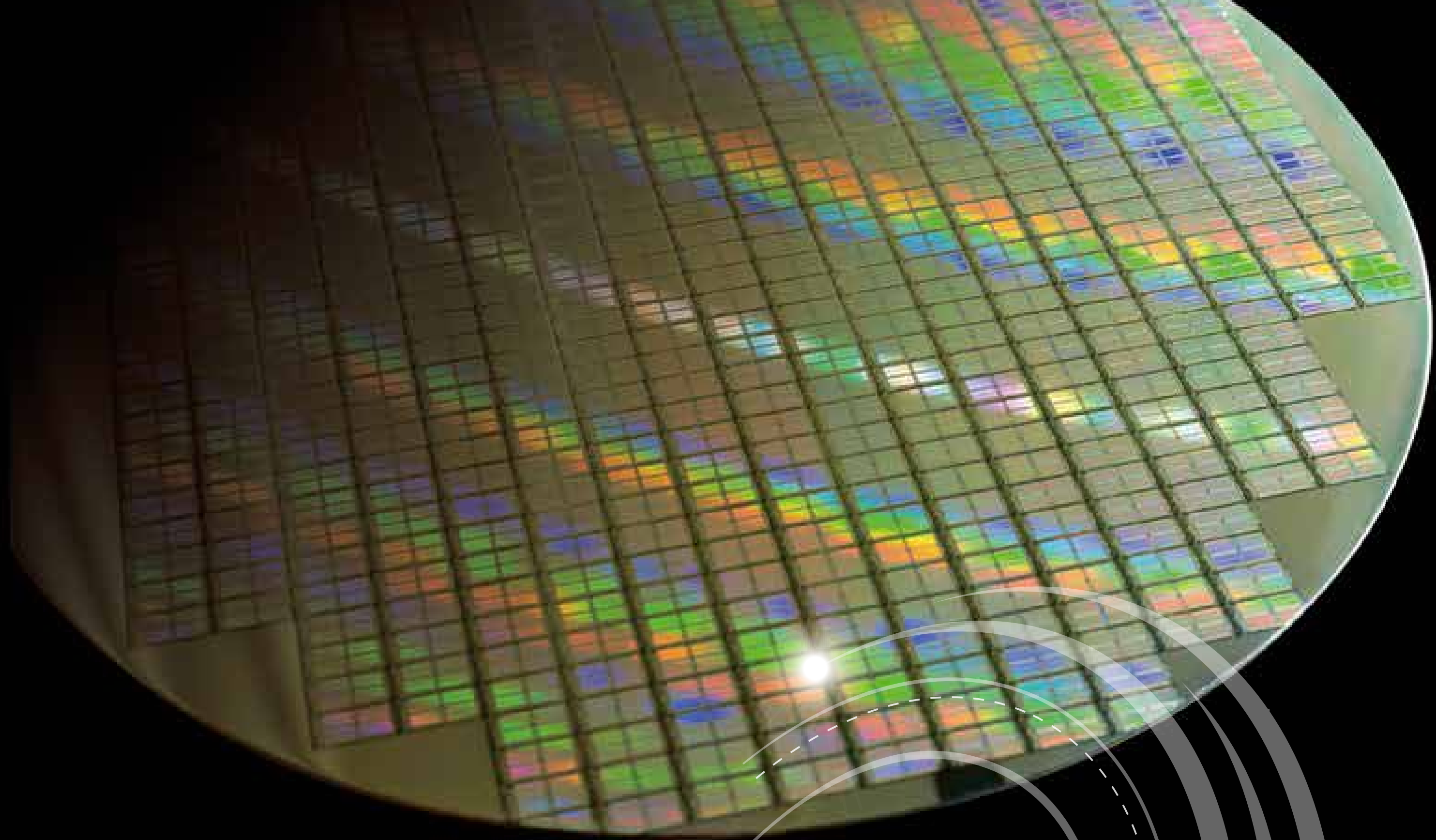

Grinding Theory and Troubleshooting for Grinding Difficult-To-Cut Materials

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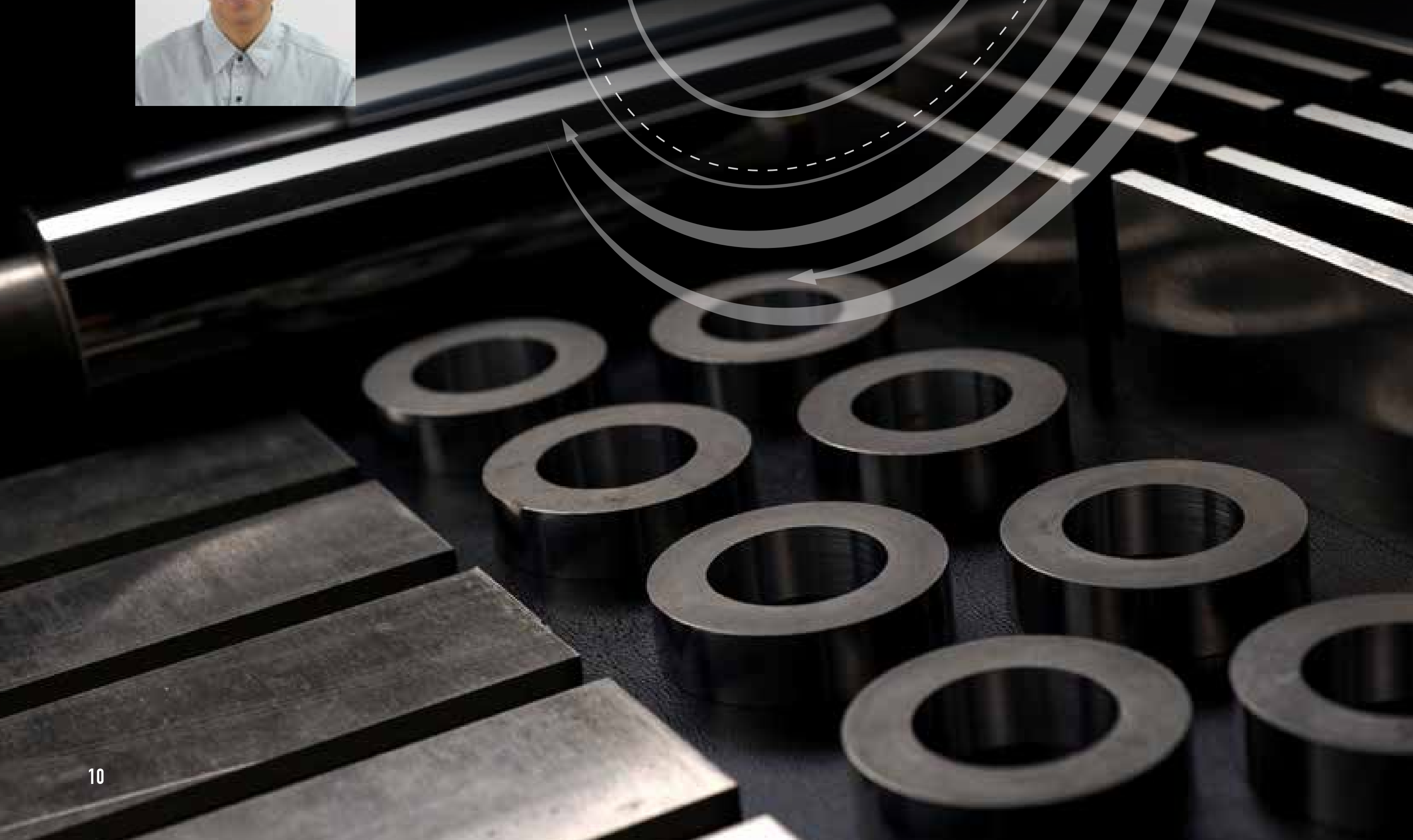


Issues in Grinding Difficult-to-Cut Materials

There is a wide variety of materials used in industrial products. These materials can be classified in the following categories: metallic materials, non-metallic materials, and composite materials. They can be further divided into different subgroups (Table 1).

