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Advanced Techniques in Machining of Aerospace Superalloys: A Review

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Abstract

Aerospace Superalloys are heat-resisting alloys based on nickel, nickel-iron, or cobalt that exhibit a combination of mechanical strength and resistance to surface degradation. They have unique combination of properties like high strength at elevated temperatures, resistance to chemical degradation and wear resistance & ability to maintain these properties at elevated temperatures severely hinders the machinability of these alloys, thus they are generally referred to as difficult-to-cut alloys. The aerospace and space sector has traditionally been promoter for the development and application of advanced superalloys. The demand for these materials is generally spurred by the performance requirement of component, which usually an integral part of complex technical system. Improvements achieved from research and development activities in this area have particularly enhanced the machining of difficult to cut nickel base and titanium superalloys that have exhibited low machinability due to their peculiar characteristics such as poor thermal conductivity, high strength at elevated temperature, resistance to wear and chemical degradation, etc. The present review paper highlights an overview of major advances in machining techniques that have resulted to step increase in machinability. Hence lower manufacturing cost, without adverse effect on the surface finish, surface intergrity, circularity and hardness variation of machined component.

Keywords: *High temperature alloys; Hot machining; Rotary cutting tooling, cryogenic cooling.*

INTRODUCTION

1.1 What is Superalloys?

A superalloy, or high-performance alloy, is an alloy that exhibits excellent mechanical strength and resistance to creep (tendency for solids to slowly move or deform under stress) at high temperatures; good surface stability; and corrosion and oxidation resistance. Superalloys typically have a matrix with an austenitic face-centered cubic crystal structure. Superalloy [1,2] development has relied heavily on both chemical and process innovations and has been driven primarily by the aerospace and power industries Superalloys are heat-resisting alloys based on nickel, nickel-iron, or cobalt that exhibit a combination of mechanical strength and resistance to surface degradation. Because they have unique combination of properties like high strength at elevated temperatures, resistance to chemical degradation and wear resistance. Ability to maintain these properties at elevated temperatures severely hinders the machinability of these alloys, thus they are generally referred to as difficult-to-cut alloys. Hence, The driving force for the continual development of many materials over the years is the need for harder, stronger, tougher, stiffer, more corrosion resistant or oxidation resistant material that can also exhibit high strength to weight ratio, in the case of aero-engine alloys and also ability of retain high mechanical and chemical properties at elevated temperatures make superalloys ideal materials for use in both rotating and stationary components in the hot end of jet engines.

There is significant advances has been made in understanding the behaviour of aerospace superalloys materials at higher cutting condition from practical and theoretical point of view. A lot of research is going on machining of low machinability aerospace materials. Specially, the new research is focussed on manufacturing process new tools & machining system. The typical problems that can be associated with machining operation range from high cost of consumable tooling & set up time for high volume production to components often requiring several machining operations, thereby making it difficult to effectively control the machine shop & consequently an increase in work in process. These, in addition to large amount scrap produced, tend to form the basis for continued research and development activities in this area of manufacturing technology. The aerospace and space sector has traditionally been a promoter for the development and application of advanced superalloys. The key issues to be addressed by advanced material development are material properties, material fabrication and finally costs. The availability of suitable fabrication methods plays a crucial role with regard to both material properties and costs and may therefore finally determine whether an advanced material will find application.

1.2 Types of Aerospace Superalloys

The following are the some of the major superalloys used in aero-space industry along with uses: [1]

a) **Nickel-based**: There are superalloy which are the most widely used, and currently constitute over 50% of the weight of advanced aircraft engines. They exhibit higher strength to weight ratio, relative to steel that is denser. They are used in these aggressive environments because of their ability to maintain high resistance to corrosion, mechanical and thermal fatigue, mechanical and thermal shock, creep and erosion at elevated temperatures.

b) **Titanium alloys**: There were developed in order to satisfy the need for a class of strong and lightweight materials for aircraft engine and airframe manufacture, because of their outstanding strength to density ratios. They are also widely used in many other industries because of their good corrosion resistance as well as a range of mechanical and physical properties that can be developed.

c) **Cobalt based alloys**: There are alloys display superior hot corrosion resistance at high temperatures compared to nickel-based alloys. But they are more expensive and more difficult to machine, and hence their use in turbines is restricted to combustion parts in the hottest engine areas. They are also used for components in nuclear reactors and surgical implants, which utilise their inherent corrosion resistance.

d) **Iron base alloys**: These are weaker at elevated temperatures than nickel alloys, are in chemical processing applications such as heat exchanger, piping, retorts, mixing tanks, heat treatment equipment, muffles, conveyors, baskets and boxes.

