably with heat treatment, so they are also called age hardening. Due to the creation of second phase units, the alloy is both robust and further abrasive, thus making it harder to machine. In this case, it is advantageous to process the material while it is soft [16]. Whenever possible, a positive insert is suggested for semi-final and final operations. Its positive geometry ensures efficient removal of chips from the workpiece. The grain size of the Inconel 718 was found to have little effect on flank wear, but notch wear was strongly associated with large grit [43]. Excitingly, the feed rate and grain size greatly influenced firstly tool wear and cutting force [44]. In addition, chip removing rate has been cited as one of the crucial machinability pointers to determine the cutting state, especially at high speed machining [45].

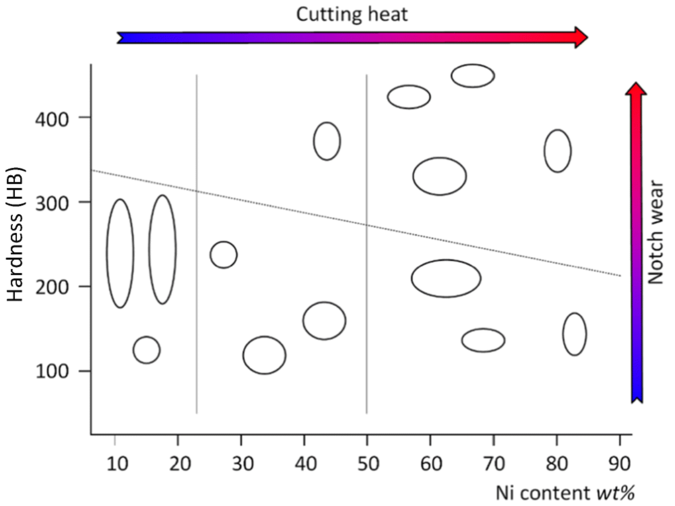


Figure 6. Machinability of superalloys (Süperalaşımların işlenebilirliği) [42]

Titanium alloys cover 30% of engine mass in the field of commercial and 40% in military [46]. The use of this material will increase with processing techniques that reduce faults that are harmful to the effective operation of the engine by early collapse of the relevant parts. One of the faults is the onset of fractures in the alloy that triggers structural breakdowns in the engine [30]. Machinability of nickel and titanium alloys can be improved using high concentration cooling technology, hot working, cryogenic machining, and the rotary tool technique [16]. The materials can be classified according to their machinability into (i) simple-to-work materials, (ii) conventional forged steels and iron, (iii) hard-to-work materials. When we create a category such as machinability index, it is possible to categorize such as surface properties, energy necessity, tool properties, chip morphology, bench and material hardness. Researchers face many difficulties in finding different ways to develop the material's workability without upsetting the industry's productivity and cost-cutting. As shown in Figure 7, there are many factors influencing the machinability of materials [47–49].

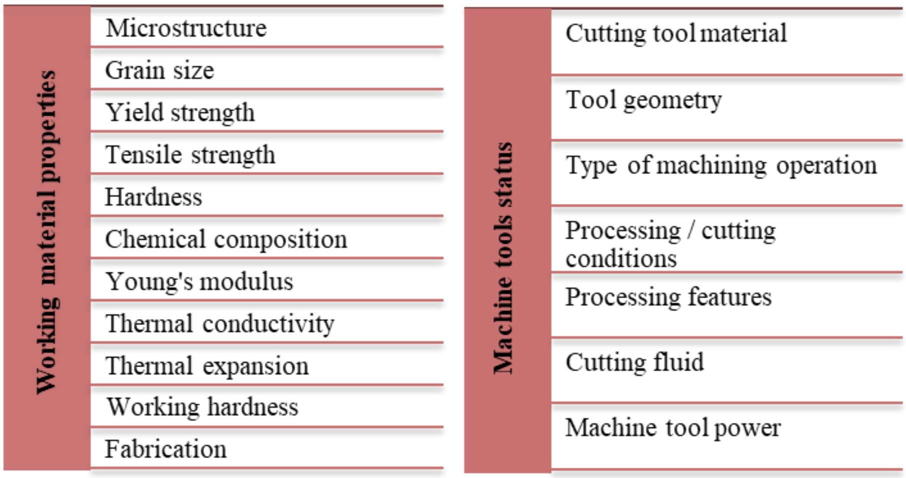


Figure 7. Factors affecting machinability (İşlenebilirliği etkileyen faktörler) [48–50]