In recent years, as the demand for higher functionality and precision has increased, many materials with superior mechanical properties have been developed. For example, aerospace and automobile industries are using heat-resistant alloys aiming to improve fuel efficiency. They are also replacing steel with materials such as aluminum alloy, titanium alloy, and composite materials to reduce the overall weight. Additionally, the technology of machinery and materials is progressing on a daily basis and the use of new materials with high hardness, strength and durability are constantly applied.

Table 1 Classification of Materials

Large classification	Small classification	Remarks
Metallic material	Ferrous material (pure iron, steel, cast iron, etc.)	·A material that contains iron as a main component mixed with different elements such as carbon as an additive ·Relatively high strength
	Non-ferrous metallic material (Aluminum alloy, titanium alloy, etc.)	·Materials mainly composed of metals other than iron ·Compared to ferrous material it is lighter and superior in corrosion resistance
Non-metallic material	Inorganic material (Ceramics, glass, etc.)	·Sintered inorganic material ·Lightweight and high hardness but brittle
	Organic materials (plastic, rubber, etc.)	·Material composed of carbon as a main element ·Lightweight but low in heat resistance and strength
Composite material	Composite material (CFRP, CMC, etc.)	·A combination of reinforcement material and a base material acting as supporting medium ·Exhibits properties of the base material with high strength

On the other hand, due to their superior characteristics, many of them are more difficult to grind than conventional materials, and thus are called difficult-to-cut materials. When grinding difficult-to-cut materials, various problems and negative effects to the production need to be considered. Any of them can seriously effect the production lead time and the overall cost (Table 2).

In this article, we will introduce reasons why it is more challenging to grind difficult-to-cut materials and clues to solving the problem. The reasons for the difficulty of grinding difficult-to-cut materials vary. In this article, we'll approach this from three perspectives: (I) high hardness, (II) low thermal conductivity, and (III) high elongation (ductility). Furthermore, Noritake's approach to new materials will be presented in section IV.

Table 2 Examples of Possible Problems and the Effects on Productivity with Grinding Difficult-To-Cut Materials

Problems	Effects on Productivity
Wheel wear increases and its life is shortened	Increased tool costs
Dress interval shortens to ensure workpiece quality (more frequent dressing is required)	Reduced productivity Increased tool costs
Longer grinding time is required to achieve required quality (grinding efficiency needs to be lowered)	Reduced productivity
Grinding quality is degraded (grinding burn, effected layer occurs)	Reduced productivity (the number of scrap increases)
Not able to grind	Delayed commercialization plans

Problems and Effective Countermeasures (I) ~Materials with High Hardness~

Examples: Hardened steels, Tool steels, Carbide, PCD, Hard chrome plated materials, etc.

Let's take high speed tool steel as an example and compare with carbon steel. The hardness of carbon steel is HRc53, but high-speed tool steel is about HRc68, which is approximately 1.3 times harder. When grinding such hard material, wheel break down rate or abrasive grain fracture tends to accelerate due to weak grain shape maintainability and grain gripping force. As a result, wheel wear becomes much higher while grinding high-speed steel.

Excessive breaking down can be prevented by increasing the grain gripping force by choosing a harder grade or switching to a stronger bond type. If the grains' shape maintainability is insufficient, utilitizing mono-crystal or ceramic grains instead of normal aluminum oxide (such as WA) is suggested. If the aim is to achieve further finish quality and longer dress interval, testing a Diamond/CBN grain is also suggested.