Out of all above mention aerospace superalloy nickel and titanium based are mostly used in aerospace industry.

1.2 APPLICATIONS OF SUPERALLOYS

- Steam turbine power plants: bolts, blades, stack gas re-heaters
- Reciprocating engines: turbochargers, exhaust valves, hot plugs, valve seat inserts
- Metal processing: hot-work tools and dies, casting dies
- Medical applications: dentistry uses, prosthetic devices
- Space vehicles: aerodynamically heated skins, rocket engine parts
- Heat-treating equipment: trays, fixtures, conveyor belts, baskets, fans, furnace mufflers
- Nuclear power systems: control rod drive mechanisms, valve stems, springs, ducting
- Chemical and petrochemical industries: bolts, fans, valves, reaction vessels, piping, pumps
- Pollution control equipment: scrubbers
- Metals processing mills: ovens, afterburners, exhaust fans
- Coal gasification and liquefaction systems: heat exchangers, re-heaters, piping.
- Aircraft gas turbines: disks, combustion chambers, bolts, casings, shafts, exhaust systems, cases, blades, vanes, burner cans, afterburners, thrust reversers

1.4 Difficulty in Machining of Superalloys

The Machinability of aerospace alloys will continually decline as service demands increase in order to satisfy the demand for higher temperature capability for structural engine alloys. Machinability [2,4] of a material is mainly assessed by measuring the tool life, surface finish generated and component forces during a cutting operation. Poor machinability of aero- engine alloys, particularly nickel-based and titanium alloys, are due to their inherent characteristics, which include the following :

1) The high strength of nickel-base superalloys at cutting temperatures causes high cutting forces, generates more heat at the tool tip (compared to alloy steel machining), and limits their speed capability. High hot hardness and strength causing deformation of the cutting tool during machining.

2) High dynamic shear strength during cutting process, resulting in localisation of shear stress and the production of abrasive saw-tooth edges which encourage notching of cutting tools when machining titanium alloys.

3) The austenitic matrix of nickel-based alloys causes rapid work hardening during machining. This is one of the major causes of severe wear at the depth of cut line.

4) Low thermal diffusivity, leading to localisation of cutting temperatures at the tool tips to cause high thermal gradient. The low thermal conductivity of these alloys transfers heat produced during machining to the tool, subsequently increasing tool tip temperatures and causing excessive tool wear, which can limit cutting speeds and reduce useful tool life.

5) Welding of the workpiece to the tool cutting edge forming unstable built-up edge which deteriorates machined surfaces as well as worsening components integrity.

6) The high capacity for work hardening in nickel-base alloys causes depth-of-cut notching on the tool, which can lead to burr formation on the workpiece & the chip produced during machining is tough and continuous, therefore requiring acceptable chip control geometry

Hence, effort has been made for continues improvements in machinabilty of aerospace superalloys. The poor machinability of aerospace superalloys subject cutting tool materials to extreme thermal and mechanical stresses close to the cutting edge, often leading to plastic deformation and accelerated tool wear. The Cutting tools used for machining aerospace superalloys should possess adequate hot hardness to withstand elevated temperatures generated at high speed conditions. Under these conditions most tool materials generally lose their hardness resulting in the weakening of the inter-particle bond strength and consequent acceleration of tool wear. Cutting tool materials often encounter extreme thermal and mechanical stresses close to the cutting edge during machining due to the poor machinability of nickel base and titanium alloys. However, Efficient machining of aerospace alloys depends on the choice of tool materials, cutting speed, processing time and the functionality of the machined component for an economic production.

