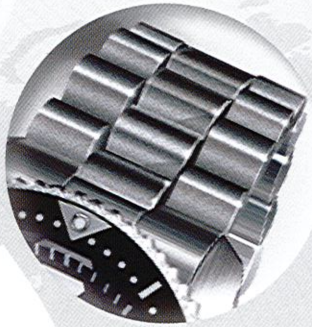
Polishing Technology for Watch Industry Handbook 钟表行业打磨技术手册

Polishing Technology for Watch Industry Handbook

钟表行业打磨技术手册



Dr. Jonathan C.Y. Chung
钟志源博士

香港城市大學
City University
of Hong Kong

物理及材料科學系
Department of Physics
and Materials Science

CONTENT

Section A Fundamentals

Section B Grinding, Polishing and Buffing

Section C Practices

Acknowledgements

I would like to thank my wife, Tiffany, for her continuous support. She was very patient with me even at times when I needed to continue working on this project during our oversea holiday trips. Thanks to my daughter, Gloria and her friend Heiken To, who gave me unconditional help in editing and proofreading.

The support from Mr. John Mak, Dr. Christina Lam and Dr. Robin Ma in arranging the technical visits to surface finishing factories in Guangdong area is also indispensible. I am also grateful to the financial support from HKSAR Government Trade and Industry Department SME Development Fund (SDF# D11 003 001) and the Federation of Hong Kong Watch Trades and Industries Limited.

Section A Fundamentals

Chapter 1

1. Introduction

In the making of a masterpiece, the artist may use a rough and unrefined surface to present depth and meaning. The imperfection of appearance reflects reality, an imperfect world that often touches the heart of the viewer. Such a presentation is highly subjective and depends very much of the cultural and artistic interpretation and the story behind the masterpiece.

The brilliant rays reflecting off a diamond draws our immediate attention. Attractive though it is, its brilliance also blinds the viewer. It is uncomfortable for us to keep our eyes trained on the brightness for more than a moment. But at the same time, its irresistible appearance attracts our eyes to return to if incessantly. Its beauty is delightful to the eye. And so we become blinded again and again.

Across many cultures, artifacts with a shiny and highly reflective surface are accepted as beautiful and glamorous. The difference in charisma between a rough, lack luster black surface and a finely polished gleaming black surface suitably illustrates this point.

Finer polishing technique are usually more expensive and time consuming; hence, they are only used in the manufacture of high quality goods to produce beautiful appearance. more time, effort and resources are invested in the grinding and polishing process, a better surface finishing can be achieved to satisfy the ever increasing demand of high quality products.

However, this also implies that the cost of production will be substantially increased, which is not in favor of the manufacturer. Optimization of the grinding and polishing process with reasonable control of the manufacturing cost is thus the desirable balance to be achieved. Understanding of the basic principles of grinding and polishing mechanisms enables the surface finishing process to be manipulated so as to satisfy the demands of customers, while limiting cost and time.

Currently, the training of skilled and semi-skilled polishing technicians is a lengthy and slow process. It takes 2-5 years for a technician to gain sufficient knowledge and on surface finishing techniques. Furthermore, most of these apprentices are not knowledgeable enough to handle more complicated problems that arise when varied finishing techniques are required.

The objective of this handbook is to provide a scientific approach to understand the technology most polishing factories and technicians are using nowadays to optimize existing surface finishing processes. This is not a handbook for frontier scientific researchers. There are no new scientific findings included. Nevertheless, this handbook can be used as a introductory guide for training technicians and undergraduate students.

Section A Fundamentals

Chapter 2

2. Fundamental Metallurgy

Metals and alloys are widely used in the manufacturing industry due to their superiority compared to other materials in various aspects. To name a few, metals and alloys are:

- Strong and hard
- Thermally stable and durable
- **Formable, malleable**
- **Hardenable, heat-treatable**
- Chemically resistant
- **Can be alloyed**
- Ductile
- …

Not all metals and alloys possess the above advantages over other classes of materials such as ceramics and synthetic plastics (polymers). However, metals can be **melted** and **combined** (i.e. **alloying**) to form a wide range of alloys with many of the superior properties listed above.

The most outstanding properties of alloys include their being **hardenable** and **heat-treatable**. Some alloys can be hardened by deformation such as hardening of relatively soft alloys or metals can be formed by simply hammering or forging. The simple hammering process renders the final product stronger and more wear resistant.

Alloys can also be **heat-treated** heating in a high temperature furnace for a designated period of time. The required temperature depends on the alloys composition and required properties. Usually, a longer heat treatment will result in softer material upon **slow cooling**. However, a fast **cooling rate** produces materials many times stronger. These alloys are known as **heat-treatable**.

In simple words, two or more metals can be melted and mixed to form an almost unlimited number of alloys to cater industrial and domestic needs. The strength and shape of alloys can also be changed at appropriate temperatures.

2.1. Mechanical properties of metals and alloys

In general, the strength of the three major classes of materials can be arranged in the following order:

Ceramics > Metals & Alloys > Polymers

Describing metals as "**stronger**", is subjective and qualitative, which may lead to confusion because new engineering polymeric materials are created to be "**stronger**" than metals. Hence, it is important to use objective and scientific engineering terms to describe the "**strength**" of materials.

2.1.1. Strength

*A wire with a 10mm diameter is expected to be **approximately** 100 times **stronger** than a wire with a 1mm diameter. This is because the cross sectional area is 102 times bigger. The above relationship is described as approximate due to other factors affecting the strength of a component such as length.*

A simple inference due to probabilistic consideration is that the larger the component, the greater the probability of **defects** *existing within the component, thus the strength would likely be lower. On the other hand, the properties of smaller components are more varied because one component may contain more defects than the other. However, since the variation is relatively small, this consideration can be neglected in most light metals manufacturing industry.*

The **strength of a component** is defined as the load (N: Newton, kgf, lb ··· etc.) that it can withstand before **plastic deformation** or **fracture**. The **strength of material** is defined as the maximum stress σ_{max} (Maximum force divided by cross sectional area: F_{max}/A).

$$\sigma = F/A$$

The larger the cross sectional area, the higher the force required to deform it or break it. However, the **strength of material** is almost **constant** for different cross sections. Hence, when specifying how "strong" a material is, its **strength** is described by the international units are **MPa** (or MN/m^2 or $10^6 N/m^2$) for metals and alloys. Table 2.1 is a list of the strength of commonly used alloys.

When something is said to be strong, it could mean that it is stiff (high **Young's Modulus**), can resist to change shape permanently (high **Yield Strength**) or cannot be broken easily (high **Ultimate Tensile Strength, UTS**). The UTS is always larger than yield strength.

Table 2.1 List of mechanical properties of some pure metals (annealed, i.e. heat-treated and softened).

Materials	Young's Modulus* (GPa or 1000MPa)	Yield Strength* (MPa)	Ultimate Tensile Strength, UTS * (MPa)	Appro. Vickers Hardness * (HV)
Tin, Sn	47	9-14	15-200	10
Aluminum, Al	70	15-20	40-50	17
Gold, Au	79	--	120	40
Silver	83	124	207-283	70
Titanium, Ti	120	100-225	240-370	200
Copper, Cu	130	33	210	50
Platinum	168	--	125-240	130
Nickel, Ni	170	14-35	140-195	130
Tantalum, Ta	186	180	200	200
Iron, Fe	211	80-100	350	100
Tungsten, W	411	550	550-620	360

** The properties of some pure metals depend sensitively on the inclusion of other elements. Hence, it is difficult to find the "accurate" values of the "pure" metals.*

As shown in Table 2.1, when the Young' s modulus is higher, the yield strength, UTS and hardness are usually also higher; however, there are many exceptions too!

The stiffness (**Young' s Modulus**) of a material is usually not highly sensitive to the composition. Yet, the yield strength, tensile strength and hardness can be very sensitive to addition of foreign elements. Elastic deformation would lead to no change in mechanical properties. **Young' s modulus** of metals and alloys will be increased due to severe plastic (permanent) deformation; however, the changes are usually within 50%. In many alloys, such changes are less than 10-20%.

On the other hand, the strengths of alloys can be easily raised 5-10 times by **alloying** and/or **thermo-mechanical treatments.** Metallurgists can choose the right addition of alloying elements and alter the mechanical properties dramatically without changing other physical and chemical properties substantially.

For some "soft" materials (**ductile and malleable**), the **difference** between the yield strength and the UTS is very large. This usually implies that these alloys can be **hardened by plastic deformation** (changing the shape permanently). It means metals can be shaped by hammering and forming without experiencing damage. In fact, many alloys can be strengthened by hammering/forging. The process is called **strain hardening** and is very useful.

For "hard" material (usually **brittle**), if it is deformed beyond the yield strength, cracks or micro-cracks would often be introduced to the material. **Micro-cracks** are small and hard to observe and are prone to sudden failure. Hence, hard materials are usually not formed to the final shape by simple mechanical force. **Casting** from melt or **powder metallurgy** methods are usually employed to obtain a form similar to final shape.

Cracking might also occur in **ductile** materials after strain hardening. In order to prevent cracking of **strain-hardened** materials, heat-treatment (**annealing**) process is required to soften the material before further mechanical forming procedures.

2.1.2. Hardness

The Young' s modulus, yield strength and tensile strength of materials are usually provided by materials suppliers. These material properties can be obtained by tensile tests. However, tensile tests are not convenient, as well as costly, for manufacturer in the quality assurance of incoming materials.

The hardness test is a simple and fast method to sample the hardness of a material. The hardness testing machines are also much cheaper, more robust and durable. Hence, it is desirable to use hardness test results to qualify the incoming materials before using them.

There are many types of hardness tests. Indentation hardness tests are used to find the resistance to deformation of the metals and alloys. The primary principle of choosing an appropriate hardness test is to obtain a hardness value/number, which correlates linearly with the UTS. The following are some popularly used hardness tests:

- **Vickers hardness (HV)**
- **Brinell hardness (HB)**
- **Knoop hardness (HK)** for small area and thin films
- Rockwell hardness (HR)
- Janka hardness for wood

- Shore hardness for polymers
- Barcol hardness for composite materials

There is no simple relationship between the results of various hardness tests. However, conversion table can be used to find the approximate hardness values for comparison. **Vickers and Brinell hardness** values correlate quite well over a wide range. Vickers hardness test has the **widest testing range** and will be used in this book for most discussion.

The Vickers hardness test can be used for all metals. The hardness value determined is known as **Vickers Pyramid Number (HV)** or Diamond Pyramid Hardness (DPH). The hardness number is determined as the load divided by the contact area. The shape of the indentation is rhomboidal while the diagonals (l) of the rhombus are used to calculate the HV number. (Table 2.2)

$$HV = 1.8544\, F_{kgf} / l^2 \quad or$$

$$HV = 0.1891\, F_N / l^2$$

where F_{kgf} and F_N are the force applied in kgf and Newton (N) respectively. l is the diagonal in mm.

Vickers hardness numbers are expressed as **xxxHVyy**, e.g. 200HV50, or **xxxHVyy/zz** if the duration of force applied falls outside 10-15 seconds, e.g. 200HV50/30, where:

200 is the hardness number,

HV is the hardness scale (Vickers),

50 is the load used in kgf.

30 is the loading time if it differs from 10-15 sec

Table 2.2 Examples of the Vickers Hardness Values (HV) of some materials.

Materials	Vickers Hardness Number
Lead	4HV
Aluminum	17HV
Gold	22HV
Silver	26HV
Copper	37HV
Iron	30-80HV5
Carbon steel	55-120HV5
Platinum	56HV
Tantalum	89HV
Zirconium	92HV
Titanium	99HV
Cobalt	106HV
Chromium	108HV
Nickel	130HV
316L s.s.	140-225HV30
Beryllium	170HV
347L s.s.	180HV30
304L s.s.	Upto 210HV
Tungsten	350HV
Silica	800HV
Martensite (steel)	170HV
Garnet (silicates)	1000HV
Zirconia	1150HV
Emery	1400HV
Zirconia-alumina	1500HV
Alumina	2000HV
Boron carbide	2000HV
Silicon carbide	2500HV
Cubic Boron nitride	2750HV
Boron	5000HV
Diamond (Carbon)	10000HV

s.s. = stainless steels

Sometime the HV will be given in GPa or MPa. They can be converted to HV numbers by

$$\text{MPa divided by } 9.807 = \text{HV number}$$
$$\text{GPa divided by } 0.009807 = \text{HV number}$$

When the Vickers Hardness is expressed in SI units (MPa or GPa), it can be used to estimate the yield strength:

$$\text{Yield strength} \approx HV/c \approx HV/3$$

where c is a constant determined by geometrical factors usually ranging between 2 and 4.

More details of the testing method can be found in the ISO 6507-1 and ASTM E384 standards.

2.1.3. Brittle or Ductile

Materials can be strong (high stiffness, high yield strength, or high UTS) but easy to break. These materials are called **brittle** materials. Brittleness is due to the incapability of the materials to deform conveniently by any efficient plastic deformation mechanisms, such as **dislocation** movement, deformation twinning, or shear band formation. An everyday life example is the fracture of glass (silica), which is strong but brittle.

On the other hand, if a material can be deformed plastically, it will not be brittle under normal loading conditions. This type of materials is known as **ductile** materials. Ductile materials are most welcomed by manufacturers because they can be formed into various shapes without cracking. Pure gold, silver, aluminum and copper are ductile which can be pressed, rolled, forged into different shapes easily. This properties is also described as malleable.

When materials are hardened by strain hardening, alloying or heat-treatment, they will become stronger but usually more brittle. However, it is sometime possible to **soften** these alloys by suitable heat-treatment to reduce the brittleness before further cold working or forging. Such softening heat treatment is known as **annealing** which may include three stages, namely **recovery, re-crystallization** and **grain growth**. Higher temperature and longer time will usually give more rigorous transformation; hence softer and more ductile materials will be obtained. Furthermore, the **grain size** might become larger simultaneously.

Not all alloys are heat-treatable. Carefully designed heat treatment programs should be established after consulting the suppliers and materials engineers. Other undesirable or irreversible change in properties might be introduced when an unsuitable heat treatment program is adopted.

Brittleness of material is a qualitative term. Fracture **toughness** is the corresponding quantitative term used by materials engineers. A higher toughness value infers less brittle materials. Table 2.3 is a list of fracture toughness of some commonly used engineering materials.

Fracture toughness is related to the resistance to fracture of material with an existing crack. Larger fracture toughness implies tougher (less brittle) materials with better fracture properties. It must be noted that there are different modes of fracture failure and the correct mode and geometry of component must be chosen to ensure accurate prediction of fracture failure behaviors.

Table 2.3 *Fracture toughness and hardness of some commonly used engineering materials.*

Materials	Fracture Toughness (MPa $m^{1/2}$)
4340 Steel	50
Titanium alloy	44-66
7075 Aluminum alloy	24
Aluminum	14-28
Cubic boron nitride	5.7
Boron carbide	3.2
Silicon carbide	2.5-5
Emery	2.4
Aluminum oxide	2.3-5
Silica	1.14
Garnet	1.12
PMMA	0.7-1.6
Polystyrene	0.7-1.1
Soda-lime glass	0.7-0.8
Concrete	0.2-1.4

The **fracture toughness** of some materials is sensitive to temperature. For most metallic materials, fracture toughness is higher at high temperature. However, it must be noted that fracture toughness of some materials will be reduced substantially when cooled down to a critical temperature known as **glass transition temperature.**

Fracture behavior and fracture toughness are also sensitive to **impact.** Usually, higher impact rate **(strain rate)** results in lower fracture stress for the same material. Below the glass transition temperature, impact fracture will also become easier.

2.1.4. Wear Rate

When two materials were "rubbed" against each other, both materials will wear. Softer materials usually wear faster. Although there is no simple relationship between mechanical strength and wear rate, most often materials with a lower strength will wear faster.

Wear rate would be higher if the same material is "rubbed" against another material with much higher hardness such as aluminum oxide or silicon carbide (SiC).

Table 2.4 shows the UTS, Vickers Hardness and approximate abrasion rate when the pressure applied is about 30kPa. A higher the hardness usually gives a lower wear rate (abrasion rate). However, there are many exceptions because the wearing mechanism is quite complicated.

2.2. Physics of metals and alloys

Our everyday misconception might be that heavier materials are stronger. However, there are plenty of "exceptions" such as gold (Au) and lead (Pb) which are heavier but not necessary stronger.

