1. Introduction

Development of superalloys and processing have been the focus of considerable research effort over the last 5 decades. The range of superalloys available to meet the specific requirements includes iron, cobalt, titanium and nickel based alloys. The nickel-based superalloys are characterized by their high strength at elevated temperature, together with high corrosion resistance and good fatigue properties. Inconel 718 is getting wide applications for its excellent strength properties, even at elevated temperatures, availability and reasonable cost in addition to material homogeneity, ductility, formability and resistance to creep and corrosion. Inconel 718 is commonly used as a benchmark in assessing the machinability of superalloys relative to other workpiece materials [1].

But like other superalloys Inconels are quite difficult to machine in comparison to conventional metals and alloys like steels. As a result of poor machinability in processes like turning milling, etc., and the consequent problems including poor surface integrity, grinding is often preferred for semifinishing and finishing such superalloys. However, even in grinding difficulties are encountered due to their high temperature - strength characteristics.

1.1 Characteristics of Inconel 718

Inconel 718 is an Iron-Nickel based superalloy available in both cast and wrought form. In general, cast form is used in the hot section area of gas turbines, etc. Wrought forms are obtained from cast billets but are deformed and reheated number of times to get the final forms having the required properties. Wrought forms are more homogenous than cast forms. It is available in annealed form, but also some times as solution treated and aged to impart high strength and ductility.

Nickel based superalloys get their strength mostly from solid solution and precipitation phases. Principal strengthening precipitate phases are the γ' and γ'', that are found in Inconel 718. Gamma prime (γ') is an inter metallic compound that precipitates in an FCC matrix, with chemical formula Ni_3Al, generally expressed as $Ni_3(Al, Ti)$ as the aluminium (Al) can be substituted by the titanium (Ti). An ordered FCC crystal structure of γ' phase is schematically shown in Fig.1.1. where ● (solid circles) indicate nickel atoms, shared with adjacent cube, ○ (open circles) indicate aluminium or titanium atoms, shared with eight cubes at each corner and ⊜ and ◌ (doted circles) show hidden atoms. Nickel atoms are on faces, titanium or aluminium atoms are at cube corners [2].

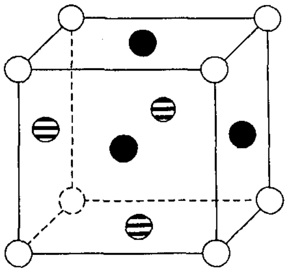


Fig.1.1 An ordered FCC crystal structure of γ' phase.

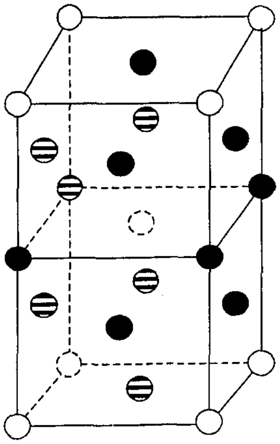


Fig.1.2 Line sketch, crystal structure of a γ'' phase.

Gamma double prime (γ'') is the principal predominant strengthening phase in Inconel 718. These γ'' precipitates have a body centered tetragonal (BCT) structure and generally precipitate as coherent disc shaped particles (on the {100} planes), and can also precipitate as orthorhombic structure or as plates [3, 4]. The chemical formula is Ni_3Nb. The γ'' phase having a BCT structure is schematically shown in Fig 1.2. where ● and ⊜ *indicate nickel atoms,* ○ *and* ◌ indicate niobium atoms and ◌ and ⊜ show hidden atoms [5].

Inconel 718 also gets its strength from the precipitation of MC, M_6C and $M_{23}C$, etc., types of carbides. The Iron, Chromium, Molybdenum, Niobium or Titanium, etc., either as a single element or in more number of elements combine with Carbon to form the above carbides.

1.1.1 Composition of Inconel 718

Inconel 718 is generally composed of (in wt %) [2]

Nickel – 52.5%.
Chromium – 19.0 % .
Iron – 18.5 %.
Niobium – 5.1 %.
Molybdenum – 3.0 %.
Aluminium – 0.5 %.
Titanium – 0.9 %.
Carbon – 0.08 %.