2 ADVANCED MACHINING TECHNIQUES FOR SUPERALLOYS

2.1 SPRT (Self Propelled Rotating Tool).

The principal difference between rotary cutting and conventional cutting is movement of rotary tools in addition to main cutting and feed rate motion. The addition movement of rotary tools results in a portion of cutting edge begin in action for only a brief period, followed by long rest period which permits the conduction of thermal energy, associated with cutting process away from the cutting zone. Tool [5] is motivated by either external driver or by self-propelled action of cutting forces exerted on tool by adjusting its axis at an inclination with respect to cutting velocity. The former is called **DRT(Driver rotary tool)** & later is called **SPRT (self propelled rotating tool).**The rotation of the tool ensures that the entire circumference of the round insert is used for machining, with portions of the circumference in cutting action periodically. This ensures that tool wear is uniformly spread across the cutting edge. The superior wear resistance and extra ordinary improvement in tool life of the SPRT technique, relative to conventional turning, when machining nickel and titanium base super- alloys can be attributed to the reduction in relative cutting speed, the use of the entire cutting edge and the lower cutting temperature associated with improved heat transfer as a result of the rotation of the tools during machining.

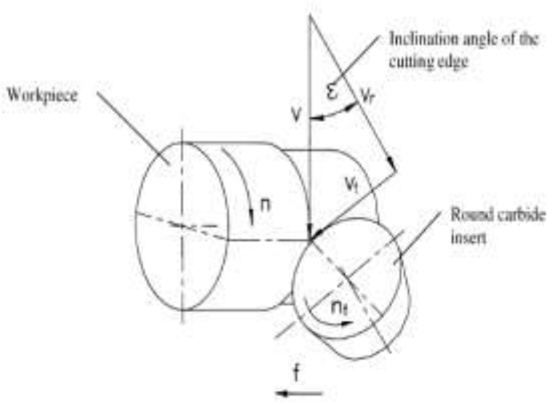

Figure.2.1 Principle of rotary cutting [5]

The constant shifting of the cutting edge during rotary machining results in shorter tool & workpiece contact time. Therefore, the wear rate of a rotary tool may be influenced by the ratio of the length of the entire round edge to the length of the cutting edge engaged at a time. Machining of aerospace alloys with SPRT generates better surface finishes even at higher feed rate and compressive residual stresses than in conventional cutting. The improved tool performance is also due to the very low flank wear rate as a result of reduced amount of work done in deformation and friction at the primary shear zone and on the rake face, respectively, as well as the improved heat transfer from the cutting zone due to the tools rotation during the machining process. Cutting and radial forces generated with SPRT techniques are lower than those obtained in conventional machining due to reduced amount of work done in chip formation and lower friction on the rack face of the tool under rotary cutting. An increase in inclination angle will lower the cutting force due to increased rotary speed and higher effective angle of the SPRT, while feed force increase due to increased feed resistance at higher inclination angles.

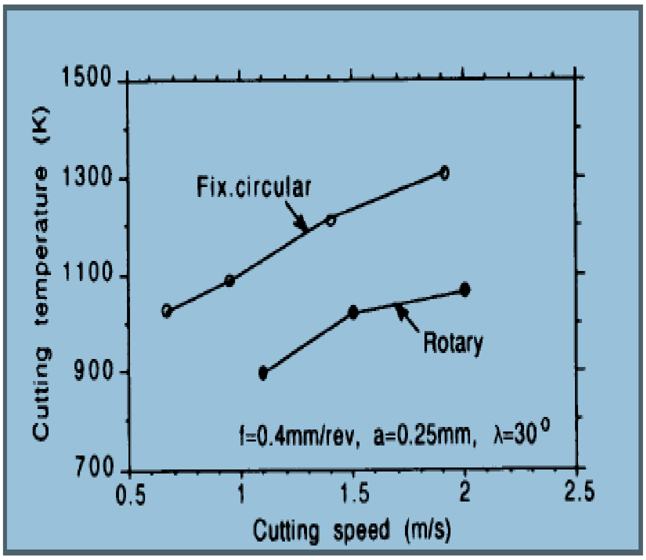

Figure 2.2 The cutting temperature v/s cutting speed in machining superalloy **[7]**

The study was conducted by researcher [7] for the evaluation of the cutting force and cutting temperature in relation to machining by this technique & the temperature analysis was done based on model of heat source moving cyclically along the cutting edge. Both analytical and experimental results indicate that the rotating motion of the cutting edge transfers heat away from cutting zone with result being a reduced cutting temperature. The cutting forces and temperature also drop significantly when machining Ti-6Al-4V alloy with use of this technique.