Table 2.4 Approximate abrasion rate using P240 silicon carbide paper

Materials	UTS[a] (MPa)	Approx. Vickers Hardness[a] (HV)	Abrasion rate (μm/m)
Lead, Pb	8	6	12
Tin, Sn	14	10	3.5
Aluminum, Al	70	17	2.5
Gold, Au	79	22	0.08
Silver, Ag	83	26	1.1
Copper, Cu	130	37	0.6
Nickel, Ni	170	130	0.1
Pure Iron, Fe	28[a]	30-80	0.1
Titanium, Ti	120	99	0.05
Chromium, Cr	--	108	0.05
Tungsten, W	411	350	<0.05

[a] *The properties of some of these pure metals depends sensitively on the inclusion of other elements. Hence, it is difficult to find the "accurate" values for these "pure" metals.*

The strength of materials depends on the **bond strength.** In layman terms, this is equivalent to how the atoms are "glued" or "stuck" together. There are three main types of bonds namely **covalent, ionic** and **metallic** bonds.

Atoms in **ceramic** materials usually are bound together by **covalent** bonds and ionic bonds giving them higher strength. Ionic bonds are sometime weaker in specific solvent. **Metallic** bonds of metals and alloys are slightly weaker, yet strong enough to make structural materials. Furthermore, the unique properties of metallic bonds make them more ductile and malleable.

In general, stronger bonds contribute to materials with higher strength. However, there are other factors controlling the mechanical properties of metals. The physics of **metals and alloys** will be further discussed in the following sections.

2.2.1. Crystal structure

Besides the characteristics of the bonds, the regular and periodic arrangement of atoms (**crystal structure**) in three dimensional 3D space is key to the strength and behavior of metallic structures.

Iron-carbon alloys (**steels**) have face-centered cubic (FCC) structure at high temperatures which is relatively softer and can be hammered (**forged**) into different shapes easily. The FCC structure of steel is also known as **austenite.**

When austenite is slowly cooled down to room temperature, it transforms into body centered cubic (BCC) structure that is harder and is more difficult to be forged into various shapes.

The crystal structure of steels at room temperature can be changed to FCC structure by adding nickel (Ni) and chromium (Cr). The most widely used stainless steels are 304 and 316 stainless steels. They have FCC structures and are classified as austenitic stainless steels. 300 series stainless steel is **softer than high carbon steels.** They contain less than 0.15% carbon. More than 16% chromium. Nickel and/or manganese is added to increase its thermal stability. Chromium and nickel are essential to achieve the corrosion resistance property.

Both of the FCC and BCC are symmetrical crystal structures, which are usually softer than less symmetric crystal structures. (e.g. such as hexagonal close packed and body centered tetragonal (BCT)).

2.2.2. Deformation and fracture of metals

When stress is applied on an alloy crystal structure, the metallic bonds will be stretched (lengthened), compressed (shortened) and sheared (bent). Below the yield strength, the change is recoverable and the material is only elastically deformed. Further increasing the stress might lead to **slipping of crystal** planes in the metallic crystal that results in yielding and subsequent plastic deformation.

The theoretical yield strength, calculated from the bond strength between atoms, of metals is usually 100 to 10000 times higher than the actual strength. This is usually due to the present of defects in the crystal structure, such as **dislocation** on **slip planes.**

Different crystal structures have different numbers of slip planes. Dislocations can slide preferentially on some **slip planes** along specific slip directions. Slip planes and slip direction for dislocation movement are known as **slip systems.** When there are more slip systems, plastic deformation would be more likely to occur.

FCC and BCC crystal structure have 12 slip systems and can be plastically deformed and thus softer. HCP and other crystal structures, which have less slip systems, are usually stronger. Table 2.5 shows a list of commonly used pure metals. The FCC metals are more ductile and can be formed into different shapes by forging.

Table 2.5 Crystal structures of various pure metals

Materials	Standard atomic weight	Vickers Hardness (MPA)	Crystal Structure
Aluminum, Al	27	167	FCC
Gold, Au	197	216	FCC
Silver, Ag	108	251	FCC
Copper, Cu	64	369	FCC
Nickel, Ni	59	638	FCC
Pure Iron, Fe	56	608	BCC
Titanium, Ti	48	970	HCP
Chromium, Cr	52	1060	BCC
Tungsten, W	184	3430	BCC

Dislocations assist the plastic deformation. Furthermore, when dislocations glide along slip planes, more dislocations will be produced through the **Frank-Read Source** mechanism. Consequently, this will lead to avalanche and "traffic jam" of dislocations, leading to the **strain-hardening** effect. With the dislocation density ever increasing, further increase in stress will cause the breaking of the bonds. Cracks will be formed and propagate, leading to the final fracture.

In metals that do not have viable slip systems, there will be no plastic deformation. Consequently, the yield strength would be higher. Right after exceeding the yield stress, cracks will form and propagate. The propagation of these hard materials is usually faster because less deformation energy is required to form larger crack surface when plastic deformation takes place around the crack tip. This explains why stronger metals are usually more brittle.

2.3. Heat treatment of metals and alloys

Alloys that can be hardened by **hammering** (plastic deformation strain hardening) are known as hardenable. Strain hardened alloys are more brittle and further forming and shaping might not be possible. These strain-hardened alloys can be **softened (annealed)** by heat treatment at elevated temperature. **Annealing** of deformed alloys will lead to three different but overlapping stages namely **recovery, re-crystallization** and **grain growth.**

The most important mechanisms responsible for the softening of deformed alloys is the **re-crystallization** process which lower the **dislocation** density, thus the hardness. The **recovery** process might not be noticeable if the annealing temperature is high. The **grain growth** process leads to larger grain size alloys. Deforming large grain size (>100 μm) alloys can produce the undesirable **orange peel effect.** Extra efforts will be required to grind and polish such a rough surface to become a mirror surface. Hence, annealing treatments with unnecessary high temperature should be avoided.

Heat treatment can be performed in vacuum, air (or gas), liquid (or molten salt, oil). The maximum attainable temperature of heat treatment in liquid is the boiling point of the liquid. Hence, heating some materials in a bath of boiling water (100°C) using a heater at 300°C is similar to the effect of using a 120°C heater. However, the 300°C heated water bath will introduce more vigorous convection and is similar to adding a stirrer **(forced convection)** in the 120°C heated water bath.

The efficiency of heat treatment is higher at:

Liquid > Gases > Vacuum
Forced Convection > Natural Convection > Static
Higher temperature > Lower temperature
Smaller component > Larger components

Some alloys can also be hardened by heat treatment alone. **Precipitation hardening (age hardening)** and harden by fast cooling rate **(quenching)** are the most popular hardening processes because no forging (changing shape) is necessary in the hardening processes.

Some steels and alloys can be hardened by a high cooling rate **(quenching).** The alloys should be heated above a critical temperature that allows it to transform to the high temperature phase. Cooling down it slowly will give a softer metal which is more suitable for machining. After machining, the alloy should be heated above the phase transformation temperature **again.** When cooled down quickly **(quenching)**, a non-equilibrium phase **(martensite phase)** might form which can be extremely hard.

Alloys to be **age hardened** should be heated above the **solid solution temperature** to dissolve all precipitates and cool down slowly to obtain the softest properties suitable for machining. The machined component is then heated above the solid solution temperature **again.** However, the component should be cooled down quickly **(quenching)** to low temperature prevent the formation of soft phases. The component is then **aged** at intermediate elevated temperature for a relatively longer duration **(ageing)** allowing the formation of some **hard precipitates** from the quenching hardened alloy.

A proper heat treatment process should be carefully designed after consulting the materials engineer and materials supplier. Improper heat treatment process downgrades the mechanical performance, as well as making the machining, grinding and polishing process more difficult and time consuming. Some heat treatment processes, such and the grain growth process, is irreversible and result in sub-standard surface finishing of the product.

Section A Fundamentals

Chapter 3

3. Mechanical Polishing mechanisms

Polishing is a process that makes use of hard particles (abrasives) to smoothen a surface. The final surface can be made mirror-smooth when a series of coarse to fine abrasives are appropriately used to polish a metal.

The hardness of the abrasive should be at least 1.5 times harder than the material to be processed. In practice, only abrasives with hardness less than 3 times of that of the workpiece should be used for efficient polishing. Table 3.1 is a list of abrasive materials and their hardness.

Table 3.1 HV hardness of various abrasives.

Abrasives	Hardness (HV)
Silica	850
Zirconia	1150
Emery	1400
Aluminum oxide	2000
Boron carbide	2000
Silicon carbide	2500
Cubic boron nitride	2750
Diamond	10000

Polishing processes using harder abrasives are more effective and efficient. In fact, only aluminum oxide (Alumina: Al_2O_3), silicon carbide (SiC) and Diamond (C) are used most industrial processes. Zirconia-alumina ($ZrO_2 . Al_2O_3$) is occasionally used.

In the polishing process, these hard abrasives create scratch the surface of the workpiece. When the scratches are very fine, they become invisible to the naked eye and a mirror surface is produced.

3.1. Mirror surfaces of metals, roughness and measurement

A perfect mirror is a surface that can reflect light rays without distortion and without absorbing light. However, perfect mirror surface does not exist in practice. A very high quality dielectric mirror can reflect 99.999% of light for a specific range of wavelength, while a simple mirror may reflect up to 99.9% of light covering broader wavelengths. The reflected combined wavelengths contribute to the "color" of the materials.

Another factor that affects of the quality of a reflecting surface is the percentage (%) of **diffuse reflected light.** A matte surface, such as plaster or woven cloth, reflects almost 100% diffuse light. On the other hand, a glossy surface, such as polished glass or metallic surfaces, can give close to 100% **specular reflection.**

When an apparently flat surface is magnified thousand times, a lot of scratches and can be seen on the surface, which form mountains and valleys. These scratches increase the amount of diffuse reflection and distortion of the reflected images. **Abrasion** (grinding) using finer abrasives can reduce the **"height"** differences of these scratches and the corresponding diffuse reflection. Consequently, more specular reflection is achieved with less distortion of reflected images.

Eyes of people with perfect vision (20/20) are sensitive but still cannot clearly distinguish two lines closer than 70μm (i.e. 0.07mm) at a 20cm testing distant.

Grade 120 silicon carbide paper (sandpaper) can produce scratches with depth and width of about 5μm. Although the human eye cannot see these fine scratches individually and clearly, it can still see such scratches made. This is because these scratches are not of uniform width and **are not distributed uniformly.** They produce sufficient contrast to be observed. In fact, a lot of undetached debris can be seen on the edges of these scratches using microscopes. The "**rough**" surface produces a high percentage of diffuse reflection leading to poor reflected images.

The easiest way to examine the quality of a mirror surface is to examine the reflection of a sharp straight line, e.g. a long and straight fluorescent tube. By rocking the polished workpiece to and fro, the distortion of the straight fluorescent tube can be observed. Bumpy area and areas with unacceptable scratch marks can be located.

A more scientific way to describe the roughness of a material is by finding its roughness parameter using contact type equipments such as **profilometer** and **atomic force microscope**. Other non-contact equipments include **interferometer** and **confocal microscope.** Roughness profile parameters can be quantitatively determined for easier reference and comparison with the aid of these equipments.

The most commonly used roughness parameter to quantify roughness is **Amplitude parameter (Ra)**. Ra is the arithmetic average of the vertical deviations of the peaks and valleys **from the mean line.** Ra is expressed in units of height such as millionth of an inch or μm. It might be inaccurate to use only one number to describe the roughness. Other roughness profile parameters like RRMS (root mean squared), Rv (maximum valley depth), Rp (maximum peak height) etc., should also be considered whenever necessary.

In general, the smaller the roughness profile number, the less diffuse reflection produced. Hence, the polished surface is shinier giving less distorted reflected images.

3.2. Grinding, polishing and buffing

After the workpiece is shaped and formed into the final shape, surface finishing is usually performed according to the product design requirement.

Grinding is a process using a hard grinding wheel (e.g. sandstones or abrasives bonded disc/wheel) or manual grinding aids (e.g. **sandpapers**) to **abrade** the surface removing a small amount of material. The expected outcome of grinding should be a flat surface or a desired curved surface. The main purpose of grinding is to abrade and cut so that unnecessary materials (e.g. burrs and oxides) are removed from the surface.

Polishing, lapping and **Buffing** are mechanical surface finishing processes that use abrasives and work wheels in the metalworking industry. The term **polishing** is very often vaguely defined as a process to **produce a smooth and shiny surface.** Hence, any finishing cut process leading to a mirror or near-mirror surface can be classified is polishing. Technically speaking however, **sanding** is defined as smoothing a surface using fine abrasives coated on a paper or cloth substrate, which is adhered on a **rigid** work wheel. We can use coarse sandpapers to grind the surface and fine sandpapers to perform sanding leading to high quality surface finish. The sanding process is similar to grinding. Sanding using sandpaper with grade P1500 or above can produce mirror surfaces to the naked eye and should be classified as polishing.

As shown in Table 3.2, only the abrasion process using grit no. P1500 or above can produce surfaces of a **near mirror reflection** quality. However, fine scratches can still be seen when magnified using a good magnifying glass or optical microscopes. In fact, most mirror bright finishings are actually **buffed**, or **lapped** instead of polished. **Lapping** and **buffing** usually refer to the use of loose abrasive applied to the work wheel and flexible wheel respectively. Fixed abrasive lapping is also available; however, the surface quality usually is not as good as loose abrasive lapping. All lapping refers to loose abrasives lapping hereafter.

Table 3.2 Sandpaper Grit standard (ISO/FEPA) vs. particle size for various surface finishing processes

Quality	ISO /FEPA Unit	Abrasive particle size (μ m)	Processes
Extra coarse	P20	1000	Grinding / Abrasion
Coarse	P50	336	
Medium	P100	162	
Very fine	P220	68	
Extra fine	P400	35	
Superfine	P800	22	Grinding to Polishing
Ultra fine	P1500	13	
Ultra fine	P2500	8	Polishing

The proper order of mechanical surface finishing after machining should be:

1. Remove oxide, de-burring and flatten (Rough sanding)
2. Grinding Abrasion (Fine sanding)
3. Polishing (Ultrafine sanding)
4. Buffing or Lapping (**Mirror** effect)

In the final surface finishing process, sandpaper is very often used to **abrade** the surface. The objective is to enhance the shine of the surface, to remove oxides, and to create flat surface. **Sandpapers** of different grit standard are made by bonding abrasives particles of different sizes (Table 3.2) to the backing materials such as **cotton, polyester, rayon, PET film** and **rubber**. Waterproof backing is more durable if water is used at the lubricant in the abrading process. The finely sanded surface should be **buffed** or **lapped** to produce a good mirror reflective surface.

3.3. Wearing mechanisms

When hard abrasives are pressed onto the surface of the workpiece, the abrasives make indents on it. When the abrasive particles travel along the surface, scratches will be made leading to the removal of surface material **(grinding and abrasion)**. Usually, the abrasive particles are single crystals with a random sharp fracture surfaces. The sharp fracture surface is ideal for cutting and abrasion.

The shape and orientation of the abrasive particles will affect the effectiveness of abrasion. Round particles with **obtuse** cutting angles cannot abrade the surface effectively. Particles with **acute** cutting edges at the inappropriate orientation cannot abrade effectively either. The number of effective cutting points is much smaller than the number of contact points. Table 3.3 shows the number of **contact points** and **cutting points** of various SiC sandpapers.

The force applied to press the workpiece against the sandpaper will affect the depth and width of the scratches made. A pressure of **20-40 kPa** is recommended. Table 3.4 shows the force required to grind workpieces of various sizes in kg and lb for reference.

Table 3.3 Characteristics of SiC sandpapers

Characteristics	SiC papers			
	150	280	400	600
Contact points /cm^2	50	100	400	450
Cutting points /cm^2	10	14	52	55

Apart from pressure, the depth and width of the indents will also depend on the hardness of the materials. Assuming the indentations are square in shape, the diagonal of the square can be approximated using the no. of contact points from Table 3 and the following formula for materials with different hardness.

$$HV = 1.8544\, F_{kgf} / d^2$$

Table 3.4 Force conversion table for circular workpiece of various diameters

Diameter (mm)	Area (mm^2)	Pressure (kPa)	Force		
			N	kg	lb
25.4 (x10 pieces)	5067	20	101	10	23
	5067	40	203	21	45
25.4 (1 piece)	507	20	10	1.0	2.3
	507	40	20	2.1	4.5
12.7 (1 piece)	253	20	5	0.5	1.1
	253	40	10	1.1	2.3
6.35 (1 piece)	127	20	3	0.26	0.6
	127	40	5	0.52	1.1

Table 3.5 FThe relationship of estimated width of scratches under different pressure

Pressure (kPa)		20			
Area (mm^2)		506.7			
Force (N)		10.13			
Force (kgf)		1.033			
	Sandpapers	600	400	280	150
	Contact points/cm^2	450	400	100	50
HV of workpiece	Contact points	2280	2027	304	253
	d^2(mm^2)	Diagonal, d (μm)			
50	0.03831	4	4	9	12
100	0.01916	3	3	6	9
200	0.00958	2	2	4	6
400	0.00479	1	2	3	4
800	0.00239	1	1	2	3
1600	0.00120	1	1	2	2
Pressure (KPa)		40			
Area (mm^2)		506.7			
Force (N)		20.27			
Force (kgf)		2.066			
HV of workpiece	d^2(mm^2)	Diagonal, d (μm)			
50	0.07663	6	6	12	17
100	0.03831	4	4	9	12
200	0.01916	3	3	6	9
400	0.00958	2	2	4	6
800	0.00479	1	2	3	4
1600	0.00239	1	1	2	3

Table 3.5 shows the relationship between the estimated width of scratches when different pressures are applied during the abrasion process. When higher pressure is applied, the width of the scratches will be larger. The width of the actual scratch might be smaller because scratches also have elastic recovery when the imposed stress is removed.