1.1.2 Physical and Mechanical properties of Inconel 718

The salient properties of Inconel 718 as compared to Bearing Steel and Ti6Al4V superalloys are listed in Table 1.1

Table 1.1 Properties of Bearing Steel, Ti6Al4V and Inconel 718. [2, 6, 7]

materials properties	Bearing Steel IS: 103 Cr1	Ti6Al4V	Inconel 718
Density (gms/cc)	7.7 – 8.03	4.42	8.19 – 8.22
Melting Point	≈1540 °C	1649 ± 15 °C	1260 ~ 1335 °C
Hardness	62 HRC (hardened)	36 HRC (annealed)	36 - 40 HRC (annealed) 40 – 50 HRC (age hardened)
Thermal Expansion Coefficient (α)	11.9 x 10^{-6}/°C (at 0°C – 100°C)	8.6 x 10^{-6} / °C (upto 100°C) 9.2 x 10^{-6} / °C (at 300 °C)	13.0 x 10^{-6} / °C (upto 100°C) 14.4 x 10^{-6} / °C (at 500 °C)
Thermal Conductivity (K)	46.6 W/mK	7.2 W/mK	11.4 W/mK
Specific Heat	481 J/kg K	560 J/kg K	444 J/ kg K
Ultimate Tensile Strength (σ_u)	2240 MPa	1035MPa (at 25 °C) (annealed)	1435 MPa (at 21 °C) 1275 MPa (at 540 °C) 950MPA (at 760°C)
Yield strength (σ_y)	2033 MPa	890 MPa (at 25 °C) (annealed)	1185 MPa (at 21 °C) 1065 MPa (at 540 °C) 740 MPa (at 760 °C)

1.1.3 Unique properties of Inconel 718

Inconel 718, a nickel – iron based superalloy strengthened primarily by ordered body centered tetragonal (BCT) γ'' - Ni_3Nb and ordered face centered cubic (FCC) γ' - $Ni_3(Al, Ti)$ precipitates [3] possesses high yield strength, ultimate strength, high shear strength and high fatigue strength, low thermal conductivity, adequate toughness, and high structural stability at elevated temperatures (650°C). It is also known for its remarkable corrosion resistance and creep – rupture strength and high fatigue strength upto 700°C [8, 9, 10, 11, 12].

Inconel 718 not only possesses, like several other alloys, good yield and ultimate strength and low cycle fatigue (LCF) resistance but also possesses quite adequate resistance to creep which are essential for low - intermediate temperature applications.

Mechanical and thermal cycling of loading produce fatigue i.e. low cycle fatigue (LCF) in the components. The LCF resistance of Inconel 718 is quite adequate to meet the requirements when employed in high stress-temperature cycling.

Virtually all components are subjected to fatigue in service life and especially low cycle fatigue. The morphology and volume fraction of γ' and γ'' affect the crack growth behaviour and LCF. The finer precipitation results in longer LCF life of Inconel 718 which has very good resistance to LCF even at elevated temperature.

Inconel 718 can be heat treated to attain enhanced levels of strengths and toughness. The heat treatment may be designed to obtain proper fracture toughness and resistance to fatigue crack propagation [13]. It also retains reasonably good amount of ductility, toughness, and even yield and ultimate tensile strengths at subzero temperature.

Inconel 718 bears good forgeability, may be forged to get distinctly different structures with significantly different properties, capable of reaching excellent tensile strength levels with good creep-rupture characteristic. Fine grain size, maintenance of low strain rate in forming process and as well maintenance of constant temperature makes superplastic deformation possible. The superplastic behavior of Inconel 718 allows the production of large, more complex and detailed parts.

Strain hardening and flow softening occurs when Inconel 718 is superplastically deformed. It is known that grain growth plays an important role in hardening of superplastic materials while dynamic recovery, cavitations formation, grain refinement and dynamic precipitation contribute to flow softening [14].