Fig. 2 shows the hardness of diamond and CBN grains* which are classified as super abrasive grains. The hardness is much higher than that of aluminum oxide abrasive grain (A grain) or silicon carbide abrasive grain (C grain), which are classified as conventional abrasive grains. However, diamond grain is not suited for carbon-steel and other ferrous materials as it is highly reactive. So selecting the CBN grain would be suggested for such materials. For other materials, such as carbide and PCD, diamond grain is commonly selected. However, super abrasive grains are expensive, so if the initial cost is a factor of consideration, utilizing mono-crystaline grains or ceramic grains would be suggested.

Depending on the combination of workpiece material and grinding wheel, there could be some cases where grains have difficulty biting into the workpiece and slip. When this happens, instead of grain fracture, attrition wear of the grains will occur. As a result, the grinding will be performed with dull grains. This will cause the power consumption to raise and may cause deflection or grinding burn against low rigidity workpieces. In such cases, choosing an open structure wheel (lowering the volume percentage of grain in grinding wheel) will be an effective measure due to its increased cutting ability.

Table 3 Test Conditions

[Grinding wheel]

Specifications	WA60-V
Dimensions	φ205 × T17 × φ76.2 mm

[Grinding conditions]

Grinding method	Surface grinding
Workpiece material	Carbon steel, high-speed tool steel
Grinding wheel speed	33 m/s
Table speed	0.33 m/s
Cutting depth	10 μm/pass
Grinding efficiency	3.3 mm³/mm·s

Fig. 1 Test Results

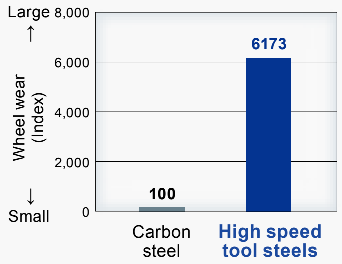
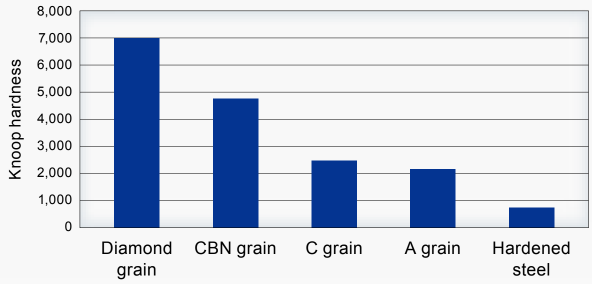


Fig. 2 Hardness (Knoop Hardness) of Abrasive Grains[1]



Problems and Effective Countermeasures (II) ~Materials with Low Thermal Conductivity~

Examples: Titanium alloy, Nickel alloy, Stainless steel, etc.

Let's take nickel alloy (Inconel 738LC) as an example and compare with carbon steel. Since the thermal conductivity of nickel alloy is about one-third (1/3) that of carbon steel, the grinding heat generated at the grinding point is difficult to be diffused and this can lead to local temperature rise (fig. 3). Therefore, when grinding nickel alloys, loading* is frequently generated on the grinding wheel surface, lowering the cutting ability, thus increasing the power consumption during grinding. This may lead to grinding burn on the workpiece (Table 4, Fig. 4).

When grinding materials with such low thermal conductivity, a grinding wheel which generates less heat and has high heat dissipation is required. In order to reduce the grinding heat generated, selecting an open structure grinding wheel with large pores is an effective measure. This may reduce the number of grains where the heat is generated and better