The estimation is calculated using the number of contact points of new pieces of sandpaper. It is also assumed that the abrasive particles are approximately diamond in shape. The approximations shown in Table 3.5 are close to experimental findings. Furthermore, the value of contacting points increase when the sandpaper is used for a longer period of time and reaches a stable value after a relative rubbing distance of 20-100 revolution (for 160mm diameter sandpaper disc). Sandpaper of a larger grit number tends to produce the stable surface roughness more quickly.

3.4. Deformation depth and abrasion parameters

In sanding, polishing and buffing of softer materials, lower pressure and finer grit sandpapers should be used if smooth and finer surfaces are desired. Table 3.6 shows the depth of the scratches produced by different sandpapers on Cu30%Zn at 40kPa using SiC papers.

Table 3.6 The depth of the scratches after abrasion using various sandpapers.

	Sandpaper Grit	220	400	600
Max. depth of scratches (μm)	Fresh sandpaper	5	3	1.3
	After 20m	2.4	1.5	0.9

Table 3.7 Depth of plastically deformed layer produced on Cu30%Zn by various machining, grinding and polishing methods.

	Grade	Cutting fluid	μm		
			Marks / scratches	D_s	D_d
Hand hacksaw	18 teeth/in.	None	100	55	750
Cutoff wheels	Alumina 60 mesh	Oil-water emulsion	4	16	700
Cutoff wheels	Diamond wheels	Proprietary fluid	1	14	--
Filing	Bastard cut	None	70	55	450
Filing	Second cut	None	30	50	370
Lathe turning	0.001 in. feed	Oil-water emulsion	1	15	150
Machine surface grinding	Alumina 28 mesh	Oil-water emulsion	6	50	350
Hand grinding	Alumina 38 mesh	None	15	40	170
Belt surfacing	Alumina 100 mesh	None	15	35	250
	SiC P120	Water	5.5	25	19
	SiC P240	Water	3.5	15	95
	SiC P400	Water	1.2	5	60
Sand-papers	SiC P220	Water	2.0	7.5	77
	SiC P400	Water	1.5	6.5	43
	SiC P600	Water	0.8	5.0	22

The values shown in Table 3.6 are the depth of the scratches that we can see or measured. However, the effects of machining, grinding and polishing are not merely reducing the roughness of the surface. Plastically deformed layers are produced beneath the surface. Immediately under the scratch grooves, there is a layer of materials called a **significantly deformation layer** (shear band layer, D_s) which is full of shear bands deformation structure. The next layer is the deformed layer (D_d).

The depth of D_s and D_d can be up to 14x-50x of the depth of the scratches. Table 3.7 shows some known significant deformation layer and deformed layers. The actual D_s and D_d depends on the pressure applied on the abraded surface and can usually be minimized if lower pressure is imposed.

Table 3.8 Depth of significantly damage produced on austenitic steels and zinc by various machining, grinding and polishing methods. (Pressure: 30kPa)

	Abrasive type	Mesh/ Grade	Conditions	D_s (μm)	
				Austeni-tic steels	Zn
Machine surface grinding	Alumina	38	25 μm feed with cutting fluid	35	125
	Alumina	38	Hand held dry	43	130
Manual belt surfacing	Alumina	100	Hand held dry	12	85
Manual abrasion	SiC	220	Hand held dry	6	50
	SiC	400		2.5	45
	SiC	600		2.2	15

The hardness of austenitic steel such as stainless steels is higher than CuZn alloy and the significant deformation layer is much more shallow. Table 3.8 shows the damage produced by manual various abrasion processes.

The presence of significantly damaged layer usually does not lead to immediate obvious abrasion defects if the surface is smoothened by subsequent polishing and buffing. However, the deformed surface is more susceptible to corrosion and chemical attack. This will lead to accelerate deterioration of the mirror surface when the workpiece is exposed to the corrosive atmosphere.

Furthermore, if PVD, CVD or chemical polishing are performed on the surface with a significantly damaged layer, an undesirable rough surface might be produced. Hence, it is important to minimize the thickness of the significantly deformed layer by adopting appropriate grinding and polishing processes.

A simple method to minimize the effects of the deformed layer is to lower the abrasion pressure. Besides, between one abrasion and the next, the direction of stroke should be **rectangular** (i.e. **perpendicular** to the previous stroke). When changing the grade of the abrasion, the abrasive marks generated by the previous abrasion must be **completely removed** before the next abrasion is applied.

3.5. Abrasion rate and abrasion parameters

Abrasion and removal of surface materials is in fact a very complicated process. Hence, there are quite a lot of exceptions. However, the abrasion rate of the workpiece is roughly inversely proportional to the hardness of the workpiece. Table 3.9 shows the relationship between abrasion rate of iron base alloy and the corresponding hardness.

Table 3.9 Abrasion rates obtained with various metals using various abrasive papers. (Pressure: 40kPa)

	Hardness (HV)	Abrasion rate (μm/m)		
		SiC P240	Alumina P240	Diamond 220
Aluminum:				
High purity, annealed	24	2.61	1.93	1.76
Alloy, heat treated	105	1.29	0.85	0.65
Chromium:				
High purity, annealed	200	0.25	0.20	0.16
Copper:				
High purity, annealed	50	0.61	0.28	0.19
Brass 30%Zn annealed	45	0.81	0.72	0.40
Brass 40%Zn leaded	155	2.06	1.48	0.77
Aluminum bronze	200	0.78	0.66	0.40
Gold:				
high purity, annealed	22	0.26	0.16	0.18
Nickel:				
Commercial purity, annealed	130	0.08	0.17	0.08
Steel:				
Austenitic, 304	155	0.09	0.36	--
Titanium:				
Commercial purity, annealed	200	0.25	0.15	0.11
Ti-6Al-4V, heat treated	295	0.25	0.15	0.07

Abrasion rate is linearly proportional to the mean particle diameter of the abrasives. A larger particle diameter will usually give a higher abrasion rate. However, the maximum abrasion rate available is found in abrasive particles with diameter ~100 μm (between grade 220 and 150). Table 3.10 shows the abrasion rate of various grades of abrasives.

Table 3.10 Abrasion rates with various grades of abrasives on annealed Cu30%Zn. (pressure: ~40kPa)

Abrasive grade	Mean particle diameter (μm)	Abrasion rate (μm/m)
P1200	15.3	0.25
P800	21.8	0.37
P240	58.5	0.75
220	63	0.95
150	90	1.00
100	150	0.90
80	180	0.70

A higher applied pressure can also lead to an increase in abrasion rate. However, the deterioration of the sandpaper will cause problems in rapid reduction of the abrasion rate. Thicker and deeper scratches will also be produced, which is not good for high quality polishing process.

3.6. Polishing, lapping and buffing

Distinctions between grinding and polishing are not as clear in practice. Using SiC sandpapers of P600 or smaller grit number to abrade the surface will leave clear grinding marks on the surface and thus should not be classified as polishing. On the other hand, sanding by grit 1500 or above to abrade the surface may leave unnoticeable scratches to the naked eyes. Should it be classified as polishing? If yes, what about the range from grit 600 to 1500?

This ambiguity cannot be overcome easily because these processes produce surface finishing with overlapping quality. The term "polishing" is generally used to describe a process where a surface is rubbed against abrasives to produce a surface with mirror-like reflective abilities. There is no clearly defined objective roughness to qualify that a surface has attained the "polished" quality. The purposes of various industrial processes are listed in Table 3.11.

Table 3.11 Purposes of various mechanical industrial processes.

Operations:	Shaping, forming	Grinding, abrasion	Polishing
Purposes:	*Produce the shape*	*Fine tune dimensions and/or produce surface texture*	*Surface finishing*
Examples:	Cutting Turning Drilling Boring Milling Lathing	Wire brushing (texturing) Honing Sanding (50-1000)	Sanding (1500-2500)* Buffing Lapping Electro-polishing

* *"fine grinding"*

A mirror reflection constitutes mainly of specular reflections with diffracted light rays reinforcing one another; hence, these rays should be refracted in parallel and with regular spacing. Theoretically, repeating parallel grooves with regularly spacing can give good reflected images if these grooves are fine. However, the spacing, depth and contour of the grooves vary over a wide range on real surface.

In practice, when abrasives are bonded to the backing materials or matrix, the chances of having irregular and non-uniform scratches are higher. It can be technically defined as "fine grinding".

If abrasives of similar sizes are applied loosely on the work wheel, the random abrasion due to these fine abrasives usually produces a much "flatter" and smoother surface. It can be defined as lapping-polishing. The main purpose of this process is not to fine-tune the dimension or to produce surface texture, but to produce a good reflecting surface with less image distortion.

All mechanically ground or polished surfaces carry scratches. Scratches on ground a surface can be observed easily without visual aids. The scratches on a polished surface are finer but can still be found using optical microscope.

Lapping and buffing can be defined as surface finishing process as that use **loose abrasives** to produce high quality mirror surfaces. Therefore, the sanding process using sandpapers can be classified as grinding. In **lapping**, the backing material (e.g. paper, cloth, felt) is relatively more rigidly held, while the **buffing** process make use of **more flexible** held fabrics, cloth or paper.

Lapping and buffing both involve rubbing loose abrasives against a workpiece. The abrasives will **roll** on the workpiece compressing the immediate surface layer beside making scratches on it. The abrasives might also break into finer particles during this process. This combined **rolling-breaking-abrasion** process will usually gives smoother and shinier surface. Hence, more specular reflection and less diffuse reflection will be obtained from the processed surface.

In general, lapping and buffing can achieve an average roughness in the range of 0.4-0.05 μm. Of course, if coarse abrasives are used, the abrasion effect may dominate producing a rougher surface instead of a smoother surface.

Abrasives used in lapping include:

- Alumina (Aluminum oxide)
- Diamond
- Magnesia (Magnesium oxide)
- Silica (Colloidal)

3.7. Friction and lubrication (binder)

The abrasion and polishing processes will be inefficient if the friction between the workpiece and the work wheel is high. **Jerky** motion of the work wheel will also lead to a rougher surface finishing.

Table 3.12 Effects of lubricants on abrasion rate.

Lubricants	Relative abrasion rate
Flowing water	1.0
Silicone fluid	1.0
Extreme pressure lubricating oil	0.7
Dry (no lubricant)	0.5
Waxed but no liquid	0.4
Stagnant water	0.4

P240 SiC paper, on annealed Cu30% Zn

The addition of appropriately chosen **lubricants (binder carrier)** can make the rubbing process smoother giving higher quality mirror surface. However, the abrasion rate might be altered by the nature of lubricants and ways of applying lubricants. Table 3.12 shows the importance of selection of appropriate lubricants.

The liquid applied may also serves other purposes, such as acting as a coolant, etchant and dispersant:

> **Coolant:** The flowing liquid can carry away heat generated due to continuous and rigorous rubbing of the surfaces. This will limit the rise of temperature and prevent damage to the workpiece surface
>
> **Etchant:** If the liquid can react with and dissolve the workpiece materials mildly, the abrasion rate might be increase without an increase in pressure. Less scratch will be produced and a mirror like surface can be produced more easily. However, the workpiece must be thoroughly cleaned to remove the etchant that will corrode the surface if left on the workpiece.

> **Dispersant:** Localized abrasion will leave machine marks and produce a poor surface finish. The corresponding abrasion rate will also be lowered. A good selection of abrasion fluid can help to disperse the abrasive more uniformly on the polishing mat and buffing wheel. When kerosene is used as the polishing fluid instead of water with diamond abrasives, the polishing rate can be 5 to 10 times higher.

In a typical buffing process, the elevated temperature leads to higher fluidity of the **buffing compound (wax)**; hence, the abrasives can abrade and polish faster, more evenly and better. If the temperature is not high enough, localized abrasion will give prominent undesirable scratches. However, if the temperature is too high, the buffing compound will be burnt and hardened leading to undesirable localized abrasion and scratches as well.

3.8. Protection of the polished surfaces

In the polishing workshop, the work wheels of coarser and finer abrasives should not be put together. They should be ordered progressively putting coarse work wheel at one end of the room and fine work wheels at the other end of the room.

Different work wheels should be used for workpieces of different hardness. Otherwise, debris from the harder workpieces could create scratches on the softer workpieces.

The airflow in the workshop should be minimum such that debris from grinding and coarse polishing will not contaminate the polished surface. The airflow directions should be from ceiling to ground, as well as unidirectional from coarse work wheels to fine work wheels. If possible, debris (dust) should be directly collected from the grinding/buffing wheels. The debris on the floor should be cleared regularly.

The polished surface should be cleaned and kept in places where no abrasives are present. Clean and soft packaging should be used to contain these polished products. The container should also be free from vibration and impact.

Section B Grinding, Polishing and Buffing

Chapter 4

4. Abrasion, Polishing and Buffing techniques

The primary objective of the **grinding** process is to give the surface **dimensional accuracy**, which machining cannot achieve. Reasonable surface finishing can also be realized by proper fine grinding practices.

If a surface full of oxide is buffed directly, its process would be more difficult and ineffective. In fact, more **shape distortion** would be inherited if coarse abrasives are used to replace the sandpapers grinding and polishing processes. The dimensional accuracy and repeatability cannot be guaranteed. It would be a waste of time and effort if a proper surface treatment sequence is not carefully designed.

Coarse grinding machining is taught in metal cutting and shaping courses and will not be covered in detail in this book. **Fine grinding** using sandpapers, or buffing using work wheels and wax are popular metal finishing techniques in watch making industry, which will be elaborated in the following sections.

A typical metal processing route can be summarized as:

1. *Forming and shaping*
2. *Machining*
3. *Grinding with grinding wheel*
4. *De-burring (Section 4.2)*

5. *Oxide Removal (Section 4.3)*
6. *Sanding with sandpapers (Section 4.4)*
7. *Lapping with loose abrasives (Section 4.5)*
8. *Buffing (Section 4.6)*

4.1. Preparation for grinding, polishing and buffing

Prior to choosing the sequence of grinding and polishing, the following information must be given:

- Material composition
- Previous thermo-mechanical treatment and hardness
- Previous machining and forming processes
- The desired surface finishing to be achieved

Using the above information, the following grinding and polishing parameters can be estimated by consulting suppliers, handbooks and literature:

- Abrasion rate with various grinding and polishing methods
- Corresponding deformed layers thickness
- The cost and time required for various available processes

Grinding and polishing sequence should be proposed and iteratively evaluated to minimize the cost and production time. If the deformed layers are likely to affect the future appearance of the polished surface, the deformed layers must be removed either by fine polishing or electro-chemical polishing.

Machining chips must be removed from the surface before grinding. **Grease and oil** will affect the grinding and polishing processes and must also be removed. **Coarse abrasive particles** and **debris** need to be rinsed off the surface before finer grinding and polishing. If possible, the workpiece should be **demagnetized** before fine grinding and polishing; otherwise, the debris will be cluster on the surface leading to poorer finishing quality.

4.2. De-burring

Burrs can be removed by **filing, wire brushing, abrasive belts, abrasive jets**. Batch type processes such as **vibratory finishing** and **barrel finishing** processes can be used to improve the surface finish and remove burrs from large numbers of workpieces simultaneously. These automated processes can be performed by pre-programmed robots can provide consistent surface finishings.

Buffing should be avoided in de-burring whenever possible because buffing is a slower process. If coarser abrasives are used in order to increase the de-burring rate, substantial distortion in shape (especially at the sharp edges of the workpiece) would result. **Sanding** process should be adopted only if the burrs are relatively small and can be abraded effectively using the sandpaper polisher.

4.3. Oxides and surface layer removal

If the workpiece is heat treated, oxide films will be formed on the surface. The thickness of the oxide film should be considered when choosing grinding abrasives, abrasion parameters and abrasion time. Furthermore, the surface composition might be altered due to out-diffusion of composing elements leading to a change in the microstructure of the surface layer. Grain size, hardness and corrosion resistance might also be affected, leading to poorer surface properties.

Many **oxides are harder** than the metals. If possible, the oxides should be **machined** off the surface before using sandpaper to process the surface. Grinding with abrasives bonded onto solid grinding wheels is more efficient in removing hard oxide layers. The wearing and consumption of sandpapers would be too high and not cost effective.