Inconel 718 is reasonably well castable, formable and weldable. It has unique welding characteristics, its hardening phase γ'' is precipitated more sluggishly at a lower rate than γ' so that welding associated strains, that must be redistributed, are more readily accommodated in the weld metal and heat affected zone. Inconel 718 can be aged after welding to produce a fully strengthened structure with very high ductility.

1.1.4 Applications of Inconel 718

Nickel based superalloys are widely used accounting for about 50% of materials used in aerospace applications. They possess higher strength to weight ratio as compared to denser steel. Inconel 718 is the most frequently used superalloy among the nickel based alloys, accounting for 25% and 45% of the annual volume product for cast and wrought nickel based superalloys [15, 16].

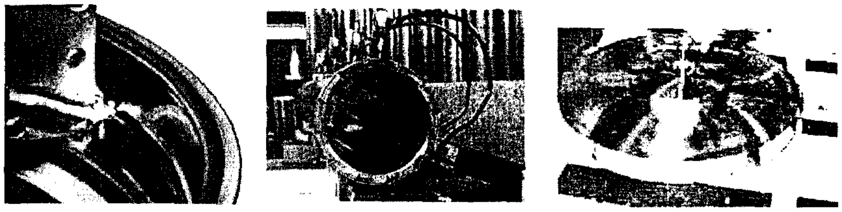
Inconel 718 is widely used for making various components in aerospace industry, nuclear reactors, pumps, gas turbines, cryogenic containers, I.C. engines, high pressure compressors and also in equipment and in tooling.

Many nickel based superalloys retain good ductility and toughness at subzero temperature. Among these, Inconel 718 is used for critical structural components of prototype super conducting motors and generators [17].

Inconel 718 has been the world standard for use as gas turbine disks due to its costs, availability accompanied by favorable strength properties upto about 649^0C. Superplastically formed Inconel 718 is used in noise suppressor assembly and exhaust mixer nozzle component. Also it is used in stack gas heaters, reciprocating engines, various parts of I.C. engines like shafts, exhaust manifolds, valve bodies, etc., seals, fasteners and in petrochemical industries. Some of such applications are typically shown in Fig. 1.3.

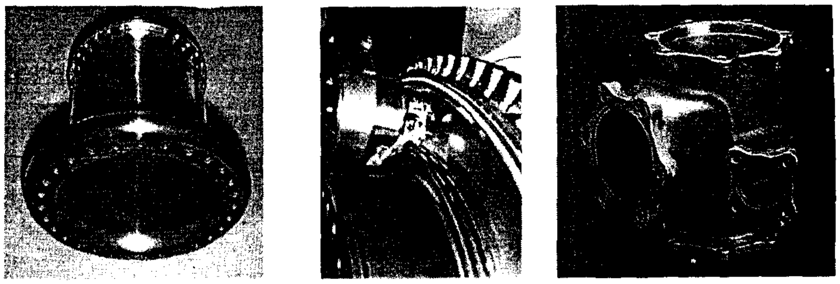
1.1.5 Problems in machining and grinding Inconel 718 and causes of such problems

Machining and grinding of Nickel and its alloys have been a great challenge to the manufacturing industries. Considerable research and effort have been on and is going on to understand the basic science of machining and grinding of this unique group of alloys in terms of cutting forces, chip formation, heat generation / increase in temperature, tool / grit wear, surface integrity, suitable environment and above all tool / grit material and type of grit bonding.

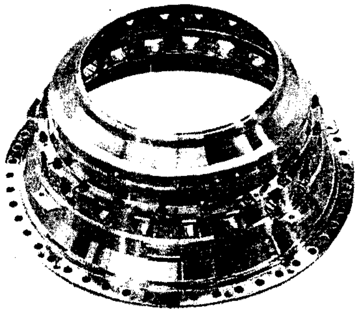


engine housing (www.mmsonline.com) flow formed tube (www.floform.com) machined comp disc (www.advancedglobalmaterials.com)

turbine case combustion chamber case (www.flanaganindustries.com) turbine gear (www.surfacenehancement.com)



turbine cover (www.techno;ogie-entwicklung.de) compressor disc (www.ccl.franhofer.org) valve body (www.genuinemachine.com)



intermediate case (www.flanaganindustries.com)

Fig 1.3 Some salient components made of Inconel 718.