Limitation:

1) No matter how precise (or accurate) the rotating parts have been produced, a cutting edge in motion may always generate more errors that a stationary one.
2) Severe chatter may occur due to the large tool radius and poor stiffness of the rotary system.
3) The round inserts used in the SPRT failed mainly by chipping, caused by thermal and mechanical shock induced by the continuous shifting of the tool edge during machining.
4) Slight deterioration in surface finish occurs when machining at higher feed rate due to increased smearing action between the tool and the workpiece.

2.2 High Pressure Coolant Delivery

The use of a high-pressure coolant supply during machining is one of the many ways to dissipate extensive heat generation in the cutting zone. Machining with high pressure coolant supply enables the coolant flow to traverse the machined surface faster, significantly increasing heat transfer of the coolant, penetrating deep into the cutting area and achieving high chip breakability through increased chip curl. This consequently reduces the tool-chip contact area, minimises friction at the tool-chip interface, removes more heat from the cutting region and consequently improves tool performance during machining.

The primary objective of this machining technique is to significantly reduce the temperature generated at the tool-workpiece and tool-chip interfaces when cutting at higher speed conditions. This is achieved by directing coolant under high pressure at the chip-tool interface this process can also achieve high chip breakability and control through increased chip upcurl and compressive stress. Flood cooling of the cutting zone can effectively reduce the cutting temperature when machining at lower speed conditions with significant sliding region and where relatively low cutting temperatures are generated. The coolant also acts as a lubricant, thus minimising friction and lowering component forces and consequently tool life.

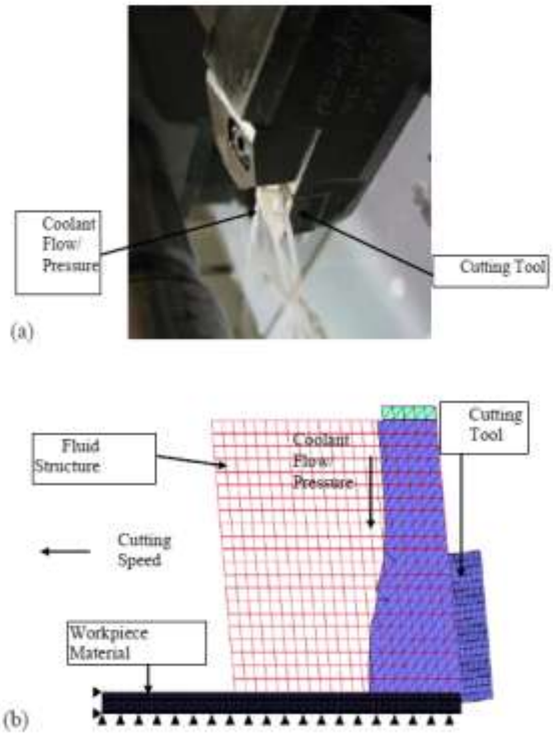

Figure 2.3 (a) Machining with high pressure coolant (b) The model for the cutting process with conventional coolant and high pressure coolant delivery.[9]

Coolants tend to be vaporised by the high temperature generated close to the tool edge, forming a high temperature blanket that renders their cooling effect ineffective. The high speed coolant jet traverses the surface faster, thus significantly lowering the film boiling action of the coolant at the cutting area. This consequently minimises heat transfer to the cutting tool.

During machining with conventional coolant, the applicant of coolant has neglible effect on the resultant cutting force where comparsion with dry machining exhibited almost similar value. This is due to the fact the cutting fluid has neligible access to tool workpiece or tool chip interfaces due to high pressure between the cutting tool and the workpiece material. Such a chip type hinders coolant access to the cutting zone and increases the tool chip contact length/area, this restricts coolant ability to provide cooling and lubrication at the tool chip-tool interface resulting in a temperature rise and consequently accelerating tool wear developing within a short time, leading to substantially higher cutting forces during machining. When high-pressure coolant is employed, the high-pressure jet provoked the chip to bend and consequently induce chip breakage. This provides more space for the high-pressure coolant to penetrate the cutting region. The temperature difference between the coolant and the tool-chip interface along with the continuous flow of coolant additionally enhance heat removal from the cutting zone resulting in further reduction in the cutting tool temperature.