After the oxide layer or the deformed layers are ground off, the oxide and debris must be thoroughly removed from the workpiece due to the oxides being much harder than the metals. Otherwise, the hard debris will create undesirable scratches on the surface.

Table 4.1 election of abrasives for various grinding-finishing operations

Operation		Abrasive grade
Stripping		12-20
Stock removal	Heavy	24-40
	Medium	50-80
	Light	100-150
Finishing		180-240
Polishing		280-600

Various grades of abrasives should be used for different purposes such as stripping, stock removal, finishing and polishing. Table 4.1 is a summary of various operations and the corresponding grade on the coated abrasive belt. Clear abrasion marks and lines are still visible after the above processes.

4.4. Sanding with sandpapers

After various processes of machining, shaping and removal of oxides, the thickness of remaining deformed layers to be ground off should be estimated. Good and durable surface requires the total removal of the significantly deformed layer (D_s). If the best surface quality is required, the whole deformed layer (D_d) should also be ground off carefully. Information in Table 3.6 may be used to estimate the surface thickness considered necessary to be removed.

The abrasion rate of SiC sandpaper is higher with larger abrasives. However, maximum abrasion can be achieved at the abrasive grits between P240 and 150. 150 grit is a classified as the screen grit size range, P220 is classified as the macro-grit range, while the P240 is within the micro-grit range. In order to produce the ultimate "polishing" grade surface, micro-grit range sandpapers (P240 or finer (i.e. larger grit numbers)) should be used because the size range of abrasive particles is better controlled. With narrower range of particle size, more uniformly distributed scratches can be formed, which will also affect the final polishing/buffing quality.

The pressure applied should normally be in the range of 20 to 40kPa. The actual force required depends on the size of the polishing surface. Table 3.4 can be used to estimate the force required for the grinding process. Higher pressure will usually give a higher abrasion rate. However, the surface will also be rougher with deeper deformed layers to be removed in the next grinding or polishing step. Furthermore, higher pressure will increase the rate of deterioration of the sandpapers.

The abrasion rate using P240 on Cu30%Zn alloy is ~0.8 μm/m at the pressure of ~40kPa with flowing water lubrication. If no lubricant is applied, the abrasion rate will be lowered and the sample might overheat causing other undesirable effects. When a previous significantly deformation layer

(D_s) of 50 μm is to be removed, the abrasion stroke should be 62.5m long. If the grinding track on the work wheel is 0.5m per rotation and it rotates at 1000rpm, then the grinding stroke is 500m/min. Hence, it will take ~7.5 second to remove the D_s thickness.

Abrasion rate is approximately proportional to the square root of pressure. When the pressure is doubled, the abrasion rate will be $\sqrt{2}$ (i.e. ~1.41 times of the original rate). When the pressure is halved, the abrasion rate is ~0.7 times of the original rate.

Table 4.2 Time required to remove the deformed layers for Cu-30%Zn.

Process	Abrasion rate (μm/m)	Preceding process	Preceding D_s & scratches (μm)	Required abrasion stroke (m)	Approx. time* (sec.)
P240 SiC	0.8	Machining surface grinding	50	62.5	7.5
P800SiC	0.4	P240 SiC	9	22.5	2.7
P1200SiC	0.25	P800 SiC	5	20	2.4
P2500SiC	0.1	P1200 SiC	4	40	4.8
6 μm Diamond lapping	~0.05	P2500 SiC	3	60	7.2
1 μm Diamond lapping	<0.01	6 μm Diamond polishing	~1	>100	>12

**work wheel speed = 500m/min*

The new D_s layer due to P240 SiC sandpaper grinding is ~7 μm. The depth of the scratches left is ~2 μm. At least 9 μm of thickness need to be removed. If P800 SiC is used to grind it, the abrasion rate is ~0.4 μm/m and the corresponding abrasion stroke should be ~22.5m. Using the same work wheel setting, the process can be completed in ~2.7 seconds. The scratches and D_s layer left are lowered to 0.7 μm and 4 μm respectively.

The surface can be further refined using P1200 SiC sandpapers or above if necessary. When the speed of the work wheel is doubled, the time required will be halved. However, overheating might occur if coolant is not present.

Furthermore, if the abrasion rate is 10 times higher, the time required to finish grinding may be too short and difficult to control accurately. Abrasion rate is approximately inversely proportionally to the hardness of the workpiece. If the workpiece is hard, the work wheel speed or the work pressure should be increased. Appropriate lubricant and cooling should be chosen. The working parameters and polishing time of these processes are summarized in Table 4.2. If the whole deformed layer (Dd) should be removed, the abrasion time will be several time longer.

4.5. Polishing/lapping with loose abrasives

The main purpose of lapping is to produce smooth and shiny surface on either a flat, spherical or gently curved surface. This is a relatively a low speed process while the abrasives are pressed lightly between a hard (rigid) surface and the surface to be lapped. Soft and fine felt cloth can be put between the hard backing and the surface to be polished to produce a better surface finishing.

Sanding is used to remove grinding lines and scratches that affect the flatness of the workpiece. It allows relatively more aggressive abrasion than lapping. **Lapping** or **buffing** should be used after grinding and sanding for best quality and minimum shape distortion. Lapping and buffing can be used on metals and some nonmetals to refine the surface, thus producing a more **accurate** (lapping) or **decorative** (lapping or buffing) mirror surface.

Usually, loose abrasives are carried in an appropriate **binder carrier** such as water, oil, grease, **wax** or water-soluble compounds. The role of the binder carrier is to retain abrasive in **uniform** suspension and prevent **abrasives agglomeration.** The binder carrier also helps the abrasives to adhere to the polishing surface and minimize wastage.

Table 4.3(a) The use of abrasives and wheels in different finishing processes.

Process	Wheel backing	Abrasives	Abrasive Bond strength
Grinding	Hard and rigid	Bonded to grinding wheels	High
Sanding	Flexible and softer	Bonded to abrasive belt	Low
Lapping	Hard wheel with optional softer coatinga	Not bonded	Usually loose
Buffing	Flexible and soft wheel	Not bonded	Loose

Lapping is an expensive and slow process, which is not commonly used in the surface finishing of watchcases. Buffing is usually adopted because the equipments are much cheaper. However, buffing may lower the dimensional accuracy.

In general, lapping and buffing can achieve an average roughness in the range of 0.4-0.05 μm. Of course, if coarse abrasives are used, the abrasion effect may dominate producing a rough surface instead of a smooth surface. Table 4.3 (a)&(b) are a list of finishing processes with different effects.

4.6. Buffing

The working principle of buffing is similar to lapping. However, loose abrasives are applied on relatively **flexible wheels** instead of rigid wheels. Grease is a popular binder carrier for holding, as well as spreading of abrasives onto the surface of the workpiece. Abrasives of various grits can be used. Generally, finer abrasives give finer surface finishing.

Table 4.3(b) The quality after various surface finishing processes.

Processes	Abrasives particle size	Abrasives bonding	Surface finishing shininess	Dimensional accuracy
Grinding	Coarse	Strong	Bad	Coarse
Polishing	Medium	Low	Good	Good
Lapping	Small-fine	Loose	Excellent	Excellent
Buffing	Small-fine	Loose	Excellent	Shape Distortion

Appropriate buffing produces smooth and reflective surfaces. The random scratching of the surface by fine abrasives is the key to a shiny mirror surface. There are several reasons leading to this highly reflective surface:

(1) The flexible cloth buffing wheel limits the pressure applied. This results in finer scratches that are less visible to naked eyes. This creates less diffuse reflection.

(2) The random vibration of the flexible wheel gives more uniform distribution of clusters of scratches.

(3) The debris is blown away by the airflow during buffing. Hence, there will be less localized scratches.

(4) The fibers in the buff are flexible and will not deepen existing scratches. Hence, the surface will become smoother.

There are various kinds of buffing processes to serve different purposes as shown in Table 4.4.

Table 4.4 Various buffing processes

	Purposes	Buffing compound/ wheel	Finishing quality
Hard buffing	Cut and polish	Hard buff, coarse abrasive, fast	Smooth and semi-bright
Contact buffing	Automatic imitating manual movement	Hard buff, coarse abrasive, fast	Smooth and semi-bright
Color buffing	Refine surface	Soft buff, fine abrasives, slow	Lustrous, shiny, mirror, scratch-free, final finish
Mush buffing	Automatic, slower and finer than contact buffing	Soft buff, fine abrasives, slow	Shiny, scratch-free, mirror finish

The following factors should be carefully selected and controlled to produce the desired surface finishing effects:

1. Buffing **wheel** hardness (flexibility)
2. Buffing **compound** (wax, abrasives)
3. Buffing **pressure**
4. Buffing **speed**
5. Buffing **duration**

In general, **harder** buffing **wheels** provide a faster abrasion and smoothening rate. If the buffing pressure is too high, **shape distortion** and **loss in fine details** in the workpiece might be increased. Optimum pressure should be applied when using rigid buffing wheels. However, since the control of buffing pressure is more difficult for harder wheels, hard wheels are usually not used for final buffing. The more rigid buffing wheel can also be shaped into the desired geometry providing higher dimensional accuracy.

Softer buffing wheels with **finer** buffing compounds should be used if a finer mirror surface is desired. More flexible wheels such as a loose cotton wheel or string buff gives higher quality and more reflective surface finishing. However, the abrasion rate will be very low and not be suitable for removing rough surface grinding marks, machining deformation layers or scratches.

> **Cut buffing:** In cut buffing, the workpiece can be moved quickly against the direction of the rotating wheel. When medium to high pressure is applied, the relatively higher buffing rate will give more cutting with smooth and semi-bright surface.

> **Color buffing:** When the workpiece is moved along the direction of wheel rotation with a light pressure, a bright, shiny and clean surface will be produced.

Sandpapers of grade 600 should be used prior to buffing. Sandpaper grinding/polishing usually leads to less shape distortion and is much faster than buffing. If design features are to be retained, sandpaper grinding up to P600 to P1000 grit should be applied before buffing **watchcases.** On the other hand, contact buffing may be used to substitute sandpaper polishing for **watchbands** if detail features are not too critical.

Buffing compound (wax) contains abrasives firmly cemented in grease. The buffing compound is the **lubricant, coolant,** as well as the **dispersant** for the buffing process. Abrasives are hard for abrading the surface, while binders must not react, etch, corrode or leave marks on the metal surface. Fatty acids and wetting agents are used to make the buffing compound. However, they must be suitable for the cleaning processes prior to plating or anodizing operation.

The **buffing compound** should response to the change in temperature so that it changes from grease to oil under slight heat and pressure during lapping. It should also revert back to greasy characteristics quickly when lapping pressure is released. The appropriate viscosity is important to the uniform distribution of scratches.

Table 4.5 Various buffing compounds (wax)

Color	Composition & applications
Black	Emery compound with coarse abrasive for cut (abrasion) and scratch removal in **hard buffing**
Brown	Tripoli/silica compound for general purpose **cut and color buffing** on soft metals and plastics
Green	Green chromium oxide powder used almost exclusively for high quality stainless **steels color buffing.** Also used for plastic product, brass, aluminum, nickel and chrome. This is considered the best all round buffing compound.
White	White calcite alumina fine abrasive, cutting lightly and usually used for **color buffing** of chromium, nickel, stainless steels and ordinary steels
Red	The original **jeweler' s rouge (meaning red in French).** Red iron oxide powders for color buffing of gold, silver, nickel and precious metals. Used with very soft cloth wheels loosely stitched for ultra smooth finishing. It stains gold and gives sunny glow.
Blue	Drier, almost greaseless compound also known as **jeweler' s rouge.** For fine **color buffing** with no cutting effect used on steels, aluminum, brass, wood, lacquered surface, plastics, gold, platinum, silver and plates after white bar.

If the viscosity of the **binder** is too high, the agglomerated abrasives will form clustered scratches on the lapping surface leading to poor surface finishing with clear scratches. However, if the viscosity of the **binder** is too low, the abrasives will "flow" to the outer edge of the lapping wheel leading to wastage of buffing compounds.

Buffing compounds are usually color-coded and should be adopted for various purposes. Table 4.5 shows the characteristics of various buffing compounds.

There are also different ways to classify buffing compound according to their role in buffing (Table 4.6).

Table 4.6 Buffing compounds for different buffing purposes

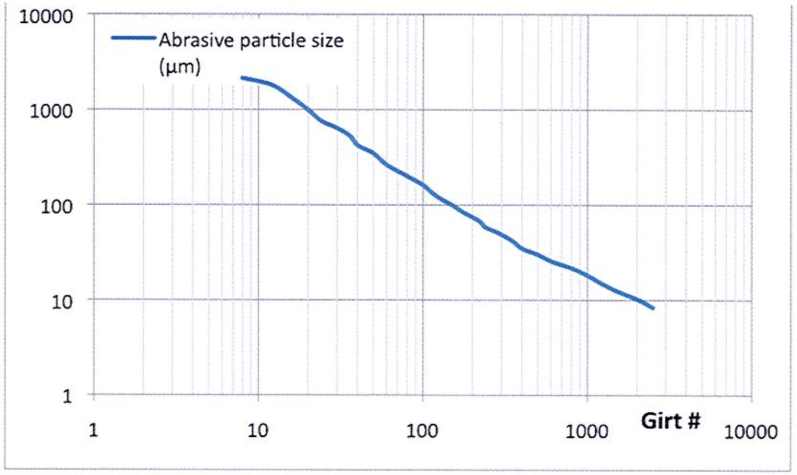
Purpos	Description
Cutting	Black emery, brown Tripoli
Intermediate	Gray Tripoli
Polishing	Yellow, white, green
Super finish	Blue, red rouge (1-5 μm)

The fineness of the buffing compound depends on the grit size of abrasives in the binder. However, some manufacturers use different abrasive size for the same color. Hence, the buffing compound must be tested before being adopted for the mass production process. It is confusing and risky to rely solely on the color code. In fact, the fineness of buffing depends critically on the grit number (particle size) of the abrasives in the buffing compounds. Table 4.7 and Figure 4.1 are information about the coarseness of abrasives and their applications.

Table 4.7 Buffing compounds with different abrasive size for various buffing purposes.

Purpose	Relative coarseness	Grit #	Particle diameter (μm)	Roughness (~Ra μm)
Cutting	Coarse	8-24	800-2000	--
Cutting & polishing	Medium	30-60	250-650	>3.5
Pre-Polishing	Fine	70-180	80-230	0.5-3.5
Sanding	Very Fine	220-1200	15-68	0.1-0.5
Lapping & Buffing	Ultra fine	>1200	<15	<0.1

Figure 4.1 Grit number vs. Abrasive particle size.



It is a general rule that not too much buffing compound should be applied to the wheels. If brown Tripoli compound is used for contact buffing to remove obvious scratches, excess buffing compound might be left on the buffed workpiece and need to be removed because the coarse abrasives might leave scratches on the surface in the subsequent color buffing. The buffing compound removal process is time consuming and will also increase production cost.

Masking part of the workpiece to allow more extensive buffing of the **recessed (shadowed) area** might be necessary if sanding is not preferred due to other constraints. **Softer** buffs should be used so that mush buffing can be performed by pushing the workpiece into the mush buffs for more than 0.75 inch.

4.7. Buffing compound removal and coating

Buffing compound remover can be used to clean the excess buffing compound. Buffing compound remover solution is a blend of surfactants, detergents, and emulsifiers to be mixed with water and applied at recommended elevated temperature (e.g. 80°C). The optimum cleaning temperature should be recommended by the manufacturer.

If possible, rough buffing should be replaced by fine sanding or choosing buffing compounds that can be removed easily. Furthermore, buffing with cutting compounds will lead to more severe shape distortion.

Removal of buffing compounds is difficult but essential,if further coating or surface finishing is necessary. If no further surface finishing is required, we can consider putting wax, oil or lacquer on the buffed surface to prevent further unwanted oxidation. This is more important for copper alloys such as brass and bronze with lower corrosion resistance. Excess buffing compound must be removed; however, complete removal of buffing compound is sometimes not necessary because the greasy oily binders can also serve to protect the workpiece from rapid corrosion. If buffing compounds are not removed, we must ensure that the binders have NO etching effect on the workpiece.

The following are typical steps for buffing compound removal:

1. Dilute the Buffing compound remover according to recommendation
2. Increase the temperature as recommended
3. Switch on the stirrer/agitator
4. Allow for degas for about 10 minutes. Use ultrasonic degassing if appropriate
5. Put the parts into the Buffing compound remover solution for the shortest possible duration
6. Dilute and rinse the parts thoroughly several times
7. Dry the parts completely

Buffing compound removers are usually mildly acidic, or alkaline; hence, step (6) is indispensable because Buffing compound remover residue might corrode the surface leading to immature deterioration of the surface shininess. Buffing compound removers suitable for stainless steels, copper, aluminum alloys might attack zinc and leave a slight stain on brass surfaces.