Reported literatures on various observations and techniques of machinability and grindability of this group of alloys have also been reviewed in depth and critically [15, 16, 18, 19].

Nickel based alloys have become well used engineering materials, that are available in a wide range of alloy groups. They are not only available in cast form but are also available in wrought forms such as sheets, plates, strips, billets, hollow sections, wires, etc., to cater to the needs of the user industries. However, inspite of increasing production and usage, these alloys are expensive as compared to many other alloys due to the complexity of extraction processes, problems in melting, difficulty in fabrication, machining and grinding. Near net shape processes such as hot isostatic processes, different casting processes like investment casting, single crystal casting, powder metallurgy and superplastic forming processes are introduced in order to reduce the cost of nickel based alloy components, however, manufacture of most of the nickel and its superalloy components essentially need conventional machining like milling, drilling, boring, reaming, tapping, turning and grinding.

The machining and grinding of nickel-based superalloys is characterized by large cutting / grinding forces for its inherently high strength and its retention at elevated temperature, and workhardenability. The low thermal conductivity of this alloy causes high localized cutting temperature at the tool / grit tip or the machining / grinding zone effecting high thermal gradients and workpiece burn. High specific energy requirements and poor thermal diffusivity result in high cutting temperature.

Machining and grinding of Inconel 718 is also characterized by rapid tool or wheel damage, due to intensive stresses, work hardening during machining, temperature at the work tool interface and severe abrasion and diffusion. Cutting tool suffers from high abrasive wear owing to the presence of hard abrasive carbide particles in the superalloy. Chemical reaction [18] occurs at high cutting temperatures during machining leading to a high crater wear.

Generation of large amount of heat and hence high temperature during machining or grinding, chemical reactivity [20, 21] of Inconel 718 and its work hardening impairs surface integrity.

Effective grinding of such ductile but strong alloy will require grinding wheel with high grit – bond strength and wide inter-grit spacing to provide spaces for chips and cutting fluids. For such purpose, monolayered superabrasive wheels may be suitable.

1.2 Grinding of metals and alloys by superabrasive wheels

The preformed blanks are essentially finished by machining and grinding to appropriate dimensional accuracy and surface finish for the desired or improved performance and longer service life of the engineering products. *Grinding* is usually employed for high accuracy and surface finish specially when the work material is very hard or hardened by heat treatment after machining or preforming. Tremendous progress has essentially been made in last few decades in grinding technology through development and use of more effective and desirable abrasive materials, wheels and techniques as well as highly rigid and powerful grinding machine with precision control to meet the growing demands for higher material removal rate, ultra high precision and ability of finishing the hard and tough materials and newer exotic materials which are regularly coming up with the rapid advancement of science and technology but are extremely difficult to machine and grind conventionally.

Through mid 1950's aluminium oxide and silicon carbide abrasives dominated most applications though natural diamond had been in use for grinding very hard nonferrous materials, in particular glass and ceramics, over a very long period. However in late 50's *synthetic diamond* was made available commercially and in late 60's a newer super hard material cubic boron nitride (cBN) was introduced to the market.
The characteristic properties of both conventional abrasives and superabrasive are listed in table 1.2.1.

Table 1.2 Characteristics of different abrasives used for grinding [22]

Properties	Abrasives			
	Superabrasive		Conventional	
	Diamond	cBN	Aluminium oxide	Silicon carbide
Density, gms / cm^3	3.52	3.48	3.92	3.21
Knoop Hardness, HK, GPa	60 – 110	40 – 70	21	24
Thermal conductivity at 25°C, W / cm.K	20	13	0.35	3.5
Coefficient of thermal expansion, 10^{-6} mm / mm / °C	4.8	4.6	8.6	4.5
Threshold temperature, °C	800	1400	1750	1500

Diamond superabrasive wheel

Diamond is well known for its extraordinary hardness, excellent thermal conductivity and low co-efficient of friction.