Fig. 3 Grinding Heat Transfer Models for Carbon Steel and Nickel Alloy

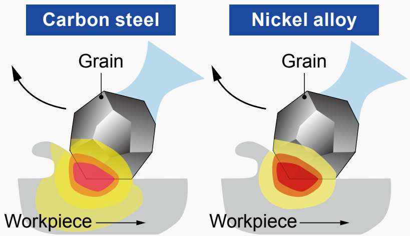


Table 4 Test Conditions

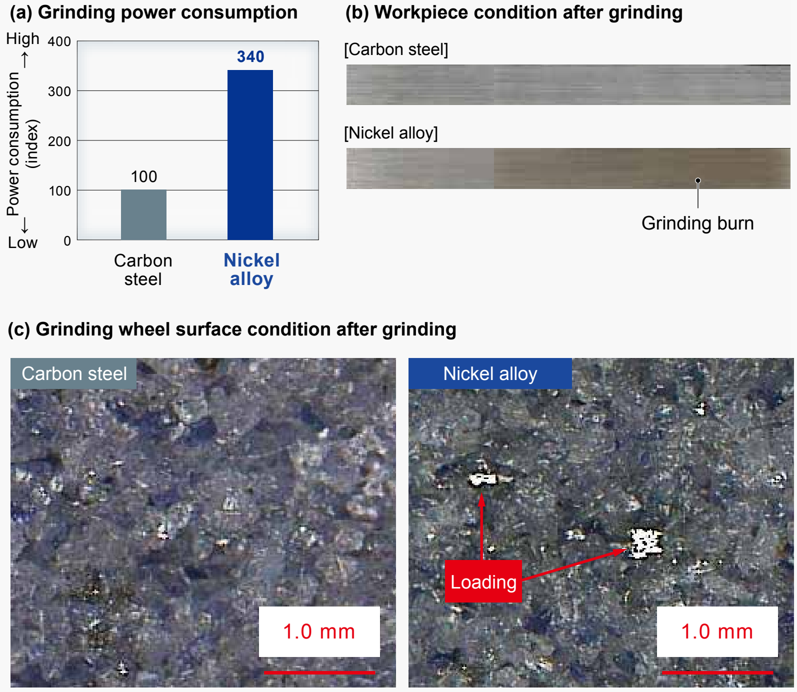
[Grinding wheel]

Specifications	SH80-V
Dimensions	φ255 × T19 × φ76.2 mm

[Grinding conditions]

Grinding method	Surface grinding
Workpiece material	Carbon steel, nickel alloy
Grinding wheel speed	20 m/s
Table speed	6.6 mm/s (creep feed)
Cutting depth	0.3 mm/pass
Grinding efficiency	2.0 mm³/mm·s

Fig. 4 Test Results



allow coolant to enter the grinding zone.

Using super abrasive wheels is another useful measure when grinding materials with low thermal conductivity. The thermal conductivity of super abrasive grains are higher than that of conventional grains and also greatly exceeds that of common workpiece material such as iron (Fig. 5). In other words, as shown in the heat transfer models (fig. 6), with conventional grains the grinding heat diffuses through the workpiece. Whereas super abrasive grains diffuse heat through the grain, preventing the heat from being accumulated in the workpiece. Therefore super abrasive grains are especially effective when grinding workpieces with low thermal conductivity.

Fig. 5 Thermal Conductivities of Super Abrasive Grains, Conventional Grains and Iron[1]

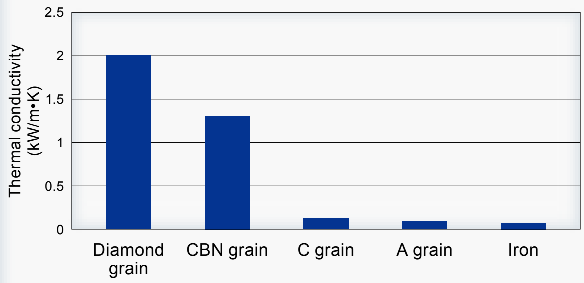
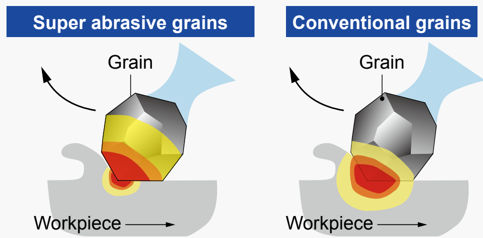


Fig. 6 Grinding Heat Transfer Models for Super Abrasive Grains and Conventional Grains



Problems and Effective Countermeasures (III) ~Materials with Large Elongation (Ductility)~

Examples: Stainless steel, Untreated steel, Pure metals such as copper and aluminum, Plastics and etc.