The buffed workpiece can also be vapor degreased or cleaned with whiting (calcium carbonate), powdered chalk, dehydrated lime applied on soft flannel cloth.

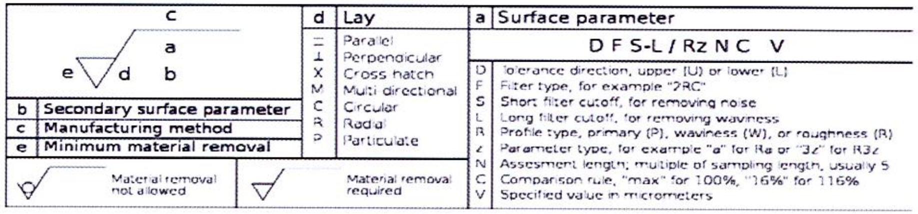
Section B Grinding, Polishing and Buffing

Chapter 5

5. Selection of Sanding and Buffing Equipments

5.1. Specification of surface finishing

Surface finish should be specified clearly in the contract. It can be specified using ASME Y14.36M or ISO 1302.



Surface finish, also known as surface texture, can be defined in terms of roughness, waviness, lay and flaws:

Lay is the direction of the predominant surface pattern such as vertical, horizontal, radial, cross-hatched, circular and isotropic … etc. The pattern is a repetitive impression created during a specific manufacturing operation.

Roughness (surface finish) is a measure of the finely spaced irregularities. The profile roughness parameter Ra (amplitude parameter = arithmetic average of the vertical deviations of the peaks and valleys from the mean line) is the most commonly used parameters. (See Section 3.1 for other roughness parameters.)

Waviness is the measure of irregularities with a wider spacing relatively to roughness. The cause of waviness is vibration and workpiece deflection during machining and buffing.

Flaws are defects such as cracks, nicks (small notches), scratches and ridges made on the surface due to unintentional, unexpected or unwanted process.

Table 5.1 Examples of mill finishes specification for steels.

Finish No.	Processes
Unpolished finishes	
1	Hot rolling + annealing + de-scaling
2D	Dull cold rolling + annealing + de-scaling
2B	Bright cold rolling + final light cold rolling using polished rolls
2BA	Cold rolling + bright annealing (in controlled atmosphere or vacuum) + single light skin pass cold rolling (good for architectural application)
Polished finishes	
3	Polished with 100 mesh (~150 μm) abrasives
4	Polished with 120-150 mesh (~105-125 μm) abrasives (good for kitchen equipment)
6	Brushing #4 finish with abrasive and oil. A dull finish having reflectivity lower than #4.
7	High degree of reflectivity produced by buffing finely ground surfaces. Not all grit lines are removed. (good for architectural applications.
8	The most reflective finish obtained by polishing and buffing extensively with successively finer buffing compounds. Surface is free from grit lines.

Another way to define the surface finish is to adopt the sheet finishes with a system of number according to Table 5.1.

Similar machining and surface finishing processes can achieve a range of roughness Ra. The roughness depends on many processing parameters. Hence, a more scientific specification can be specified using Ra. Table 5.2 shows the range of Ra obtained from various machining surface finish processes.

Table 5.2 Roughness (Ra in μm) achieved by various manufacturing processes

Ra (μm)	50	25	12.5	6.3	3.2	1.6	.8	.4	.2	.1	0.05	0.025
Casting												
sand		■	■									
investment					■	■						
die						■	■					
Forming												
hot roll		■	■									
forging			■	■	■							
cold roll					■	■	■					
burnish								■	■			
Metal cutting												
sawing		■	■	■	■	■						
drilling			■	■	■	■						
milling				■	■	■	■					
turning				■	■	■	■	■				
Abrasion												
grinding						■	■	■	■	■		
barrel finish							■	■	■			
sanding								■	■	■	@	
buffing								■	■	■	■	@
lapping								■	■	■	■	@

@ Sanding lapping and buffing can achiever smaller Ra when carefully performed with finer abrasives.

Sanding with various higher grit numbers will give better roughness in sanding. See Table 4.2 and Table 5.3 for more information.

Table 5.3 Roughness (Ra in μm) by various buffing processes

Abrasive grit no.	Average Roughness, Ra (μm)
500	0.1-0.25
320	0.15-0.38
240	0.2-0.51
180	<0.64
120	<1.14
60	<3.56

Obviously, these polishing lines (groves) cannot be seen with naked eyes. Only the non-uniform distribution of polishing lines with different reflective-specular ratio can be observed. For example, if the 500 grit sandpaper is used and one area achieve 0.2 μm Ra while another area showing 0.5 μm Ra, the contrast produced will be easily observable. Hence, the waviness and the range of Ra due to sanding and buffing will control the quality of the surface finish. The finishing condition of various operations are listed in Table 5.4

Table 5.4 Surface finish conditions of various belt sanding operations.

Operation	Grade	Condition
Stripping	12-20	Removal of rust and old finishes
Heavy cutting	24-40	Rapid abrasion rate
Medium cutting	50-80	Medium abrasion rate with rough finish
Pre-finish	100-240	Require only minor dimensional changes and polishing
Finishing	180-240	Desired appearance of surface for plating
Polishing	280-600	Near-mirror finishes for buffing
Buffing		Mirror finish

5.2. Polishing and buffing wheels

Both polishing and buffing wheel setups consist of the **bench, the motor and shaft, and the wheel.** The motor must be fastened to the workbench securely for the sake of safety. The **vibration** of the motor and wheel for grinding, polishing, and lapping must be minimized because rigid wheels are used. Hence, the shaft connecting the motor and wheel should also be as short as possible. Vibration problems are relatively less serious in buffing. However, if less vibration can be achieved, the desired quality of surface finish can be attained faster.

Polishing can be performed using **sand belts** or **wheels**. Endless fabric belts pre-coated with abrasive have the following advantages over bonded grinding and polishing wheels:

- Fast
- No need to **balance** the wheel
- Large belt surface area for flat surface
- Easy to setup and change abrasive belts
- Smaller inventory of accessories

Belt sanding is good for large flat surface. Extremely fine-grit belts can produce near lapping-polishing quality. The coarsest grade is usually used to achieve the acceptable finish.

The abrasion rate is approximately linearly proportional to the sanding speed when the sanding speed is below 30m/s. Normal sanding speed range from 18 to 40m/s. Fastest abrasion (cutting) can be achieved at the sanding speed of 30-40m/s. Lower sanding and lapping speed usually give a better finish quality. Lower speed should also be used in processing softer metals and alloys, e.g. 18-20m/s for Zn alloys

When using a balanced flat sanding wheel, the sanding rate depends on the diameter of the sanding path. A larger sanding path diameter will give a higher abrasion rate. Sanding wheels are better than sand belts for higher quality sanding because the same wheel can be used for sanding at different speeds.

Table 5.5 Sanding speed with respect to sanding diameter using motors with speed 2000rpm and 3000 rpm (rotation per minutes)

Sanding path diameter			Speed (m/s)	
inch	mm	Perimeter (m)	2000 rpm	3000 rpm
4	102	0.32	11	*16*
6	152	0.48	*16*	*24*
8	203	0.64	*21*	*32*
10	254	0.80	*27*	40
12	305	0.96	*32*	48
14	356	1.12	37	56
16	406	1.28	43	64

The surface finish is usually better with lower sanding speed. Table 5.5 shows the relationship between the sanding path diameter and the sanding speed. A motor with speed of 2000rpm is usually acceptable if substantial cutting (abrasion) is not always required. The high sanding speed above 40m/s is not encouraged because overheating may happen. Furthermore, the rise in temperature due to high sanding or buffing speed might cause burning of buffing compounds and melting of plastics.

Sanding can also be performed using the **edge** of the sanding wheel. **Stick-on sandpapers** can be adhered on the **rim** of the wheel. The **sanding speed** is **constant** and **relatively high.** Hence the quality of the polished surface would only depend on the **pressure** applied, sanding **time**, sanding **temperature** and whether the technician can hold the workpiece **firmly** with the assistance of the **fixture**, if any.

The power of the motor must be high enough so that the speed of the motor will not vary substantially when pressure is applied. If the rotation becomes jerky, the surface will become bumpy and wavy. Table 5.6 shows the information for the choice of motor and wheels.

Table 5.6 Maximum diameter and thickness of wheels to be used with different motors for sanding and buffing

Wheel Diameter	inch					mm				
	4	6	8	10	12	10	7.5	20	25	30
Power H.P.	Max. wheel thickness (edge)									
	inch					mm				
1/8	0.5	x	x	x	x	15	x	x	x	x
1/6	1	0.5	x	x	x	25	15	x	x	x
1/4	1.5	1	0.5	x	x	40	25	15	x	x
1/3	2.5	2	1	0.5	x	65	50	25	15	x
1/2	3.5	2.5	2	1	0.5	90	65	50	25	15
3/4	5	3.5	2.5	2	1	125	90	65	50	25
2	9	6	4.5	3	1.5	230	150	115	75	40

**1 H.P. = 746W output, x = insufficient power*

It is essential to choose the motor with sufficiently **high** power to give a steady speed for polishing and buffing. Using a 1/8H.P. motor at 1800rpm is ideal for buffing because slower buffing rate would lower the chance of burning of workpiece and buffing compounds and melting of plastics. Polishing wheels with variable speed between 3000 and 6000 rpm is desirable. Applying **paraffin** during sanding can produce a finer finish.

Buffing can be performed using a **less** powerful motor. Buffing wheels with **1200-1800 rpm** is more appropriate so that accidental overheating can be minimized. Lower buffing speed gives a better surface finish.

5.3. Buffing wheels selection and usage

If possible, use only **one buffing compound** for a 2-3 steps buffing process by changing the diameter and hardness of the wheels, say 30-20-10mm wheels:

1. 30mm diameter harder buffing wheel at high to low buffing speed for **cut buffing** (contact buffing)
2. 20mm diameter medium-hard buffing wheel for smoother buffing
3. 10mm diameter soft buffing wheel for final **color buffing**.

The use of only one buffing compound for multi-step buffing saves time and resources as the buffing compounds removal process is only done once. Such benefit is sometime huge and should be considered. Buffing can be achieved by skillful technicians moving the workpiece either against (**cut buffing**) or along (**color buffing**) the direction of wheel rotation. **Slower** buffing speed between the buff and the workpiece will produce higher **luster** through color buffing.

The efficiency, quality and cost of buffing are significantly affected by the following:

1. Density and rigidity/flexibility of the wheel
2. Wheel balancing
3. Wheel abuse due to improper use
4. Wheel speeds
5. Type and grit size of abrasive

The functions of different types of wheels are listed in Table 5.7. The simple rules of buffing wheel selection are:

1. Hard wheels for hard materials, soft wheel for soft materials
2. Hard wheels for cut buffing, softest wheel for final color buffing
3. Softer and finer wheels give better finish
4. Use all buffing wheels with compound 2-steps process: cut and then color to save time and resources

Table 5.7 The function and various sanding and buffing wheels

Buffs/ wheels	Cutting	Coloring	Description/materials
Flap wheels	Coarse	No	Tightly packed sandpapers for shaping, sanding and removing rust
Abrasive nylon	Coarse	No	Strands impregnated with tough aluminum oxide abrasive for rust removal, ideal for wood,
Scrubber	Coarse	No	Flexible material impregnated with abrasive, very aggressive for removing rust
Finger	Coarse-medium	No	Aggressive wheel for buffing irregular contour metals with less distortion on thin plates
Sisal	Coarse-fine	Low	Hard, cellular strand of fiber for removal of orange peel grit lines, light die marks, use with black emery compound for de-burring
Spiral sewn	Coarse	No	Continuous spiral sewing with 0.25" spacing made from white cotton, long-wearing,
Denim spiral	Coarse	No	More durable than cotton
Sanding drum	Coarse-fine	Medium	Rubber spindles for sanding, shaping, finishing, polishing depends of the abrasive grit
Vented	Medium	Medium	Folded pleats hold more compounds and keep the part cooler
Cushion	Light	Fine	mush and collapse under pressure, ideal for object with fine details, sewn with 2 rows, finish between spiral sewn and loose cotton
Loose cotton,	Light	Fine	One circle of stitches close to the centre, very flexible, getting into hard-to-reach areas, use with white or red rouge
Mushroom	No	Fine	Buffing contoured shapes
Facer	No	Fine	Buffing flatter areas, good for removing casting marks in Al
Canton flannel	No	Ultrafine	Very soft, loosely stitched, Use with rouge to color gold, sewn by 2-4 circles, used with BLUE or RED compounds, for gold
String	No	Ultrafine	Thin cotton string strands for plastics, give shiny surface, cool buffing
Felt bob	Medium	Medium	For different shapes, surface finish depends on abrasive
Felt	No	Ultrafine	Compressed wool fibers for maintaining sharp edges

The following practices might be useful in improving the efficiency of sanding and buffing:

1. **Sanding** with 600-1000 grit sandpaper before buffing
2. Buffing **compounds** should be applied sparingly on the buff (NOT the workpiece) and let it revolve for a few seconds before buffing
3. Hold the workpiece firmly and increase the pressure slowly to prevent workpiece from loosening
4. Apply minimum **pressure** and allow the wheel and buffing compound do the buffing
5. Lower the pressure or change the motor if the motor **slows down**
6. Slow sanding and buffing speed for plastic to prevent from **overheating** and melting
7. Move (swing) the workpiece along the motor axle direction for more uniform buffing
8. Hold the workpiece firmly and move against the revolving wheel for **faster cut.** (A mixture of metal debris and buffing compound produce black soot.)
9. Remove the workpiece in the direction of the revolving wheel to produce **color buffing** from the same buff
10. If the buffing produces thick black streak marks, lower the pressure and **clean (rake)** the buff with file or knife edge
11. Use pressurized jets of air to **clean** the buff regularly. Reapply buffing compounds before further buffing
12. **Change** the wheel if the diameter of the used wheel is too small
13. Use a smaller and softer buff with the same fine buffing compound if appropriate
14. Use **different wheels** for different buffing compounds and store these wheels separately

15. Never use a wheel for coloring when it was used previously for coarse cut buffing.
16. A **larger** softer and looser buffer increases buffing speed, improves quality and shortens buffing time
17. Repeat step 2 with finer buffing compound if necessary
18. Only color buff **plated work** and **precious metals**, never process by cut buffing!
19. **Wash** the workpiece in warm soapy water to remove excess buffing compound or dirt
20. **Dry** the workpiece thoroughly to prevent corrosion
21. **Coat** the workpiece if necessary

5.4. Buffing compounds selection

Buffing compounds should be applied from coarse to fine. The coarse compounds are more efficient in removing the deep scratches. If possible, only use one buffing compounds to eliminate the buffing compound removal process and save manufacturing cost and time. For example, buffing of soft metals such as aluminum can be completed using only white rouge.

Buffing compound should be applied lightly and sparingly on the buff. The heat and pressure due to rubbing will melt the grease and transfer the buffing compound onto the buff. There is no need to soften the compound by heating and water. Table 5.8 shows the suggestion buffing compounds for different materials.

Blue buffing compounds are made **free of grease, oil or wax**. It contains abrasive blended into **animal hide glue and water**. When applied on the revolving buff, rubbing heat softens the compound and spreads it. This coating dries immediately forming a flexible and resilient cutting surface.

No or less cleaning is required and the buffed surface allow subsequent painting or plating.

3-stages buffing are sometime adopted:

1. Stage 1: Rough cut buffing
2. Stage 2: Final cut buffing and pre-polish
3. Stage 3: Final polish and color buffing

Table 5.8 Choices of buffing for different materials.

	Coarse ← Buffing Compounds → Fine					
Materials	Black Emery	Brown Tripoli	White	Green Stainless	RED Rouge	Blue
Acrylics						X
Ni, Cr plate					X	X
Platinum			X	X		X
Hard rubber		X				X
Wood		X				X
Thermoset		X	X		X	X
Silver		X	X			X
Gold		X	X		X	X
Brass & Cu plate		X	X		X	X
Pewter	X	X			X	X
Iron	X			X		X
Nickel	X			X		X
Steel	X			X		X
Aluminum	X	X	X	X		X
Copper	X	X	X	X	X	X
Brass	X	X	X	X	X	X
Stainless steel	X	X	X	X		X

*Greaseless **BLUE** buffing compound is considered **all-purpose**.*

Each stage can be performed in sub-stage A (cut buffing) and B (color buffing) to increase the efficiency and improve the quality of buffing.

Buffing compounds should be sealed in airtight containers and stored in cool places to prevent from drying or hardening. Table 5.9 shows a list of 3 steps processes for buffing of some materials.