Diamond grits are available and used in two forms mainly monocrystalline and polycrystalline grits. Monocrystalline grits comprising of single crystal of high toughness and low friability are preferably used when large grit force is expected. Polycrystalline grits usually consist of an agglomerate of smaller crystal that undergo micro fragmentation during use and maintain free cutting action of the wheel.

Diamond wheels find extensive use in grinding a wide range of materials including ferrite, cemented carbides and non-metallic such as stone, concrete, plastics, FRP's (fiber reinforced plastics), glass and ceramics and hard stones. Carbide and ceramic tools are finished with diamond wheel. Diamond grinding wheels are used to grind the optical glass, and a variety of low and high density ceramics used in magnet, capacitor, spark plug, etc. Ceramic components such as silicon wafers, magnetic heads, optical fibers and sensors are also finished to tight tolerances and fine surface finishes with diamond grinding wheel. Recent trend in diamond grinding technology is ductile regime grinding of ceramic wherein the grit penetration to the work material is limited to a depth less than that at which fracture is initiated. This new technology not only ensures manufacture of ceramic component with precise geometry and surface finish but also very low level surface and sub-surface damage comparable with that only achieved by post grinding abrasive fine polishing.

However, diamond is not absolutely free of limitation. At about 800^0C diamond begins to react with oxygen resulting in loss of diamond. Diamond also show sign of graphitization at temperature exceeding 1500^0C under vacuum but the process is accelerated at a lower temperature (800^0C) in presence of oxygen and metal solvent or catalyst inclusion. Diamond suffers rapid wear and chemical dissolution when used for machining and grinding steels. Therefore, it is not recommended as an abrasive against ferrous group of materials.

cBN superabrasive wheel

Cubic boron nitride (cBN), invented by R.H.Wintorf from General Electric Research Laboratory, is known to be the second hardest material next to diamond [23]. In its hexagonal structure boron nitride is similar to graphite. Like diamond, cBN can readily be synthesized by direct conversion of hBN to cBN [24]. Similar to diamond, cBN grits are also available as monocrystalline type with medium strength and blocky monocrystals with much higher strength. However in recent past the advent of cBN with microcrystalline structure has been considered a major - breakthrough in the field of cBN grinding technology. Unlike monocrystalline, the microcrystalline cBN grits do not have well defined cleavage planes. Its structure consists of micron size single crystals bonded together by high pressure, high temperature technique resulting in a product which breaks down in micro level during grinding and offer much higher toughness than that provided by monocrystalline cBN grits. This microcrystalline grits are thermally stable to 1200^0C, more than nearly 200^0C above the temperature at which monocrystalline cBN grits starts to degrade.

Loss of cBN by thermal treatment in comparison to diamond is not significant. This is because of the fact that the reaction product is boron oxide, which forms a protective layer around cBN crystals preventing further degradation. Moreover, cBN has not been shown to transform to the hexagonal form upto 1400^0C in air. Also, unlike diamond cBN is not very reactive with iron and therefore is highly wear resistant in grinding ferrous materials.

cBN wheels are used in precision production grinding of wide variety of ferrous and nickel based alloys. Because of their better wear resistance, cBN grits retain their cutting point sharpness longer than aluminium oxide or silicon carbide abrasive. Higher hardness and better thermal conductivity are reported to be reason for improved surface integrity (such as low surface residual stress, better fatigue life) achieved with cBN abrasive grinding. Therefore, cBN wheels are used in automotive, aerospace, cutting tool production, tool maintenance and many other applications.

Creep feed grinding of deep grooves is one of the areas where cBN wheel has already established its supremacy over aluminium oxide wheel. The creep feed grinding exhibits clear advantage over conventional grinding for lesser chip load per grit resulting slower grit wear and better surface finish. This in turn provides better accuracy and finish in form grinding. cBN exhibits much better physical and thermal properties at higher temperature arising out of higher cutting speed and wide job wheel contact length and hence the basic advantages of high production in creep feed grinding can be derived from cBN wheel.