4. EVALUATION FOR OUTSTANDING MACHINABILITY FACTORS (ÖNEMLİ İŞLENEBİLİRLİK FAKTÖRLERİ AÇISINDAN DEĞERLENDİRME)

4.1. Cutting Tool Material (Kesici Takım Malzemesi)

Advances in the cutting tool industry are becoming more and more promising to machine difficult-to-machine parts with ease and precision. Advanced cutting tools help optimize machinability. Because hard-to-machine materials need an advanced insert to endure high heat creation, toughness and impact resistance in machining [51]. Cutting tools utilized in the machining of superalloys have properties such as wear strength, excellent thermal shock, chemical consistency, high strength and toughness, efficient hot hardness at high temperatures at the cutting edge and workpiece [4]. In the machining of nickel-based superalloys and titanium alloys, uncoated and coated sintered carbide tools and ceramic and CBN tools are generally used in continuous cutting applications at high speeds [52]. In the machining of superalloys used in aviation, part size precision and surface impacts are largely dependent on the insert materials. Based on the properties of nickel-based superalloys, insert materials should usually provide the subsequent conditions;

- Good constancy, high oxidation and temperature resistance.
- Hardness and wear resistance.
- Adequate bending resistance and impact toughness.
- Good heat treatment and high thermal deformation performance.

- Insert materials often meet intense thermal and mechanical stress close to the cutting edge in machining [16].
- Coatings applied to tools increase the wear resistance of the insert against wear, loosening and friction.

Although the coating increases the cost, it can provide many more benefits due to the improvement of the tool performance [42]. The performance of various coating materials (TiCN / Al_2O_3 / TiN, TiN / AlN, TiAlN) during turning of Inconel 718 in MQL was compared by Kamata and Obikawa. Results indicated that under MQL shear, TiCN / Al_2O_3 / TiN displayed the longest shear length at a shear rate of 3.6 km/h [53]. By applying nano-multilayer AlTiN / MexN PVD coatings to cemented carbide tools, a noticeably smaller friction coefficient is achieved at high temperatures. While nano-multilayer AlTiN / MoN coating is recommended for superior tool life once machining Inconel 718, AlTiN / VN coating is more suitable for machining TiAl6V4 alloy [54]. It has revealed that the nano-multilayer AlTiN / Cu coating is very functional in the processing of superalloy due to its proper combination of improved oiling properties and decreased thermal conductivity [55]. The nanocomposite coated cutting tool performed better than the AlTiN coating at higher speed conditions in the fine turning of the Inconel DA718 alloy. However, inserts with nanocomposite coating demonstrated a significant reduction in chip density, providing superior wear resistance [56]. There is a clear trend that coatings are being reformed from a single layer to multilayers, from macros to nanoscale, and from a single to multi-functional. Hence, research on the development of tool coating types, different processing technologies and their performance in cutting conditions continues to be important issues in the machining of superalloys.

4.2. Cooling and Lubrication Technology (Soğutma ve Yağlama Teknolojisi)

Chip flow and the lubrication between the tool-workpiece can be successfully provided by a cost-effective cooling technique through machining. Precise use of cooling maximizes process capacity, insert life and surface integrity [57,58]. Lubrication and cooling procedures have been used in industry for the past 200 years to overcome the problems arising through machining. Coolant is also linked with tool and mostly refers to styles normal wet, dry, minimum quantity of lubrication (MQL), high pressure cooling (HPC) and cryogenic types. The method considered environmentally friendly is the dry processing method. In dry cutting, the key reasons of tool wear are high cutting temperature and thermal shock, BUE formation, geometric deviations in processed parts, etc. It causes an rise in tool wear because of the quality of the processed surface [59]. Herein, a higher cutting temperature develops at high cutting speed, which reduces the strength of the workpiece material and also allows lower cutting force. A laser-assisted HSM in dry machining conditions was assessed using coated carbide, considering that a completely dry machining pattern was not suitable for machining superalloys [60]. The results revealed that the cutting force was significantly diminished, the surface quality was better by more than 25% and the MRR increased by about 800% compared to traditional machining [42]. However, their application areas are limited due to the geometric constraints and machining difficulties of cutting tools. Considering both the widespread use of a PCBN insert in the industry and its disadvantages, the coolant condition has attracted more attention from researchers. Dry and liquid cooling systems have shown that when tested at variable cutting BUE and flank wear are common wear patterns for cutting tools, but this is not always the case. Chip breaking is an important problem since there is no chip breaker in PCBN cutting tools. It deals with cutting parameters as well as tool geometry and grade. However, almost all of the factors cited as problems are not independent [42]. Conventional cutting fluids are shown in Figure 8. Water is often used as a suitable coolant to increase productivity in machining. Water-based fluids are preferred because of their low cost and heat conduction functionality [61]. In some cases, water cooling is not an effective for chip removing and reduces machinability. Therefore, some additives are added to the water to overcome these problems and ensure efficient cooling. In severe cutting environments, compressed gas-based coolant or refrigerated pressurized fluids are used [59].