Table 5.9 Choices of buffs and buffing compounds for different materials

Materials	Plastics			Al, Ag, Au & plates			Ni & Cr plates			Cu, brass, & soft metals			Steel & iron			Stainless steel		
STAGE	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
BUFF																		
SISAL										X			X			X		
SPIRAL								X			X			X			X	
LOOSE												X			X			X
FLANNEL						X			X									
STRING	X	X	X															
BUFFING COMPOUND																		
BLACK										X			X			X		
BROWN											X							
WHITE								X				X		X				
GREEN																		
BLUE	X	X	X			X			X						X		X	X
RED						X			X						X			

5.5. Sanding and buffing parameters selection: force, temperature and time

Lubricants and coolants should be used in sanding to prevent overheating of the sanding wheel and workpieces. The pressure of 20-40kPa is recommended. Table 5.10 shows the forces required for polishing of workpiece of different area.

The pressure for cut buffing with rigid and coarse buffs is similar to sanding and can be estimated using Table 5.10. For final fine buffing and color buffing, the buff is soft and high pressure will only cause collapse of the buffing wheel. High pressure will increase the rubbing and heating of the buff and buffed workpiece leading to black streaks and waviness of the surface. Hence, buffing should be performed using the lowest possible buffing force.

Table 5.10 Required force for with respect to sanding area for 20-40kPa sanding pressure

		Sanding pressure			
Sqaure		20kPa	40kPa	20kPa	40kPa
Side(mm)	Area(mm^2)	kgf	kgf	lb	lb
1	1	0.002	0.004	0.0009	0.002
5	25	0.051	0.10	0.023	0.046
10	100	0.20	0.41	0.093	0.19
1	1	0.002	0.004	0.0009	0.002
40	1600	3.26	6.52	1.48	2.97
100	10000	20.4	40.8	9.27	18.5

Surface buffing is applied on a flat surface using fast rotation and a slight penetration of the buff for regular shaped parts. The shaft speed can be greater than 1500rpm. Parts should be pushed into the buff for less than 10mm. This can ensure better uniformity of the surface.

Mush buffing is used for buffing complex shaped parts with softer and more flexible buffs so that detailed features remains after buffing. The shaft speed should be lower than 1200rpm and the buffs used should have the largest possible diameter. The parts will be pushed into the revolving buff so that a larger surface can be buffed. The parts should be buried 0.75-3.5 inches into the buff. Mush buffing can also be divided into light, moderate and deep mush.

Continuous buffing for one minute or more will usually produce a very hot surface and workpiece. The buff and buffing compound might become burnt. Hence, it is essential to design the buffing stages carefully so that prolonged buffing is not necessary.

Prolonged **manual buffing** is also tiring, leading to shaky hands and waviness of the buffed surface. Buffing usually lead to loss in detailed features if the buffed surface is not flat. Hence, it is recommended to shorten buffing time if possible.

5.6. Fixture design and selection

Simple fixture design to be used in sanding and buffing can lead to substantial improvement in sanding and buffing quality. The main reason is that it will **lower the vibration** of the workpiece, which is held manually. A fixture including a **spring** pusher will also limit the **pressure** applied according to the designed working pressure. This will prevent overpressure during sanding and buffing. **Pressure control** is particularly important in controlling the surface quality for almost all sanding and buffing processes.

The fixture can be designed to allow **translational** motion and **rotation** motion giving **flat** or **curved** surface respectively. With the help of well-designed fixtures, more accurate dimensional accuracy can also be achieved. It is also a step toward **semi-automated** or **fully automated** manufacturing for high quality surface finishing.

5.7. Cleaning before and after sanding and buffing

Most **cutting and grinding fluids** are **oily** and will affect the subsequent sanding efficiency. Thorough degreasing and cleaning is necessary before sanding to ensure efficient sanding. **Water-soluble** chemical cutting fluids or water-soluble cutting oils might lessen the difficulties of cleaning prior to sanding and is recommended.

Most sandpapers are waterproof and can be used with water lubricant. **Water** lubricant is the cheapest and serves to carry away debris that might clog the sandpaper. A continuous flow of **filtered** water that is **free from** debris should be used for **environmental** reasons. When **soap** or very dilute **alkaline** lubricants (e.g. ammonia in water) are added to water, corrosion rate will be lowered. Mild **acidic lubricants** are sometimes used to increase the sanding rate. All sanded workpieces, including wet and dry sanding, must be thoroughly washed to **remove large debris** and **abrasives** for finer sanding.

Cleaning after sanding is relatively easy for flat surfaces because abrasive can be rinsed off easily if water based sanding lubricants are used. Soaking in **neutralizing solution** is necessary if the sanding lubricant is not neutral. For more complicated geometry, an agitated flood of water should be used to remove the unwanted lubricant from every recess. The cleaned workpiece must be **dried completely** before buffing.

Cleaning after buffing is more difficult if a greasy buffing compound is used. **Buffing compound removal** process has been discussed in **Section 4.7.** It would be more problematic if overheating had occurred during buffing leaving black streaks on the surface. The black streak need to buffed away carefully again without losing the dimensional accuracy and detailed features.

Section B Grinding, Polishing and Buffing

Chapter 6

6. Defects in polishing: Inclusion / Scratches / Surface

Material defects in metallic materials may be inherited from the poor workmanship in **casting, forming and shaping** (e.g. rolling, forging, extrusion, powder metallurgy···), and **machining** (e.g. cutting, milling, lathing···). Most of the **internal defects** carried over from prior manufacturing art will not be removed by polishing and buffing. These defects may appear randomly in the workpiece and lead to high scrap rate. **Surface defects** inherited from machining are relatively less serious but will still affect the surface finish quality.

6.1. Internal defects

Internal defects cannot be removed by polishing and buffing. If these defects are near the surface, cutting, milling, lathing and other metal removal processes can be used to remove the defective portion. Internal defects are very often primary production defects formed during the **melting** and **casting** process and cannot be remedied.

1. Segregation (non-uniform distribution of elements)
2. Holes and porosity
3. Shrinkage
4. Inclusions
5. Shrinkage and hot tears
6. Cracks
7. Residual stresses
8. Oxygen embrittlement (e.g. Ti alloys)
9. ...

Forming and shaping defects are secondary production defects. Some examples are listed below:

1. Cracks (forging burst, rolling cracks)
2. Lamination (inclusions elongated during deformation)
3. Hydrogen embrittlement
4. Cracks due to extrusion
5. Wrinkle after deep drawing (earing of anisotropic/directional materials)
6. Extrusion tails (inhomogeneous materials)
7. Heat affected zone (welding defects)
8. Quenching cracks
9. ...

6.2. Surface defects

Surface defects can be removed by grinding or intensive sanding. If these defects are not removed by sanding, a poor surface finish is inevitable after buffing. The following are some surface defects that must be removed before buffing or lapping.

1. **Surface blow hole** in casting
2. **Laps** (oxidized surfaces rolled into billet)
3. **Mill-shearing** (feather like lap)
4. **Rolled-in scale** (oxide inclusions after rolling)
5. **Seams** (long patches of loose metals rolled into the surface)
6. **Scabs** (long patches of metals rolled into the surface)
7. **Hot tears** (rupture of materials during forging due to the presence of low melting or brittle phase)
8. **Blisters** (due to expansion of sub-surface gas bubble during heat treatment)
9. Mottled surface (**orange peel effect** due to large grain size after annealing)
10. **Stretcher strain** (Luder lines due to localized **yielding** and non-uniform deformation)
11. **Burn** marks (**overheating** during cutting-grinding with insufficient lubricant and coolant)

6.3. Prevention of lapping and buffing defects

If defects cannot be removed by proper lapping and buffing processes, it is very likely that they are materials manufacturing defects of the material, which cannot be removed. However, the following sections and respective measures to remove or prevent defects should be considered before jumping to such conclusions. More detailed definition of surface imperfection can be found in BS EN ISO 8785: 1999 "Geometrical product specification (GPS), Surface imperfections, Terms, definitions and parameters" .

6.3.1. **Orange peel** refers to fine peaks and valleys that give a rough surface effect like orange skin. If the grain size of the materials is smaller than 50 μm, orange peel effect might be due to buffing prolonged or excessive buffing pressure.

6.3.2. **Haze** is less shiny surface due to deposition of abrasives and buffing compound. A **neutral pH** process should be chosen so that no undesirable chemical reaction will take place. Lower working pressure can also lessen the haziness.

6.3.3. **Pitting (dimples)** is due to the presence of many small holes distributed on the entire surface. This might be due to the corrosive nature of abrasive, sanding lubricants or buffing compounds. Non-corrosive abrasives and binders should be used. The workpiece should be washed, rinsed and dried thoroughly. Non-constant working **pressure** might also be a cause.

6.3.4. **Relief** is the differential removal of different materials phase, or different orientation, having **different hardness**. Material **homogeneity** should be ensured before lapping and buffing. **Harder** polishing buffs should be used to lower the differential material removal rate.

6.3.5. **Edge effect** is the undesirable material removal at the edge of the workpiece. **Sanding and lapping** with more **rigid backing** and **lower pressure** will lessen the edge effect. **Softer buffs** used with shorter buffing time and pressure can also help.

Hydraulic cut is a defect that appears at the edge of the lapped or buffed workpiece due the higher **localized** wear rate. This defect can be minimized by using less abrasives in the lapping or buffing compound, but it may lower the material processing efficiency.

6.3.6. **Waviness** is the deviation from the desired flat or curved surface in the **mm** to μm range. It usually happens during **manual** lapping and buffing when the working pressure is not steady, which lead to uneven removal of material. Vibration of wheels is also a major cause.

6.3.7. **Grooves** are aligned marks much deeper than the roughness Ra. It is caused by incomplete removal of the deformation layers (damage) of previous machining, grinding or sanding processes. The working pressure of grinding or rough sanding might be too high.

6.3.8. **Cracks** are very deep and sharp edges as a result of wrong casting, forming, cutting or grinding processes. This kind of problem cannot be solved by sanding, lapping and buffing.

6.3.9. **Holes (pull-out)** are irregularly formed holes appearing on the surface that arise if non-metallic **inclusions** and **carbides** are present in steels. **Lower working pressure** or the use of more **homogeneous steels** can lessen the problem. **Fluoride-free** lapping and buffing cloths should be used because this can prevent carbides and inclusions from being pulled out.

6.3.10. **Peaks** are uneven elevations due to uneven removal of material or high working pressure. Uniform and lower **pressure** should be used. May consider using lapping fluid and buffing compounds with higher **viscosity**.

6.3.11. **Comet** tails are due to inclusions that leave a trail behind along the polishing direction. A **higher buffing** speed can prevent comet tails from forming.

6.3.12. **Foreign** material present on the buffed surface is usually due to insufficient cleanliness in the polishing room.

6.3.13. Corrosion of the workpiece is the result of incomplete cleaning of the reactive sanding medium and buffing compound. Insufficient drying of the workpiece after cleaning process is also a common cause. The humidity of the polishing workshop must be kept low.

6.3.14. Burn marks will form if the buffing temperature is too high due to high pressure, insufficient buffing compounds, insufficient sanding coolant, prolonged rubbing, low viscosity of lubricant. Low working pressure and vented and more flexible buffs should be used.

6.3.15. Discoloration of a localized area may be due to chemical attack, which damage the surface.

6.3.16. Foxtail at the edge of workpiece might be introduced due to the presence of irregularities. The irregularity at the edges must be removed by proper de-burring before lapping or buffing.

6.3.17. Inappropriate buffing practices

- *Too much buffing compound applied:*
    - o Large quantity of soil sticks on the workpiece
    - o Long buffing compound removal time
    - o Thick buffing compound residue on the surface
    - o Leaves smears and streaks
- *Etching binder in buffing compound*
    - o Etching of surface revealing microstructure (e.g. orange peel effect)

- *Insufficient sanding up to grit # 600 or above prior to buffing*
    - o Long buffing time
    - o Grinding and machining marks cannot be removed
    - o Large distortion at edges due to long buffing time
- *Sanding pressure too high*
    - o More obvious sanding marks
    - o Sanding marks cannot be removed easily by buffing

6.3.18. Wrong buffing compound removal processes

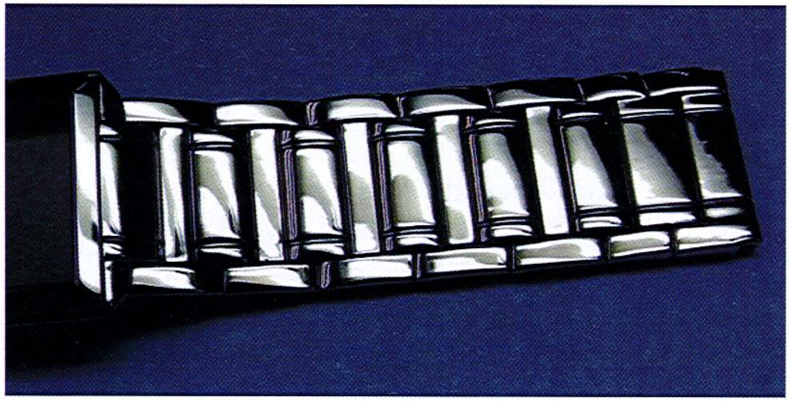
- *Buffing compound remover solution temperature too high:*
    - o Component metal attack
    - o Etching of grain boundary and exposure of different grains and phases (e.g. orange peel effect)
    - o Surfactant separates from the solution leading to a poor cleaning effect
- *Buffing compound remover solution temperature too low:*
    - o Cloudiness of Buffing compound remover solution
    - o Poor cleaning effect
- *Low concentration of Buffing compound remover solution:*
    - o Poor cleaning effect
    - o Long cleaning time

6.4. Case Studies

6.4.1. Waviness

Figure 6.1 shows a typical buffed watchband. The surface is polished and buffed. However, a mirror surface cannot be produced. The waviness is parallel to the polishing direction with substantial distortion of the reflected images. The edges and corners of the parts are rounded.

Figure 6.1 Surface waviness after buffing (Courtesy of Mr. John Mak)



Possible causes:

- Insufficient sanding before buffing
- Excess uneven rough buffing
- High cut buffing pressure
- The buff for cut buffing is not clean. Abrasives and binder clogged the localized area of the buff.

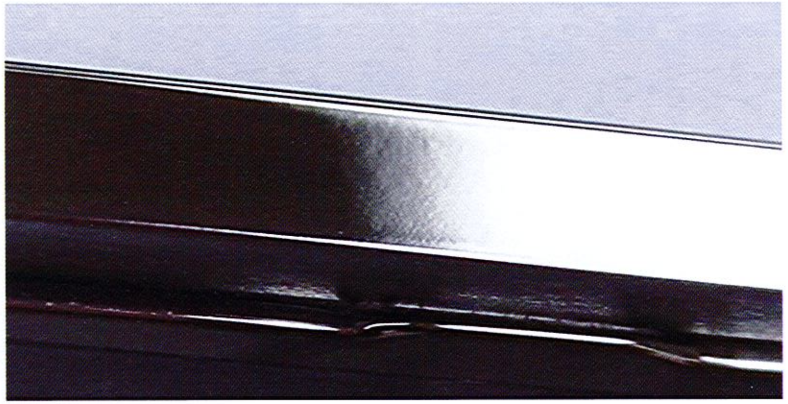
Recommendations:

- Workpiece should be sanded up to 600 grit sandpaper
- Avoid prolonged rough buffing with coarse cut
- Use fine buffing to produce the mirror surface

6.4.2. Orange peel effect

Orange peel effect (Figure 6.2) shows diffused reflection due to surface rough after buffing. It is different from waviness created by grinding and buffing processes because the waviness is not clearly directional.

Figure 6.2 Orange peel effect after buffing (Courtesy of Mr. John Mak)



Possible causes:

- Dual phase alloys with different hardness of the composing phases
- Large grain size materials due to incorrect heat treatment processes
- Insufficient sanding and rough buffing to flatten the surface
- Buffing pressure too high
- Prolonged buffing time too long
- Chemical reaction with buffing compound, cleaning reagents

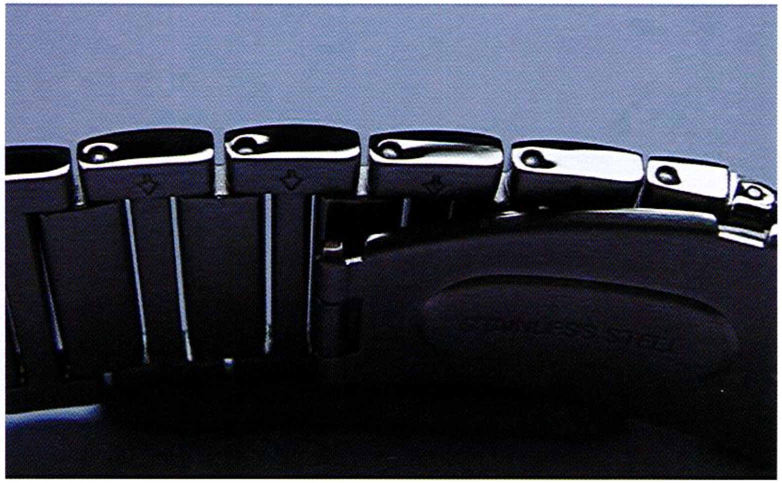
Recommendations:

- Lower the heat treatment temperature to ensure finer grain size
- Flatten the surface by sanding
- Apply gentle pressure for sanding and buffing
- Review the pH of the buffing compound and cleaning reagents

6.4.3. Edge effects around holes

Distortion from flatness is obvious around holes. The trapping of abrasive in the holes increases the local removal rate giving comet tails along the direction of lapping or buffing. Typical tear holes are shown in Figure 6.3.