The study conducted by the researchers [9] presents a series of finite element models for high-pressure jet-assisted machining of Ti-6Al-4V superalloy. The resulting motion of fluid at the tool-chip interface, chip breakage, cutting force as well as temperature generation at the tool-chip interfaces was interpreted, analyzed and compared with their real experimental results. The models simulate interactions between the fluid and solid structure, where continuous chip formation was observed when simulation in conventional coolant supply while chip breakage was clearly evident as high-pressure coolant was introduced. Increasing coolant pressure significantly reduces the friction at the tool-chip interface, which significantly reduced the cutting force and cutting temperature.

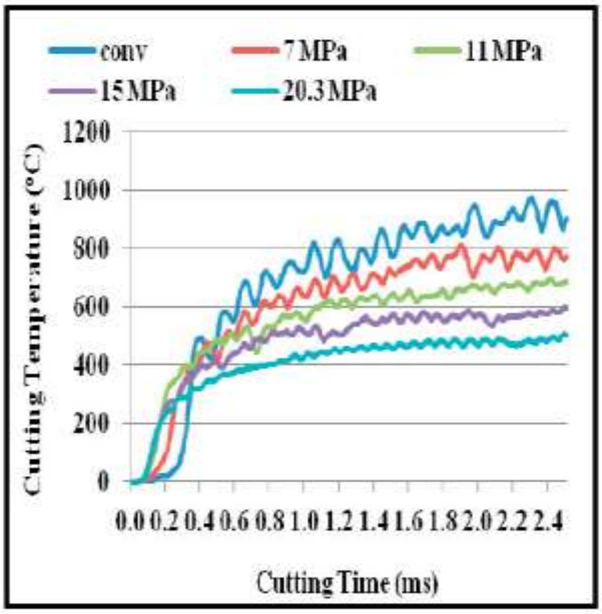

Figure 2.4 Effect of temperature generation in machining with high pressure coolant delivery [9]

2.3 CRYOGENIC MACHINING

The cryogenic machining, which is able to both lower the cutting temperature and enhance chemical stability of the workpiece and the tool, is expected to greatly increase productivity level in the machining of titanium and its alloys. Liquid nitrogen as a cryogenic coolant has been widely use especially for machining superalloys. Liquid nitrogen is safe to environment and requires no disposal facilities.

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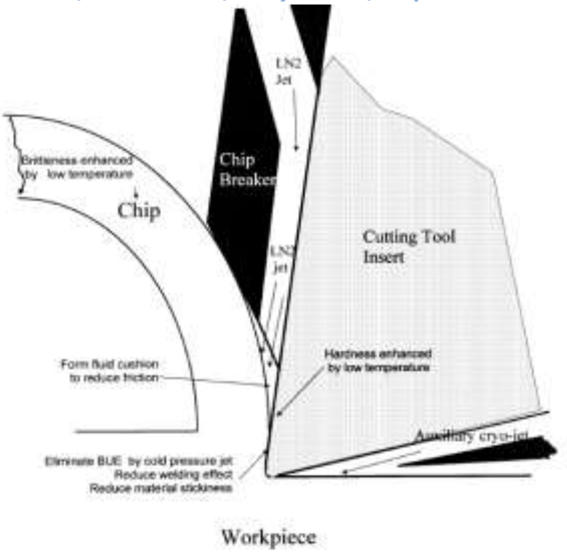

Figure 2.5 Schematic of Cryogenic cooling approach [11]

The above figure shows the cryogenic machining cooling concepts using a flat cutting insert with an obstruction chip breaker. Liquid nitrogen is released through a nozzle between the chip breaker and the rake face of the tool insert. The chip breaker helps to lift the chip to allow liquid nitrogen to reach and cool the highest temperature spot the tool chip interface. Unlike general flooding, the chip does not block the flow of liquid nitrogen. The liquid nitrogen absorbs the heat, evaporates quickly, and forms a fluid/gas cushion between the chip and tool face that functions as a lubricant. Consequently, the coefficient of friction is reduced. Both the lubrication effect and cooling the hottest spot reduce the tool temperature, in turn effectively reducing both crater and flank wears. An auxiliary cryogenic nozzle may be added to cool the flank face near the cutting point for further reduction of flank wear.