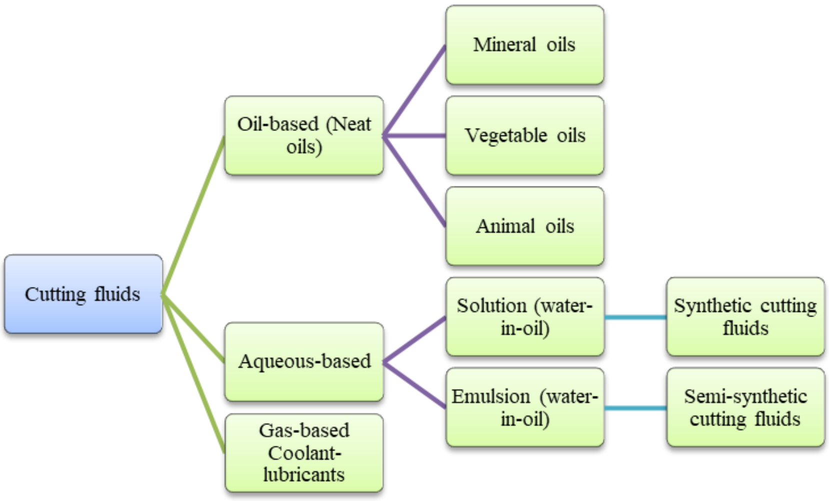
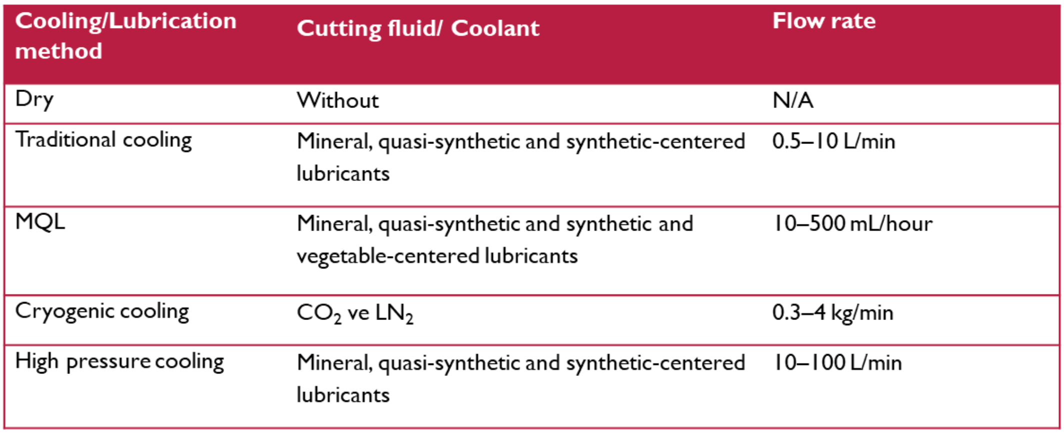


Figure 8. Traditional cooling types (Geleneksel soğutma tipleri) [62]

Cutting fluid is supplied in a variety of ways as soluble oil in cutting zone, vegetable oils, cryogenic coolants etc. The quantitative values of the flow rate are given in Figure 9. Machining close to MQL or dry machining has been used for years to address occupational hazards and environmental issues associated with coolant particles in the air. In this technique, coolant and minimum amount of lubricant are used in both areas. The blend of refrigerant and compressed air with the controlled flow is transmitted to the cut-off point through the pipe / nozzle. In the MQL, a little amount of vegetable lubricant or ecological synthetic ester is sprayed with compressed air in the tool chip interface [53]. In recent years, the use of nanoparticle fortified vegetable oils has found a widespread of applications and has taken its place among cooling technologies. The nanofluid has heat transfer ability, the effect of reducing friction coefficient and wear process to improve efficiency and reliability in machining. Nano-sized solid particles are added to water, oiling lubricants, etc. to improve the properties of lubricants or coolants. It is dispersed into base liquids such as. The excellent properties of the nanofluid are beneficial for cooling and lubrication in machining and reduce the friction coefficient [63]. Since nano liquid has convectional transmission and wettability of cooling and lubricant, it especially reduces flank wear [64].