Figure 6.3 Edge effects around holes (Courtesy of Mr. John Mak)



Possible causes:

- Recess area trap grinding and buffing compounds leading to comet tails.
- Prolong lapping or buffing
- Use of loose abrasives

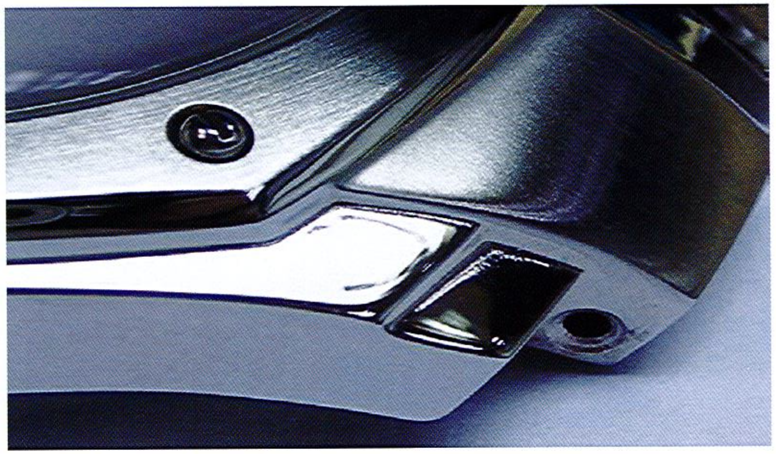
Recommendations:

- Fill the gap or hole if possible
- Use sandpaper with abrasives bonded to paper or wheel
- Avoid rough buffing
- Use less buffing compounds

6.4.4. Concave corners

Figure 6.4 shows concave corners inaccessible to sanding, buffing and most mechanical polishing techniques. Polishing pens with vibratory motion can be used to polish the concave corners manually.

Figure 6.4 Inaccessible concave corners (Courtesy of Mr. John Mak)



6.4.5. Defects due to internal defects

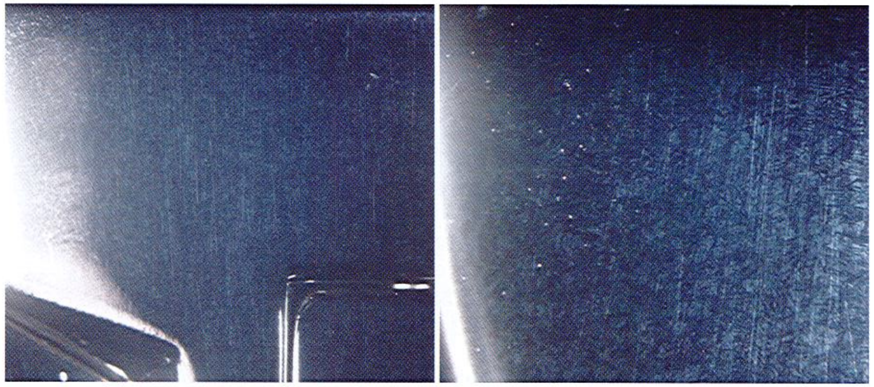
Internal defects (Figure 6.5) may be formed due to various primary production processes during casting and subsequent shaping processes. Micro-cracks and inclusion might appear throughout the workpiece or at localized areas. These defects cannot be repaired or removed by polishing and buffing.

Figure 6.5 Defects due to internal defects (Courtesy of Mr. John Mak)

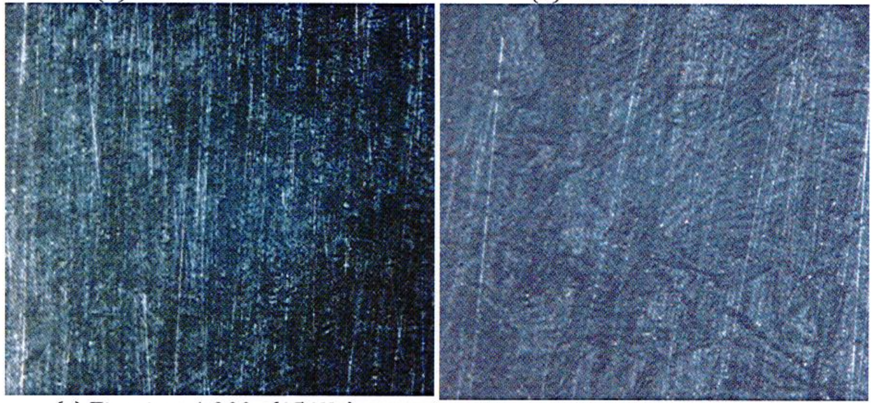
6.4.6. Edge effects around holes

Two titanium samples (A & B, shown in Figure 6.6) were polished and buffed. Sample A gives a marginally acceptable surface finish. The buffing quality of sample B is not acceptable.

Figure 6.6 Polishing and buffing defects on titanium (Courtesy of Mr. John Mak)



(a) Titanium A 100x *(b) Titanium B 100x*



(c) Titanium A 900x (154Hv) *(d) Titanium B 900x (225Hv)*

Possible causes:

- Orange peel effect due to large grain size as a result of high heat treatment temperature between cold working
- Insufficient sanding to flatten and smoothen the surface

Recommendations:

- Lower annealing temperature and short annealing time to control the grain size
- Longer sanding time with appropriate lubricant to smoothen the surface
- Use fine sanding to replace coarse buffing

Section C Practices

Chapter 7

7. Polishing 304 / 316 stainless steels

Table 7.1 Typical surface finish processes for stainless steel

Operation	Wheel	Grit, abrasive	Finish
Rough grinding	Solid wheel, rubber or bakelite bonded	20-30, Al_2O_3, SiC, dry	Flat
Fine grinding	Solid wheel, rubber or bakelite bonded, or sand belt	36-80, Al_2O_3, SiC, dry	Flat, no deep scratches
Rough sanding	Sand belt, or sanding wheel	80-100, Al_2O_3, SiC, dry	Rough polished
Medium sanding	Sand belt, or sanding wheel	120-150 Al_2O_3, SiC, dry	No. 4 mill finish
Brushing No. 4	Tampico brush	Pumice pastes	No. 6 mill finish
Satin with buffing lines	Stitched cloth, harder buff	Various grit, greaseless buffing compounds	Satin finish
Cut buffing	Stitched cloth wheels buff	180, buffing compounds	No. 7 finish with scratches
Cut & color buffing	Loose cloth wheels buff	240, green buffing compound	No. 8 finish without scratches

Researchers found that the amount of carbides and non-metallic inclusions in steels have a decisive effect on the quality of the polished surface. If there are phases with substantial different hardness and strength, lower pressure should be applied to achieve good surface finish.

Stainless steels have high tensile strength and high surface hardness; hence, hard abrasives should be used. The heat conductivity of stainless steels is low. Precautionary measures preventing substantial rise in temperature should be adopted. The rapid work hardening properties should also be noted because more residual stresses the surface might be built up during grinding and sanding. Table 7.1 shows a typical set of surface finish processes for stainless steel.

Table 7.2 Grit size and polishing surface speeds for sanding stainless steels

Product	Grit	Sanding speed (m/s)	Lubricant
Blade-tapering	180	28	Grease
Forks or knives	1500	26.5	Grease
Spoons	150, 200	26.5	Grease
Hypodermic needles	320, 400	23.5	Water soluble oil
Airfoil jet blade	120	28	oil
Coil	120, 150	17.3	oil
Pots & pans	220, 320	25.5	Grease
Press plates	120-320	20.4	Grease
No. 3 finish	100	20.4	Grease
No. 4 finish	150	20.4	Grease
No. 7 finish	180-280	20.4	Grease

For rough polishing, the **sanding speed** can be as high as 40m/s. When better finish is to be achieved using finer grits, the sanding and buffing speed should be substantially lowered. Table 7.2 shows the grit number and sanding speed with the recommended lubricant. Since loose buffs are used in buffing, the sanding speed for **hard buffing** can be as high as **50m/s**. The corresponding **color buffing** speed is ~35m/s.

Passivation or cleaning is not always necessary after fine color buffing if the surface is chemically clean and free from oil. The clean surface of stainless steel passivates gradually when exposed to air. If iron particles are present, they must be removed by pickling.

7.1. Hot working, cold working and heat treatment of stainless steels (304 & 316)

Proper heat treatment on stainless can improve the mechanical properties, lower residual stresses, restore corrosion resistance when these properties had been adversely deteriorated by previous thermo-mechanical treatments. 304 and 316 stainless steels are the most commonly used steels for watchcase making. Both stainless steels are **conventional austenitic stainless steels.**

Table 7.3 Suggested annealing temperature ranges of some austenitic stainless steels (for carbide dissolution)

Designation	Temperature (℃)
201, 202, 301, 302, 303, 304, 304L, 304LN, 305, 308, 316N	1010-1120
254SMO	1150-1205
309, 316	1040-1120
310	1040-1065
316L, 316LN, 317L	1040-1110
317	1065-1120
317LM, 317LX, 317L Plus, 317LMO	1120-1150
321	955-1065
347, 348	980-1065
904L	1075-1125

Conventional austenitic stainless can be hardened by cold working but not heat treatment. 304 and 316 stainless steels used are usually in the annealed or cold-worked state. The cold worked state is harder, while the annealed state is softer. **Chromium carbides** might form due to improper annealing, which leads to more **inter-granular corrosion**, and but can be dissolved by proper annealing. Annealing temperature range depends on composition and can be found in Table 7.3.

Mechanical forming processes can harden 304 and 316 stainless steels. Softening heat treatment is always required. Higher annealing temperature can soften workpieces faster for the next mechanical process. However, it must be noted that higher annealing temperatures will also lead to undesirable grain growth. Larger grain size beyond 50-100 μm is the cause of **orange peel** effect in subsequent deformation and buffing processes.

Unwanted chromium carbide might form at temperature between 425-900℃ leading to lower corrosion resistance. Carbide might form at 425℃ for cold rolled stainless steels. Carbides should be dissolved at higher temperature, say ~1090℃ (which should dissolve the carbide efficiently with limited grain growth), and cool down rapidly to **prevent carbide formation.** It must also be noted that the high cooling rate, such as water quench, will cause distortion. In fact, **thin sections** should be air quenched to minimize distortion.

Time for annealing at the suggested temperature should be as short as possible to prevent unwanted grain enlargement. Workpiece should be held at the desired temperature for **3-5 minutes per 2.5mm thickness.** For example, a 5mm thick workpiece should be annealed for 6-10 minutes, followed by **rapid air cooling.** Thick sections should be **water quenched.**

Annealing temperature, annealing time and cooling rate are the three important thermal processing parameters for annealing. However, we must note that they must be properly selected because:

- Higher annealing temperature to dissolve carbides
  vs.
  Lower temperature to limit grain growth
- Longer annealing time to dissolve more carbides
  vs.
  Shorter time to limit grain growth
- Rapid cooling to prevent the formation of carbides
  vs.
  Slower cooling to prevent shape distortion

Prolonged annealing at high temperature leads to more oxidation. **Bright annealing** of austenitic stainless steels properly in **pure hydrogen** or **dissociated ammonia** gives an oxide free surface. The bright annealing furnace must be clean, moisture-free and tight. If the process is not properly controlled, a thin greenish oxide will form on the workpiece, which is very difficult to remove.

7.2. Surface hardened or coated stainless steels

Stainless steels can be surface hardened by **nitriding**. The surface can also be modified to improve hardness, scratch resistance, corrosion resistance, color and appearance by **ion implantation, laser surface processing, laser alloying, plating, surface blackening, coloring, terne coating, thermal spray, diamond like coating** ··· etc. All mechanical polishing and buffing processes should be performed **before** these surface hardening and improvement processes.

In addition to the normal grinding, sanding and buffing processes, nitriding and coating of stainless steels requires the removal of the surface chromium oxide film by pickling, chemical reduction in reducing atmosphere.

Section C Practices

Chapter 8

8. Polishing Titanium alloys

Titanium is unique because of its low density **(4.5g/cm^3), high strength (434MPa)**, and excellent **corrosion resistance**. On the other hand, pure titanium has poor wear resistance due to its relatively **low shear strength** and **high coefficient of friction.**

The oxidation resistance of titanium alloys is excellent at low temperature. However, when heated to around **430°C, oxygen** will be taken up by the alloys causing **embrittlement**. Titanium alloys can be aged in the temperature range 370-540°C, and may be unstable at temperature above 260°C.

8.1. Cleaning and oxidation of titanium alloys

Heavy oxide scales can be removed by grit blasting. The oxygen rich metallic layer must then be removed by grinding to **avoid cracking** in subsequent cold working processes. The cold worked titanium should then be cleaned with detergent, solvent washing or vapor degreasing.

Gas absorption is a major problem of processing of titanium and its alloys. The titanium surface can pick up gases such as oxygen, hydrogen and nitrogen, which can embrittle the alloy.

Many titanium alloys will be strain hardened quickly during cold working and several softening annealing might be necessary. The oxide layer formed during the annealing can reach the thickness of 0.05-0.07mm and need to be ground or sanded before buffing. The oxide layer in hot rolled titanium is even thicker and might reach 0.15-0.2mm. The brittle surface is usually removed by acid or electrolytic chemical picking.

8.2. Grinding and buffing titanium alloys

Dry belt grinding (sanding) of titanium is dangerous because fine titanium powder may ignite and explode. 5% aqueous solution of K3PO4 or highly chlorinated water-soluble oils (must be rinsed thoroughly) can be used as the lubricant. The belt speeds should not exceed 6-8 m/s. 80 grit sanding belt can be used to remove 0.07mm material from the surface. A recommended sequence is:

1. 80 grit sanding to remove defects
2. 100 grit
3. 180 grit
4. 240 grit to achieve the finish of Ra=0.5-0.65 μm roughness
5. Clean/pickle with 20%HNO3, 2% HF and then rinse with water
6. Polish using SiC abrasive, mineral oil lubricants and coolants. (Dry polishing is also possible.)
7. Fine polish with several progressive polishing steps
8. Wet blasting with fine slurry for a matte finish
9. Buff with loose cloth buffs

Buffing might cause noticeable distortion for soft titanium alloys. Sufficient buffing compounds must be applied to lubricate the surface; otherwise, overheating, burning and severe distortion of workpiece might happen. After buffing, no further cleaning is required except buffing compound removal. The buffed surface will become dull gradually due to oxidation.

Section C Practices

Chapter 9

9. Polishing Aluminum alloys (soft alloys)

Aluminum and aluminum alloys are relatively soft and more easy to grind and sand. The yield strengths of pure aluminum and aluminum alloys range from 7-11MPa and 200-600MPa, respectively. Pure aluminum is very light with density of 2.7g/cm^3. Sometimes buffing with a sisal wheel and a loose cloth buff can achieve the desired surface finish.

Typical conditions for sanding wheel operation for sanding and buffing of soft alloys:

1. Wheel speed: 180-2000rpm
2. Hard-felt wheel diameter: 350-400mm
3. Greasy lubricant
4. Polishing speed: 18-40m/s
5. Light pressure

Slower buffing with lighter pressure for soft aluminum will give a better surface finish. Aluminum alloy surfaces can be cleaned by organic solvents. Heated solvent with agitation, or stirring can give higher cleaning quality. Neutral mineral oil can be applied over buffed surface to remove buffing compounds. Emulsifiable solvents, alkaline cleaner, acid and electro-cleaning can also be considered.

Chemical brightening (bright dipping chemical polish) can polish, smoothen and brighten the surface in a bath effectively. The chemical brightening bath is an acid solution (e.g. sulphuric acid, nitric acid, phosphoric acid or acetic acid) with oxidizing agents.

Section C Practices

Chapter 10

10. Alternative surface finishing techniques

Surface finishing techniques can be categorized into **abrasive** and **nonabrasive** methods. In previous chapters we focused more on abrasive methods. We will discuss other abrasive, nonabrasive and combined methods in this chapter.