Let's take stainless steel (SUS304) as an example and compare with carbon steel (Table 5, Fig. 7). Since the ductility of stainless steel is about 2.5 times that of carbon steel, the chips generated during grinding tend to stretch and adhere easily to the grinding wheel. Therefore when grinding stainless steel, clogging (large amount of metal loading up the area

Table 5 Test Conditions

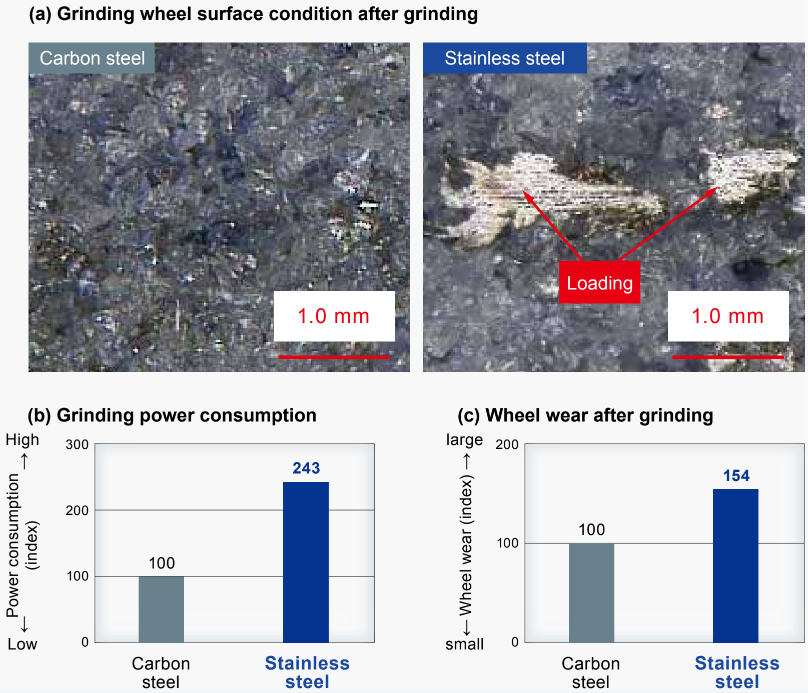
[Grinding wheel]

Specifications	SH80-V
Dimensions	φ255 × T19 × φ76.2 mm

[Grinding conditions]

Grinding method	Surface grinding
Workpiece material	Carbon steel, stainless steel
Grinding wheel speed	33 m/s
Table speed	0.17 m/s
Cutting depth	2 μm/pass
Grinding efficiency	0.34 mm^3/mm·s

Fig. 7 Test Results



between the grains) occurs on the wheel surface (Fig. 7a). When the grains are surrounded by ground material, cutting ability decreases and the power consumption increases. Additionally, the loaded grains become the starting points of break down, thus the wheel wear will increase (Fig. 7(b)(c)). When grinding highly ductile materials such as stainless steel, it is important to avoid clogging. In this case, appropriate grain selection and/or selecting an open structure wheel (high ability of discharging chips), will be effective measures.

Problems and Effective Countermeasures (IV) ~New Materials~

In this section, let us discuss the challenges while grinding two materials which have different properties than those previously discussed.

The first is silicon carbide (SiC), which is a next-generation power semiconductor. SiC is a developing material expected to increase the efficency and reduce the size of power semiconductors. But because the hardness of SiC is more than double the traditionally used silicon (Si), leading to difficulty achieving adequate grinding efficiency, it is classified as a difficult-to-cut material. Noritake had been developing multiple specialized tools in order to grind SiC. One such product is a vitrified diamond wheel that has a high strength and low elasiticity bond [2]. This ensures the durability of the wheel and maintains cutting ability. Another is a loosely held abrasive pad (LHA pad) which has a high polishing efficency that can achieve flatness [3] [4].