Cooling/Lubrication method	Cutting fluid/ Coolant	Flow rate
Dry	Without	N/A
Traditional cooling	Mineral, quasi-synthetic and synthetic-centered lubricants	0.5–10 L/min
MQL	Mineral, quasi-synthetic and synthetic and vegetable-centered lubricants	10–500 mL/hour
Cryogenic cooling	CO_2 ve LN_2	0.3–4 kg/min
High pressure cooling	Mineral, quasi-synthetic and synthetic-centered lubricants	10–100 L/min

Figure 9. Characteristic of cooling lubrication methods (Soğutma yağlama yöntemlerinin karakteristiği) [65]

In current studies, it is recommended that cooling and lubrication methods are used in a minimum amount of cutting fluid in the processing of alloys used in the aerospace industry, within the scope of environmentally friendly and sustainable production. A cooling option with a minimum amount of coolant has been noted to be beneficial for processing Ti and Nickel alloys [66]. MoS2 and graphite-centered nano-cutting liquids give good results at high cutting speeds, but graphite-based nano-fluids are improved in terms of good lubricating and cooling properties of their overall performance [67]. Although conventional coolants are not recommended to be used with ceramic tools because of their characteristics such as small thermal conductivity and shock resistance, the outcomes obtained using natural MQL are highly promising with regards to tool life and nose wear [68]. Air cooling is the method that provides safe and environmentally friendly processing that has attracted the attention of many academic and scientific researchers. When processing Ti6Al4V, the cutting forces increase due to the lower slip plane angle and chip temperature that occur when using cooled air cooling. However, tool wear and BUE formation decrease as a result of lower cutting forces contrasted to dry machining [69]. In the machining of Nimonic 80A alloy, flank wear occurred along the insert edge due to the abrasive mechanism and big BUE creation in dry cutting. Less BUE formation and longer tool life were achieved in air chilling and oil spray methods, and it was emphasized that the oil spray technique could be used as an alternative to the MQL method [70]. A recent study evaluated the overall performance of cooling approaches with a minimum amount of coolant when milling Ti6Al4V alloy. In this evaluation, it was specified that the CO2-snow cooling process performed better than the LN2, MQL and dry machining conditions, respectively [71]. In another study, the nanoagents protect the oil droplets, stopping the immediate release of cutting oil from the cutting area, resulting in better lubrication. However, a deterioration in tool lifecycle and surface roughness occurs with the rise of the hBN ratio in the cutting fluid [72].

5. EVALUATION FOR OUTSTANDING MACHINABILITY INDICATORS (ÖNEMLİ İŞLENEBİLİRLİK GÖSTERGELERİ AÇISINDAN DEĞERLENDİRME)

5.1. Cutting Forces (Kesme Kuvvetleri)

The efficiency of the cutting process is determined by the cutting conditions (cutting speed, cutting depth and feed rate), cutting force that is affected by the shape of the cutting tool and the characteristics of the workpiece material. All methods of reducing cutting resistance extend tool life and improve the finish of machined parts. Cutting loads can be reduced by using textured tools in machining as described below [73]. Again, cutting resistance, which is likely to be directly affected by controllable and uncontrollable parameters during machining (feed, cut depth, cutting speed, insert geometry, chip shape, workpiece, temperature, etc.) has an impact on tolerance violations [74]. Additionally, in the force modelling, relative to chip flow direction is permitted better predictor of cutting forces when using round inserts as well as a third component. Cooling technologies also have an effect on the cutting force. For example, lower cutting forces in MQCL cutting conditions are due to lower friction forces at the tool/chip and tool/workpiece interfaces [75].