Cryogenic machining is an environmentally safe alternative to conventional emulsion cooling. The literature review on these techniques [11] reveals that liquid nitrogen is applied to cutting Ti-6Al-4V, a difficult to machine but widely used material in aerospace industry. With the goal of identifying approach for most effectively and economically using cryogenic machining, this study evaluated cutting temperature obtained under various cooling conditions and introduces an innovative and economical suspending method that directs liquid nitrogen through micro-jets to the flank, the rake or both near the cutting edge. The cutting temperature was compared with the conventional dry cutting and emulsion cooling. The researcher found that cooling approaches in order of effectiveness (worst to best) to be: Dry cutting, Cryogenic tool back cooling.

2.4 PLASMA HOT MACHINING

The principle behind hot machining is the reduction of the large difference in hardness of the cutting tool and workpiece, leading to reduction in the component forces, improved surface finish and longer tool life. The heating techniques include electric current, arc, high frequency induction, and plasma jet. The manufacturing industry has explored various heating methods but all had limited applicability and were not suitable in all the circumstances. .

These limitations meant that hot machining processes provided no practical value to the manufacturing industry until 1970 when there was a break through with plasma arc hot machining process.

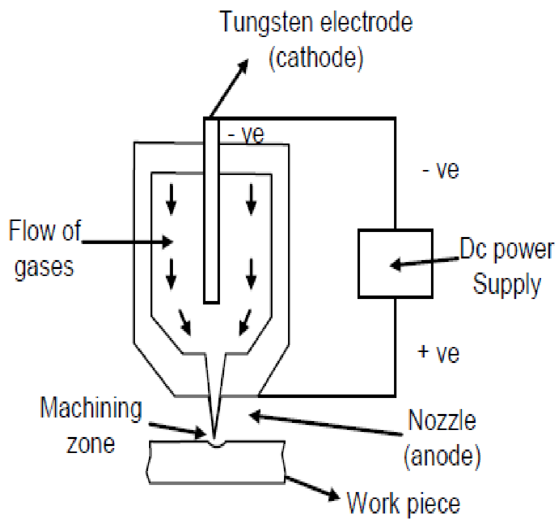

Figure.2.6 Working Principle and Process Details of PAM [13]

Plasma assisted hot machining operation utilizes a high temperature plasma arc to provide a controlled source of localised heat which softens only that small portion of the workpiece removed by the cutting too in the form of chip while retaining the metallurgical features of the remaining workpiece. Softening of the workpiece zone just in front of the cutting tool releases very high energy densities and confines the heat. A plasma arc consists of a high velocity, high temperature stream of ionized gas capable of supporting a high current (16,000–30,000 C), low voltage electric arc. Major benefits of this process are: increased metal rates; ability to machine hard and tough metals even when fully hardened and heat treated; no metallurgical damage to the machined surfaces, increase in tool life, suitability for interrupted cuts and cost saving in machining components.

Advantages of PAM Process

It gives faster production rate & Very hard and brittle metals can be machined. Small cavities can be machined with good dimensional accuracy.

Disadvantages of PAM Process

Its initial cost is very high, The process requires over safety precautions which further enhance the initial cost of the setup and Some of the workpiece materials are very much prone to metallurgical changes on excessive heating so this fact imposes limitations to this process.

CONCLUSION

a) The use of SPRT (self propelled rotating tooling) is greatly reduce the cutting temperature, cutting force, tool wear and also permits the high speed machining. Hence, increases the productivity of overall machining process. However, there are limitation which permits its use not in all circumstances.

b) The use of high pressure coolant delivery also reduces the cutting temperature, force as compared to conventional coolant delivery. It is discussed that as we increased coolant pressure, there is reduction in temperature in cutting zone which increase tool life & productivity.

c) The use of cryogenic machining approach has been discussed & this approach uses a minimum amount of LN_2 injected through a micro-nozzle formed between the chip breaker and the tool rake and assisted by the secondary nozzle for flank cooling. In this manner, LN_2 is not wasted by cooling unnecessary areas and reduces the negative impact of increasing the cutting force and the abrasion of pre-cooling the workpiece material. This cryogenic machining approach yields the best tool life compared with any machining method.

d) The use hot machining method also proves advantage of machining of the materials which have large difference in hardness.

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