Recent trend in cBN grinding technology is high-efficiency deep grinding of both hardened and unhardened steel replacing machining techniques like milling or broaching. High efficiency deep grinding employs higher wheel peripheral speed. It also employs same depth of cut as it is practiced in creep-feed grinding. However, the higher peripheral speed permits the use of workpiece speed much higher than that used in creep feed grinding. Thus, the material removal rate can be enhanced remarkably without increasing the specific grit force, which has an overriding influence on the grit wear. The chemical affinity of cBN to water has a major drawback with respect to wet grinding. Water vapour dissolves the boron oxide layer and the crystal structure is then exposed to hydrolysis with the formation of boric acid and ammonia [22].

Superabrasive wheels are made and used in several ways.

1.2.1 Monolayer superabrasive wheel

Superabrasive (SA) wheels are made of either diamond or cBN. The wheels are prepared basically in two forms:

- composite form
- monolayer form

Three bond systems are typically used in making superabrasive wheels with composite structure:

- vitrified bond
- resin bond
- metallic sintered bond

Vitrified bond (glass or ceramic)

Vitrified or ceramic wheels provide high bonding strength and enable to vary basic strength and chip clearance characteristic by altering the porosity and grit density. In addition, the composition of bonding matrix results in grinding wheel that is easily conditioned to maintain uniform performance, consistent dimensional control and surface finish. Chemical bonding is achieved between cBN grits and vitreous bonds, which consists of some alkaline components. At high processing temperature, these alkaline components present in bonding agent may attack cBN strongly leading to degradation. To prevent this, cBN grits are coated with thin film of titanium, which acts like a chemical bridge between the cBN and ceramic bonding matrix.

Resin bond

Grinding wheels with resin bond offer good resilience and vibration absorbing characteristics, which reduces chatter at grinding zone. Wheels with resin bond are easy to dress and true and are preferred for a wide range of applications. However the physical adhesion between the superabrasive grits and resin bond is not adequate in many grinding applications leading to premature grit dislodgement. A film of nickel deposited on the abrasive grit produces a rough textured surface and enhances mechanical anchorage of the abrasive crystal in the resin matrix.

Metallic sintered bond

Metal is the toughest bonding material used in the manufacturing of super abrasive wheels. This toughness makes these wheels very effective in those applications where form accuracy as well as large stock removal is desired. However, the material removal rate is lower than that possible in other bonding system.

Conventional metal bonds cannot provide chemical bonding with the abrasive grits and retention of grits throughout their service life depends on effective mechanical interlocking with the metal binder. Such type of mechanical anchoring is not very effective when strong, perfect abrasive crystals with well developed and smooth surfaces are used in the grinding wheel.

However, such composite superabrasive wheels need truing, dressing and grit conditioning before using for actual grinding and these pre-grinding preparation works are quite complex and expensive.

The single layer bond system is advantageous to the composite wheels due to:

- the manufacturing of the wheel is simple. It can be given almost any shape, which implies that the single layer bond system is very much effective to produce form wheels at low cost

- single layer metal bonded wheels can be used at very high rpm. Vitrified bonded wheels cannot survive with the stress generated due to high centrifugal force. Therefore, for heavy duty grinding e.g. Creep feed grinding or HEDG, where high rpm is must, this single layer wheels can outperform the vitrified bonded wheels.

In the presently widely used monolayer superabrasive wheels, the SA grits in a single layer only are bonded galvanically by Nickel on the cylindrical or disc type metallic (preferably steel) substrate around its periphery or faces.

The remarkable grinding properties of superabrasives (diamond or cBN) are utilized to manufacture wheels having different geometries with just a layer, monolayer of superabrasive grits for grinding various exotic materials in addition to steels and cast irons. A single layer of diamond or cBN grits is bonded to metal substrate like steels, using a galvanic metal layer that covers 50 to 70 % of the grit height by electroplating process.

The electroplating process is carried out in two stages called 'building up' and 'tacking on'. In the first stage, a layer of nickel is built-up around the external surface of the blank, the substrate, to trap the grits touching the surface. The progress of the operation needs a close inspection at regular intervals. The current density applied depends on the shape, size and number of wheels to be plated and the grits size. In the second stage, the grits adhering to the substrate surface are fixed more securely by increasing the thickness of the nickel layer by plating further in the absence of superabrasive grits in the bath except that are touching the surface [25].