In addition, superior cooling and lubrication performances and light tool wear also help to generate lower cutting forces. In a study, it was stated that minimum residual stress and shear force could be obtained by using the MQL-SiO_2 nano lubrication system [76]. In another study, in according to the dry machining environment, it was stated that the cutting force was reduced by approximately 0.3 percent and 6 percent with NFMQL with a blend of BF-MQL and hBN [74]. The formation of chip segments with the complete breaking mechanism provided a high segmentation rate in the MQL condition. The chip thickness ratio measured in the flood and MQL is less than in dry cutting. As a result, it shows the need for lower energy consumption in the above mentioned environments. On the other hand, the negative effects of the flood on the coating cause high cut forces in entire coolant conditions [77]. When using copper oxide-based nanofluid, the thin laminar structure creates less shear force and therefore lower shear temperature. [78]. Cryogenic cooling from the inside of the cutting tool with liquid nitrogen is further active than dry and conventional cutting oil applied end milling in producing appropriate machinability indicators such as lower force, improved surface texture and reduced cutting energy. Thus, the use of this cooling technology supports sustainability [79].

The use of coated or uncoated tools is another factor affecting cutting forces and thus machinability. The use of TiN/AlN multilayer coated tools resulted in a 9% reduction in surface roughness and cutting force [80]. Uncoated carbide cutting tool has greater cutting force than coated tool. In the study, a 39.79% lessening in cutting force was recorded when the coated tool was used when the highest cutting speed was selected. A higher insert temperature occurs in the coated tool than in the uncoated tool. At low cutting speed, the existence of adhering material and obvious friction marks were observed on the back surface of the chip [81]. Another factor affecting cutting forces is microstructure. In a study evaluating the cutting forces, especially when machining hard titanium alloys, thermal softening led to a reduction in yield stress when the temperature increased. Strain rate hardening also enhances the material hardness. The increase in hardness in machining also causes an rise in cutting forces [82]. In another study, the wavy cutting edge spent longer time in the cutting region than the standard helical cutting edge. In this case, the cutting force reduced the fluctuation range and improved the end milling dynamics [83].

5.2. Tool Life (Takım Ömrü)

Factors affecting tool life during machining are cutting parameters, workpiece material and coolant. Tool life is investigated by wear evaluation as it is in reverse linked to each other. Wear mechanism and surface texture also significantly influence tool life. The friction at the cutting interfaces spoils the surfaces that are being formed and affects the wear (tool life) of the tool, which causes manufacturing costs. A hybrid cooling / lubrication technology reduces surface roughness with hybrid cooling, reducing friction between tool and workpiece [84]. Another important application used in extending tool life is cryogenic cooling. At the same time, having an environmentally friendly cooling feature allows the acceptance of fine cooling technologies [79]. When a tool life model based on tool wear has been developed, the said hybrid cryogenic MQL has 30 times longer insert life compared to machining with current liquid coolers. By using the hybrid cryogenic cooling system at low and medium cutting velocities, the longest tool life of 1198 minutes was obtained in thermomechanical tool wear [85]. In a study, the effective wear mechanisms in tool wear were specified as abrasive and adhesive wear. It was also found that among the four applications of coolant (liquid, dry, MQL, and nano-fluid MQL), the nano fluid gives better outcomes at various cutting parameters from the point of tool life and surface finish [86]. Coated carbide generally gives a longer tool life than an uncoated tool as it provides superior wear resistance, but this is not always true when applied with an incorrect coating and an unsuitable condition. For example, a GC3015 grade did not outperform an uncoated tool from the point of tool life at distinct cutting velocities and feed ratios, as long as the depth of cut did not exceed 1.0 mm [87]. The data reveal that increasing the cutting speed significantly reduces tool life and affects the coating on the tool. In general, coated tool has further tool life than uncoated tool material. Notch wear is a main problem when a ceramic tool has been used for the first time in a nickel-based superalloy machining experiment [88]. Notch and flank wear have been cited as major problems in dry turning of the Inconel 718 [89]. The problems in the ceramic cutting tool are strongly related to the cutting parameters. Notch, nose and flank wear mechanisms are seen in the machining of superalloys with these tools. Nose wear was decreased by 50-65% and surface roughness under atomization-based coolant (ACF) was reduced by 39-51% due to solid lubricants that limit notch wear and tool edge breakage at the tool-chip interface [90]. Thinking the necessary properties of insert materials for machining nickel-based superalloys, ideally PCBN has a great application as it has an outstanding hardness at high temperatures. However, since these tools do not have chip breakers, there is a problem of chip breaking, and unbroken chips cause shortening of tool life or tool breakage [91]. A study examining the machinability of three different titanium alloys (Ti-64, Ti6264, Ti-5553) with carbide TiAlN-PVD coated and uncoated tools indicates that cutting tool wear is greater on uncoated inserts, indicating that the insert may be at elevated temperatures during machining. In addition, wear on the curved surfaces of the coated inserts operated in Ti-64 and Ti-6246 appears to be sticky in nature [92]. A research was performed on the chip removal performance of coated tools in milling of Ti6Al4V. In this research, the tool edge radius of uncoated, AlCrN centered, AlTiN centered and TiN coated end mills were 0.41 µm, 0.90 µm, 1.2 µm and 1.5 µm. According to the results, the wear of the uncoated micro end mill was high and chipping occurred on the cutting edge. The AlCrN centered coated mill set showed the maximum wear resistance [93]. A study on tool wear in milling of Ti-6Al-4V alloy using PVD and CVD coated tools was conducted. The cutting tool is coated with multi-layer TiAlN. It is stated that in tool wear, the effects of cutting depth on PVD and CVD coated inserts are more dominant, followed by cutting speed and feed rate [94].