The second material is carbon fiber reinforced plastics (CFRP), which has wide usage in various field from medical and sports to aerospace industries. CFRP is light and strong, but due to its strength, the wheel wear while grinding can be extremely high, and burrs and delamination can also occur.

To cope with these issues, Noritake has developed a single layer bonded abrasive tool called Grit Ace [5] , which has high grain protrusion and the ability to discharge chips. Noritake has also been developing other compatible products and researching optimum grinding conditions for various difficult-to-cut materials (Table 6).

Table 6 Noritake Proposals for Difficult-To-Cut Materials

Characteristics of material	Example materials	Expected problems	Noritake proposals
High hardness	Hardened steel, tool steel, hard chromium plated materials	Poor workpiece accuracy, Large wheel wear	Ceramic abrasive grain wheel [CXE wheel] CBN wheel
	Carbide	Poor workpiece accuracy, Large wheel wear	Diamond wheel [SD memox, MDL wheel]
	PCD, etc.	Poor workpiece accuracy, Large wheel wear	Diamond wheel
	Cermet	Poor workpiece accuracy, Large wheel wear	Diamond wheels [i-Surface]
Low thermal conductivity	Titanium alloy, nickel alloy, stainless steel, etc.	Grinding burn, Poor workpiece accuracy, Large wheel wear	GC grinding wheel, SH grinding wheel
Large elongation (ductility)	Untreated steel, copper, aluminum, plastic, etc.	Grinding burn, Poor workpiece accuracy, Large wheel wear	GC grinding wheel

[Reference] Four Types of Grinding Wheel Surface Conditions (Normal, Shedding, Glazing, Clogging)

Grinding wheel surface condition during grinding can be classified into four patterns: 1) normal, 2) shedding, 3) glazing, and 4) clogging (Table 7). The first step to improve the grinding process is to observe the surface condition of the grinding wheel and bring it closer to a more appropriate "normal" state.

1) Normal

When the grinding progresses and cutting ability drops, new cutting edges are generated by grain fracture or break down due to the increased grinding force. This action is the self-dressing of a grinding wheel and plays a key role in maintaining cutting ability. The condition in which the self-dressing is repeated consistantly and cutting ability maintains is called the normal pattern.

2) Shedding

This pattern occurs when the self-dressing of the wheel happens excessively. Shedding can also be defined as the condition where the bond holding the grain breaks due to high grinding force, dropping off the grain prematurely at a size close to its original grain size. Under shedding condition, the distance between the cutting edges widens and the cutting ability of the wheel improves as the grinding is performed with sharp grains at all times. On the other hand, due to the large wheel wear the wheel surface will be rough and the wheel profile deteriorates. As a result, defects tend to occur in workpiece dimensional accuracy and surface roughness.