The monolayer superabrasive wheels with diamond or cBN grits trapped in place, onto the steel core by a layer of nickel, have some specific advantages [26]

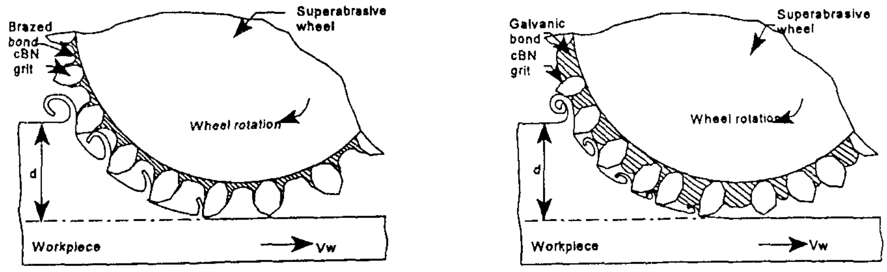
- cut free and grind faster
- grind cooler, reducing thermal damage to the workpiece
- wheels can be designed to fit the job i.e. special shapes is possible
- hold their form, producing more consistent parts.

cBN has the ability to maintain its sharpness under severe grinding conditions. The sharp grits can penetrate the work and form the chip. Considerable amount of time and effort are invested in dressing composite cBN wheels to make them sharp. Plated wheels on the other hand, do not require dressing. With approximately 40 – 50 % of the grits exposure above the bond, there is ample space for chip accommodation. As the grits are quite sharp, wheel require less power to cut and enables faster grinding and hence higher productivity.

Superabrasives are excellent conductors of heat, cBN is an excellent conductor of heat, second to diamond. Superabrasives have ability to conduct heat out of the grinding zone and thus reduces the heat input in the ground surface and hence metallurgical damage and undesirable tensile residual stresses.

Brazed type monolayer SA wheel has been recently developed. The superabrasive grits are bonded to the core by a layer of active braze alloy of copper-silver that is brazed in high vacuum. This outperforming superabrasive grinding wheel is superior to the galvanic type because of the following reasons:

- strong metallurgical bonding of the grits with the substrate
- uniform and wider intergrit spacing [Fig.1.2.1] accommodating larger volume of chips and cutting fluid and free cutting without wheel loading



Brazed type wheel Galvanic type wheel

Fig.1.4 Schematic comparison of brazed type and galvanically bonded single layer cBN grinding wheel

- Control on spacing of grits in brazed type wheel made it possible to increase the productivity without loading.

However, in spite of so many advantages, the single layer SA grinding wheels have some obvious limitations.

- Unlike the conventional grinding wheels there is no scope of truing of the single layer wheels. So utmost care is needed for the precision manufacturing of the wheel blanks. The presence of eccentricity will result into non-uniform grinding with vibration.
- It is not possible to position all the grit tips of a single layer wheel in the same radial distance. This can lead to an increase in surface roughness in the longitudinal direction. The problem of achieving low roughness value in the transverse direction is more complex in nature and can be well realised if one considers the location of grit tips in different radial distance along the width of the wheel.

1.3 Application of cutting fluids

Cutting fluids are used extensively in machining as well as abrasive machining processes. Primarily it must contribute as lubricant, coolant and as a cleaning agent.

Four basic types of cutting fluids are generally used in machining operation:

- Soluble oils
- Synthetic oils
- Semi-synthetic oils
- Straight cutting oils

Water, which has high thermal conductivity and high specific heat, is very effective coolant, but it doesn't posses any lubricating property, so it can not reduce the friction in the cutting area and more over it corrodes machine parts and workpiece surface. So instead of straight water, soluble oil i.e. oil dispersed in water is used.

Synthetic oils don't contain mineral oil, they contain some synthetic chemicals as substitutes. They are not affected by bacterial growth and are capable of forming emulsions in even hard water. Also the life of synthetic coolant is high. However, they provide very poor lubricity.