3.4. Surface Integrity **(Yüzey Bütünlüğü)**

It is characterized by changes in surface integrity, topographical, mechanical and metallurgical properties of the surface. Ti alloys and Ni-based superalloys are one of the difficult materials to process due to their high temperature resistance, high speed deformation strengthening and small thermal conductivity, and the existence of finely structured abrasive precipitates. It is known that the processed surface structure has a great influence on the equipment performance of parts such as fatigue life, wear and corrosion strength, and is closely connected to cutting conditions. It was also found that the fine structure of the alloy produced by the laminating process, unlike casting and forging, also affects the surface finish of the laminated geographic feature after the laminating process [95]. As shown in Figure 10, classics related to surface topography (defects and roughness), microstructure changes (deformation, particle miniaturization and texture) and mechanical characteristics (fine hardness and residual stress).

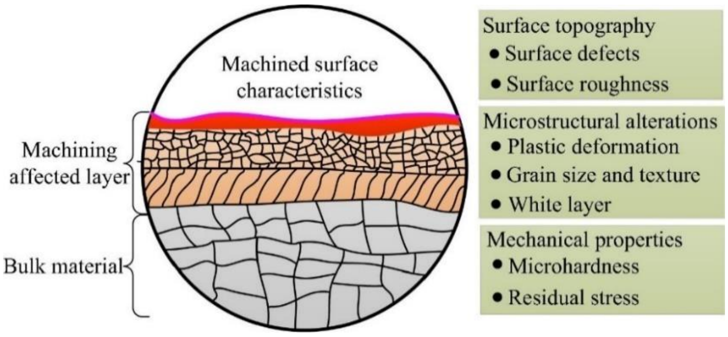


Figure 10. Scheme of machined surface integrity properties (İşlenmiş yüzey bütünlüğü özellikleri şeması) [96]

A variety of surface integrity analysis methods are used in the analysis of machined surfaces. A variety of tools and systems are used to measure and describe surface topography, as well as white light interferometric SEM and 3D laser imaging [97]. Three main systematic methods, including X-ray, mechanical earring, ultrasonic and magnetic method, and neutron diffraction method, are applied to regularly evaluate the residual stress of the treated surface [98]. Specially, the X-ray procedure is thought one of the best sophisticated techniques. The depth gradient dispersal of remaining stress here is measured via electrolytic polishing, removing the substrate layer of material [99]. In one study, the surface integrity formed during high speed turning of two different nickel-based superalloys was evaluated using a CBN insert under jet flow cooling conditions. Surface faults occurred on the machined surface of the alloy, including carbide cracks, firing flow and contamination, which affected the coating of all cutting tools. In addition, high-precision deformation was observed under the surface of the alloy [100]. Besides cutting speed, feed rate and cutting depth, insert wear also has a major effect on the alteration of surface topography. This outcome is especially noticeable in the case of quick tool wear when machining Ti and Ni alloys [97]. The effect of deformation hardening, which means a rise in hardness and strength of a ductile metal during plastic deformation, on the behavior of the microstructure of Inconel 617 was examined. Unique models have been recommended to describe the plastic and deformation hardening behavior of this material. Among the five associations suggested for the characterization of deformation hardening parameters of metallic materials, it was stated that the one proposed by Ludwigson best fits the experimental data. In addition, the contact of dislocations with carbides and γ' particles has been clearly determined by transmission electron microscopy that they lead to high deformation hardening at 700 °C [101]. Surface materials processed by processing Ti and Ni alloys will increase deformation resistance and significantly reduce plasticity. This condition is called work hardening and is related to the effects of thermomechanical stress. [102]. Several studies have shown that hardening behavior is mostly dependent on grain size and plastic deformation, whilst softening behavior is associated with dynamic precipitation and recovery as well as cavitation formation [103]. Surface imperfections belong to a serious problem in micro-surface integrity. Regardless of other cutting parameters, worn cutting tools have higher surface damage than new tools. In a study, the formation mechanisms of surface faults machined in unique tool wear conditions were analyzed. Formed surface, which includes surface breaking, pits, tearing, hollows, side flow, smearing and surface burn, has been reported to be associated with high thermomechanical loads when thinking tool wear [97].