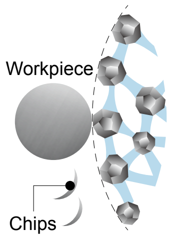
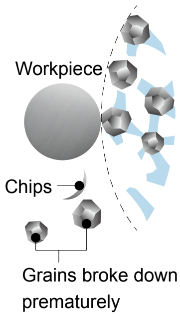
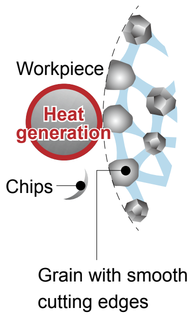
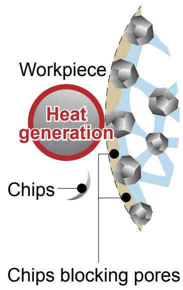
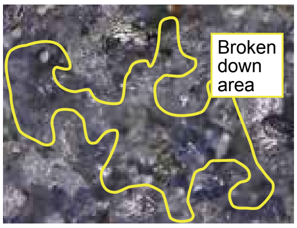
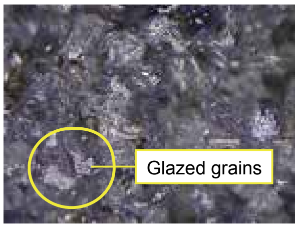
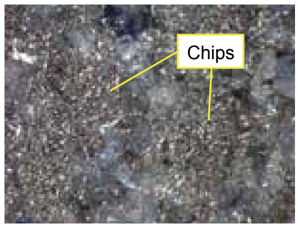
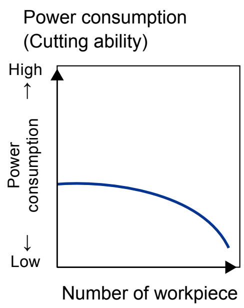
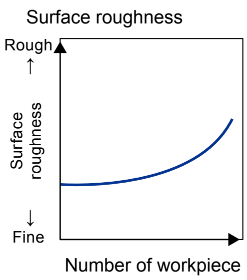
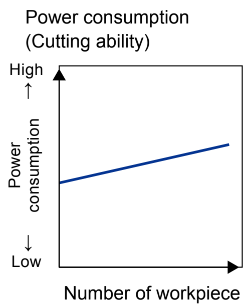
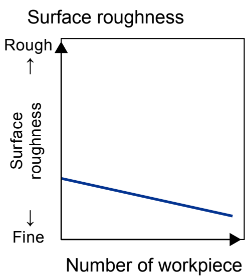
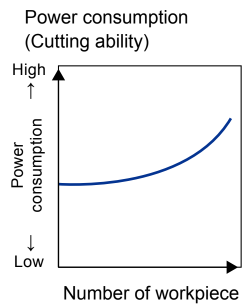
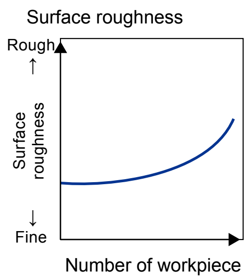
To bring it closer to the normal condition, changing the grinding wheel specification to supress the self-dressing is suggested. Specifically, changes such as increasing the bond strength (increasing hardness) and increasing the volume of grain (dense structure) can be suggested. The increased hardness will help prevent the grains from breaking down too quickly, and the dense structure will reduce the grinding force applied to each individual grain.

3) Glazing

In contrast to shedding, this occurs when the self-dressing ability is poor. This condition in which grains wear smoothly without generating new cutting edges while the cutting ability decreases is called glazing. Under glazing condition, the grinding force and grinding heat are both increased which leads to problems such as chatter and grinding burns.

To bring it closer to the normal condition, it is important to dress the wheel regularly to ensure the grains do not

Table 7 Four Types of Grinding Wheel Surface Conditions

	Normal (ideal)	Shedding	Glazing	Clogging
				
				
Grinding performance		 	 	 
Possible issues		Defective profile and surface roughness	Grinding burn Chatter	Grinding burn Chatter

become smooth. Alternatively, the grinding wheel specification can be changed to enhance the self-dressing ability. Specific changes include changing to a more friable grain type and lowering the grade (hardness) so that the grain can break down moderately.

4) Clogging

Clogging is the condition in which the pores of a grinding wheel are loaded with ground chips. Examples of clogging are as follows: when grinding soft and ductile materials such as aluminum, copper or stainless steel, ground chips may adhere to the surface of the grinding wheel and cover the cutting edges. Or when grinding cast iron or stones under dry condition, ground chips may accumulate in the pores due to poor discharge capability. In both cases, grinding force and grinding heat will increase, and will increase the chance of chatter and grinding burn.

To bring it closer to the normal condition, it is important to dress the wheel regularly to ensure the pores are not becoming clogged. Also, it is necessary to pay attention to coolant type and how the coolant is applied. Alternatively, changing the grinding wheel specification to increase the ability of discharging chips can be considered. Specifically, changes such as increasing the size of pores or using a more open structure wheel can be suggested.

[Notes]

* CBN: Cubic boron nitride (Cubic Boron Nitride), which has high hardness because it has the same crystalline structure as diamond.
* Loading: a phenomena in which the ground workpiece material adheres to grain.

[Reference]

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