Semi-synthetic coolants contain partially mineral oils and synthetic chemicals. They combine the advantage of synthetic coolants and mineral oils

Straight cutting oils or neat oils are petroleum based mineral oils with extreme pressure additives. They provide adequate lubricity that reduces the friction, prevent chip welding and wash away the chips formed. Straight mineral oils, fatty oils, sulphurised mineral oils, chlorinated mineral oils, sulphurised fatty mineral oils and sulfo-chlorinated mineral oils are available for use in industries [27, 28].

1.3.1 Purpose and methods of application of cutting fluids in grinding

Cutting fluids are employed in grinding for cooling and lubrication to;

- reduce friction, thus improving grits life and good surface finish
- reduces forces and energy consumption
- cool the cutting zone, thus reducing the workpiece temperature and so the thermal damage
- wash away the chips formed.

The main purpose of using cutting fluid is cooling the job and the wheel at the grinding zone.

To perform satisfactorily as lubricant, oil must maintain a strong protective film in the area between the grit face and the metal being cut where hydrodynamic conditions can exist. Such a film assists in sliding of two faces readily by reducing the friction between. For effective cooling, a cutting fluid should posses high specific heat so that maximum heat will be absorbed and removed.

Wider contact area in grinding, unlike machining, not only results in more heat generation and wear of the grit - tips but also prevents the cutting fluid from reaching the hot grinding zone. The type (composition, additives etc) and method of application (direction, flow rate, pressure etc) of the cutting fluid play significant role on effectiveness and efficiency of cutting fluid application [29].

It has been observed [30] that in grinding by cBN wheels EP additives are not effective, high concentration soluble oils are not beneficial and that the difference in performance between neat and soluble oils decreases with the increase in metal removal rates.

The common methods of cutting fluid applications are

- flood cooling
- mist cooling
- high pressure jet

Flood cooling may accomplish bulk cooling of the wheel and the job but the fluid is prevented from reaching the actual hot zone by the thin but stiff layer of air that remain sticking on the wheel periphery. The stiff layer of the air could be partially removed by keeping a scraper board in contact with the wheel periphery and painting the faces of the wheel.

Mist cooling supplies fluid more effectively to the hot zone of wheel – work contact. It is particularly effective with water-based fluids. Mist cooling requires venting and has limited cooling capacity [31].

Because of high speeds in grinding, an air stream (air blanket) is formed around the periphery of the wheel which prevents the fluid from reaching the wheel -workpiece interface [32].

Recent development is to use high pressure refrigerated coolant system to improve the rate of heat removal from the cutting zone. High-pressure fluid is used to deliver the cutting fluid to the cutting zone by specially designed nozzle which is projected towards the grinding zone. But due to high costs and the danger of mist formation, high coolant pressures for penetration of the air barrier cannot always be used. However, attempts are going on to overcome such problem.

Another recent development is MQL. Minimum quantity of lubricant is introduced along the air stream so as to reach the grinding area and hence reduces friction, there by reduces heat generation.

Application of cutting fluid in grinding generally aims at mainly cooling and then lubrication. But conventional methods are not that effective particularly under high speed grinding as well as machining. Conventional coolants undergo film boiling at around 350^0C and loose their cooling property. Apart from this, strict regulations in most of the countries have imposed stringent conditions on use and disposal of used coolants and lubricants, as they cause environmental pollution. The machining industries are instructed to look into alternative ways and methods of controlling the high cutting temperatures. The focus is on effectiveness and efficient cooling and lubrication with ecofriendliness as well as cost effectiveness. Cryogenic cooling with excellent cooling ability and ecofriendliness appears to be a good option.

While grinding steels under different environments, cryogenic cooling by liquid nitrogen jets [33 – 36], not only provided environment friendliness but also provided significant technological benefits in respect to grinding forces, specific grinding energy requirements and residual stresses, mainly through substantial reduction of grinding zone temperature, retention of sharp and clean grit surfaces and thus favorable chip formation.