5. CONCLUSION AND RECOMMENDATIONS (SONUÇ VE ÖNERİLER)

In this study, Ni-based superalloy and Ti alloy, which are among the superalloys used in aerospace applications, have been introduced first. For these alloys, machinability factors such as cutting tool material, cooling/lubrication technology, and machinability indicators such as cutting force, tool life and surface integrity, which directly affect both the quality of the machined part and the machining costs, were evaluated.

Also known as elevated temperature materials, superalloys; nickel-based alloys, cobalt-based alloys, iron-based alloys and titanium alloys. Among these, it is striking that Ni-based alloys are used much more widely than Ti alloys and therefore more widely used in the aerospace industry. Since Ti alloys have the highest strength / weight ratio among metals, composite materials have found an increasing use in the aviation industry. These alloys, produced in three different alloy modifications of α, α + β, β type, have high corrosion resistance and chemical stability, excellent impact and abrasion resistance. Ni-based superalloys have mechanical and physical features such as superior temperature resistance and toughness, high corrosion resistance, excellent fatigue and creep resistance. Casting, forging, powder metallurgy and machining methods are used in the process of shaping components used in the aviation industry from superalloys. However, many components are mostly manufactured using machining methods due to the part geometry, the required size and surface quality requirements. On the other hand, superalloys are hard to process materials thanks to their great temperature resistance, quick strain hardening, low thermal conductivity and the existence of abrasive deposits. In this context, it is seen that the researches made for improving the machinability of superalloys are increasing day by day.

In the studies on the processing of superalloys, it is observed that machinability indicators such as tool wear and life, surface integrity, cutting forces and surface roughness for machining operation type, coolant, cutting parameters and tool grade and geometry are evaluated. Cutting forces are one of the most important parameters to be determined for accurate machining. Optimization of other factors such as cooling/lubrication technology, tool life, energy consumption depends on the correct determination of cutting forces. Ceramic and CBN tools are used in the machining of Ti alloys and Ni-based superalloys, uncoated and coated inserts and continuous cutting applications at higher cutting speeds. It is seen that coating application with PVD and CVD technologies increases the cost of tooling, but it is seen that coated tools are used more widely due to the improvement of tool performance, but it is seen that nanocoating applications are increasing. When machining these alloys in dry cutting environment, high cutting forces and temperature, BUE creation on the cutting edge and high thermal-mechanical stresses cause rapid wear, especially in carbide tools. At the same time, these problems are the main causes of surface defects such as burning, tearing, micro cracks, increase in surface roughness, deformation hardening due to excessive plastic deformation, microhardness increase to a certain depth and residual stress formation on the processed material. With the correct selection or optimization of parameters for instance cutting speed, feed rate, cutting depth, insert geometry, these formations can be improved to some extent. Optimizing cutting forces will allow a more economical machining process to be prepared in the future. In this context, it is noticed that new cooling / lubrication technologies have been developed for enhancing tool life, keep surface integrity at the desired level and reduce machining costs. Depending on the type of processing, it is recommended to use techniques such as compressed air cooling, cryogenic cooling (LN_2, CO_2-snow), MQL and nano-fluid MQL. In particular, the industrial widespread use of MQL technology with numerous vegetable oil content will both reduce the use of lubricants in machining and will make significant contributions in terms of the damage caused by traditional cutting fluid to the operator and the environment. It seems possible to improve the machinability characteristics of superalloys with the correct selection and application of the cooling / lubrication system as well as the appropriate cutting parameters and cutting tool selection according to the material being processed.

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