10.1. Chemical Mechanical polishing

Chemical-Mechanical Polishing is a mix of chemical etching abrasive polishing. The process is faster than normal mechanical polishing. The finished parts must be neutralized and cleaned thoroughly before subsequent processes or storage. This method is widely used in the polishing of semiconductor wafers. If the chemical is not chosen properly and the parts are not cleaned properly, stress corrosion cracking may occur.

Higher concentration and temperature usually give higher polishing rate and should be carefully controlled because the polishing rate might be too fast. The polishing temperature should be lower than 100oC. Small amount of hydrogen is produced; hence, the workshop must be well-ventilated.

10.2. Tumble (barrel) finish

Tumble or barrel finish makes use of the rubbing or sliding of a mixture of parts, compound and water in a rotating barrel. Faster rotation usually produces poorer surfaces and edge conditions. This is a **mass finish** method that takes long time if a good surface finish is desired. The ratio of the parts and the compounds will also affect the quality of the surface finish. The advantage is that this is less labor intensive.

10.3. Vibratory finish

Vibratory finish is also a **mass finishing** process making use of the rubbing of parts and compounds to achieve de-burring de-scaling, burnishing and cleaning for relatively small workpieces. Parts are put inside a vibrating tub and the vibration causes the rubbing and polishing effect.

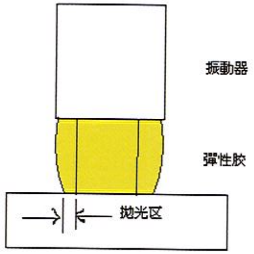
This process can be utilized in **internal** features if finer abrasives are included in the media. The operator can check the quality easily because the tub can be opened without disturbing the process. Mild **chemicals** can be added to increase the polishing rate when needed. The **frequency** (15-60 Hz) and **amplitude** (0-5mm) of the vibration can be altered for various qualities of finishing. High frequency and low amplitudes can be used for delicate parts and finer products.

10.4. Ultrasonic polishing

The principle of ultrasonic polishing is similar to vibratory finishing. The main difference is the use of ultrasonic frequency at 20kHz up to several gigahertz (GHz) in ultrasonic polishing. Slurry carrying abrasives can be directed on the surface of the workpiece leading to the desired polishing effect. Piezoelectric actuator can be used to produce the required micro-rubbing for superior polishing quality.

Very little heat is produced during the polishing process and the corresponding force required is minimal. Hence, there is almost no deformation layer after polishing. Figure 10.1 shows a schematic diagram of a typical ultrasonic polishing process used for polishing hidden corners. Simple engravers can also be used as the vibrator. High frequency, large amplitude and coarse abrasives provide high cut rate. Smaller amplitude and finer abrasives will give a finer surface finish. Less viscous slurry is recommended.

Figure 10.1 Ultrasonic polishing using ultrasonic actuator or simple engraver with vertical movement. (Courtesy of Mr. John Mak.)



10.5. Abrasive jet polishing

Abrasive jet polishing is categorized within abrasive jet machining when fine abrasive (e.g. 2500 grit glass bead) is used. High velocity gas is used to propel the abrasive that erodes the materials surface giving polishing effects with limited cutting . This method is good for polishing hard and brittle materials.

10.6. MMP Micro-Machining Process

MMP is also called micro-finishing or superfinishing. This is used to remove about 1 μm of the deformed layer left by previous process. The abrasive is oscillated or rotated while the workpiece is rotated at very low speed of 6-14m/s at very low pressure of 20-70kPa. (Normal grinding is at 13-140MPa at 1800-3500 m/min.) This can give a surface finish of 10nm (0.01 μm). Suitable lubricant, e.g. kerosene, must be used to minimize heat production. Aluminum oxide, silicon carbide, cubic boron nitride and diamond can be used progressively to obtain the desired surface. Average grain size of abrasive is usually 5-8 μm.

10.7. Electro-polishing

Electro-polishing is also known as electrochemical polishing and electrolytic polishing (for metals). This is a electrochemical process that is effective for polishing, passivation and de-burring. It should be used after appropriate mechanical polishing for the best effect. No mechanical damage will be left on the surface. Electro-polishing is a very important manufacturing process that consists of a wide scope of technical knowledge.

Section C Practices

Chapter 11

11. Safety concerns

Environment:

1. Vacuum the workshop with efficient ventilation and dust removal system for health and quality finish purposes.
2. Should check whether the metal and metal oxide dust are toxic or not.
3. Sufficient ventilation if volatile organic solvents (VOC) or other organic solvents are used.
4. Proper disposal of gaseous, liquid and solid waste to minimize pollution.
5. Cadmium and chromium elimination in surface engineering.
6. Dust collecting systems should be set up as close to the sources as possible.

Equipment setup:

7. Mount the sanding and buffing wheels securely.
8. Ceramic grinding wheels must be free of cracks. High grinding pressure may lead to disintegration of the grinding wheel with debris flying out at high speeds. Such accidents could hurt the workers around seriously and cause fatal industrial accidents. The sound produce by cracked stone wheel is sometimes different from crack-free stone wheels.

Worker' s clothing:

9. Wear safety glasses.
10. Wear dusk mask.
11. No loose clothing, rings and watches.
12. Wear gloves to protect hands if possible.
13. Put on appropriate hard workshop shoes.

Operation:

14. Hold work firmly at all times.
15. Never have eyes off the workpiece and wheels.
16. Never leave rotating wheels unattended.
17. Never touch a revolving buff.
18. Polish and buff below the centre of the rotating wheel (for vertical wheels), while the wheel edge facing the technicians should rotate downward.

References

1. Surface Engineering, Vol 5, ASM Handbook, ASM International, 1994.

2. An Introduction to Buffing and Polishing, by Caswell Inc., Lyons, NY, USA.

目录

甲部： 原理篇

乙部：技术篇

丙部：经验篇

致谢

感谢我的妻子天悦，因她给予我无限的支持和鼓励，甚至愿意忍耐我们在海外度假时仍花上不少时间去完成此书。我还要感谢孩子们的支持，他们对爸爸此书甚感兴趣，这也成了我的推动力。感谢女儿诺蓝为我的原稿作较对。没有你们的帮忙，爸爸便要少睡更多的晚上。

谢谢麦世枝先生、林咏霞博士和马诺宏博士为我安排叁观广东省内的表面加工厂，让我更了解实际的工作程序。我更要感谢香港特别行政区政府工业贸易署中小企业发展支援基金拨款赞助(SDF# D11 003 001)和香港钟表业总会的财政及行政支持。

甲部：原理篇

第一章

1. 导言

艺术家经常使用粗糙的表面来表达深层次的艺术意念，因为粗糙感更接近现实，或许更能触动人心。这种艺术表达手法较为主观，群众是否喜欢很受文化与历史背景所影响。

金刚石耀目的光芒极具吸引力，不期然地吸引了我们的眼睛。那耀目光芒也蒙蔽了我们，我们不得不看，因为它实在太美了。

闪烁的光辉是一种跨文化的美，即使是一件黑色的工艺品，它的镜面反射还是令它更美更吸引。

一分钱一分货，要把工件打磨得更光亮，便一定要花更多的金钱与时间。因此，高级的打磨技术只能用于高价货品身上。

一般制造业不能接受高昂的加工成本，必须把磨削与打磨工序的成本高必须合理地控制，企业才有持续的生存空间。

认识磨削与打磨机制和表面加工原理，是管理钟表制品成本和满足顾客要求不可或缺的部份。

现时广东省一带的钟表制品需要大量劳工，陪训一般半技术及技术工人大约需时2-5年，这些由师父教导的工人大多不能解决复杂的技术难提。

这本技术手册不是一般的科学研究报告。编写这本技术手册的目的，在于提供一个科学化的方法来处理金属打磨技术，旨在让金属表面加工从业员在一个较坚实的科学基础上优化现有技术，使其能有足够的能力与知识面对现在与未来的挑战。当然，此手册也是一本大学本科生和工专学生的实用教材。

甲部： 原理篇

第二章

2. 金属学初探

金属与合金具有很多优越性能，因此成为我们的常用加工材料。金属优点简列如下：

- 高强度与高硬度
- 高热稳定性与耐用
- 可塑性与可锻铸性高
- 可硬化与热处理
- 可合金化
- 可延展性高
- …

金属与合金具备的独有特性，不容易在陶瓷或塑胶材料找到。其中最重要的可算是通过 锻造和冷轧塑性变形达至的硬化，与及通过热处理达至的软化和强化。简单的机械及热处理加工，便能使材料脱胎换骨，性能多变而用途更广泛。

热处理的加工温度，因应不同合金的成分而不同。一般而言，

高温热处理能使金属软化，但必须配合适当的冷却速度；

慢的冷却速度能使很多的金属更软，而快速冷却速度会使部份金属更强更硬。

通过改变金属元素成份，我们可以混合成无数的合金，再加上适当的热加工、冷加工和热处理，我们便可得到更好的产品和素质。

2.1. 金属与合金机械力学性能

日用材料一般可按其机械力学性能分列如下：

陶瓷 > 金属与合金 > 塑料

金属与合金普遍被认为是较强较硬的材料，但这只是主观的描述，但不少工程用复合塑料比部份金属更强。下文我们会先简述一些常用的材料性能：

2.1.1. 强度（Strength）

直径 10 毫米的金属棒，可承重量约是直径 1 毫米的 100 倍，因为它的横切面比是金属棒 100 倍。这强度比只是估计约数，因为我们并没有考虑它的长度。

物件的强度取决于它所包含的缺陷。从统计学的角度分析，一件较大较长的学物件，其包含缺陷的机会也较高，因一个小缺陷而带来的所机会率也较高。相反，较小的物件包含缺陷的机会率也较低，但小物件之间的相异性却较大。

材料强度（σ）是物件所能承重（F 单位：N / 牛顿，1 千克重量为 9.81N）与其横切面面积（A）之比。

$$\sigma = F/A$$

横切面面积越大，所能承重越高，但物料强度不会因物件的大少而大量改变。

当我们说某材料很强，很多时候我们只是说它不易被弯曲 (高杨氏弹性模数 Young’s Modulus、高屈服强度 Yield Strength、高抗张强度 Tensile Strength 或高耐压强度 Compressive Strength）。表 2.1 列出了部份常用金属材料的机械力学性能以供参考。

表 2.1　部份常用金属材料的机械力学性能

材料	**杨氏弹性模数 (GPa 或 1000MPa)**	**屈服强度 (MPa)**	**抗张强度 UTS (MPa)**	**维氏硬度 (HV)**
锡 , Sn	47	9-14	15-200	10
铝 , Al	70	15-20	40-50	17
金 , Au	79	--	120	40
银 , Ag	83	124	207-283	70
钛 , Ti	120	100-225	240-370	200
铜 , Cu	130	33	210	50
白金 , Pt	168	--	125-240	130
镍 , Ni	170	14-35	140-195	130
钽 , Ta	186	180	200	200
铁 , Fe	211	80-100	350	100
钨 , W	411	550	550-620	360

杨氏弹性模数一般对成份没有那麽敏感，但若发生了相变和晶体结构改变了。成份对 屈服强度、抗张强度与硬度 的影响通常较为明显。弹性变形发生于应力低于屈服强度时，变形会跟随应力的减退而减少。

通过适当的合金化、机械加工和热处理，我们可将合金的机械力学性能提升 2-10 倍，而其他物理特性却仍然经常保持大致不变。

有些软合金材料的 屈服强度 和抗张强度分别非常大，这通常显示这些合金能通过冷轧或锻造等工序强化。这样的金属被归类为可硬化合金，用途十分广泛。

强而硬的材料都很脆，即容易突然断裂。此等材在应力大于屈服强度后会形成裂缝或微裂缝，因此不会通过塑性变形加工，应使用铸造和粉末冶金成形术制造这类产品。

韧性材经过不适当或过度的机械加也会产生裂缝。为了防止对工件的破坏，可使用适当的热处理来软化材料，然后才进一步加工。

2.1.2. 硬度 (Hardness)

材料供应商通常会提供材料的杨氏弹性模数、屈服强度与抗张强度等数据；当然，加工工厂也应抽样检测。拉力试验可提供的数据较多，但试验成本较高，工厂一般较少采用。硬度测试成本低，是更广泛被采纳的来料检测方法。

硬度标准有多种，必须按材料的力学特性选择，最基本的原则是硬度值与抗张强而度成线性正比，方便换算和作为叁考数据。以下为一些常用硬度标准：

- 维氏硬度 (HV)
- 布氏硬度 (HB)
- 努氏硬度 (HK) 用于小面积与薄膜
- 罗氏硬度 (HR)
- 用于木材的 Janka hardness
- 用于塑胶的肖氏硬度
- 用于 复合材料的巴氏硬度

不同的硬度值没有一套简单的对换方程，但 HV 与 HB 数值较相近。HV 值的可用 范围较大，因此会在本手册中使用。

HV 又称金刚石锥硬度标 (DPH)。重力 (F_{kgf} 或 F_N) 加于菱形的金刚钻 压头会留下菱形凹痕于工件上，使用菱形的对角线长度 (*l mm*) 用下式计算得其硬度值：

$$HV = 1.8544\ F_{kgf} / l^2, \quad or$$

$$HV = 0.1891\ F_N / l^2$$

表 2.2 是一些常用材料的 HV 硬度。

表 2.2　常用材料的 HV 硬度值

材料	HV 硬度值
铅 , Pb	4HV
铝 , Al	17HV
金 , Au	22HV
银 , Ag	26HV
铜 , Cu	37HV
铁 , Fe	30-80HV5
碳钢	55-120HV5
白金 , Pt	56HV
钽 , Ta	89HV
锆 , Zr	92HV
钛 , Ti	99HV
钴 , Co	106HV
铬 , Cr	108HV
镍 , Ni	130HV
316L s.s.	140-225HV30
铍 , Be	170HV
347L s.s.	180HV30
304L s.s.	Upto 210HV
铬 , W	350HV
硅石 (氧化硅)	850HV
马氏体 (钢)	1000HV
石榴石 , 金刚砂 (硅酸盐 , Emery, silicate)	850HV
氧化锆	1150HV
氧化锆 - 氧化铝	1500HV
氧化铝	2000HV
碳化硼	2000HV
金刚砂 (碳化硅)	2500HV
立方氮化硼	2750HV
硼 , B	5000HV
金刚钻	10000HV

s.s. = 不锈钢

HV 也可对换成 GPa 或 MPa:

$$\text{MPa} \div 9.807 = \text{HV number}$$
$$\text{GPa} \div 0.009807 = \text{HV number}$$

HV 亦可用作推测屈服强度 (MPa 或 GPa)：

$$\text{屈服强度} \approx \text{HV} \div c \approx \text{HV} \div 3$$

c 为数值 2 至 4 之间的常数。详细资料可叁阅 ISO 6507-1 或 ASTM E384。

2.1.3. 脆性或韧性

高屈服强度或抗张强度的材料有时也会显得脆弱和容易断裂，故国此称为脆性材料，玻璃就是最好的例子。物质受应力时储存能量，但不能藉塑性变形机制 (如位错滑移、孪生变形或剪切带变形等)。

很多材料因能藉不同的塑性变形机制而变形，减少兵了脆性断裂的危机，被归类为延性材料。延性材料可被塑造成很多的不同形状，所以最受制造业欢迎，其中表表者为金、银、铜和铝等。

材料经加工后可能会坚韧而不能继续塑造。这时，适当的退火可使合金变回柔软和可继续加工。高温退火包括三步骤： 回复，再结晶和晶粒生长。高退火温度能加快退火速度，使材料变得更柔软。不过高退火温度也会使晶粒变得粗大，于再加工时容易出现橘子纹，影响产品质素。

有的材料是不能或不容易热处理的，错误的退火会造成不能逆转的，所以必须小心策划。因此，必须与有经验的材料工程师或供应商仔细研究，设计恰当的退火和序。

材料的脆性通常用 断裂韧度来表示， 断裂韧度越大表示材料越韧，数值越小表示材料越容易脆性断裂。表 2.3 列举了一些 常用材料的断裂韧度以供叁考。

断裂韧度与抗断裂学特性有密切关系，也受应力加载方式和工件形状有关。

有些材料的断裂韧度受温度的影响而变化，般低温会令 断裂韧度降低，材料变得更脆。有些材料更会于玻璃态转变温度以下突然变得容易断裂。断裂韧度也受冲激速度影响。高的冲激波会使材料表现得更脆弱，材料在玻璃态转变温度以下更加脆弱。

表 2.3　常用材料的的断裂韧度

材料	断裂韧度 ($\mathrm{MPa\ m^{1/2}}$)
4340 钢	50
钛合金	44-66
7075 铝合金	24
铝	14-28
立方氮化硼	5.7
碳化硼	3.2
碳化硅	2.5-5
金钢砂 Emery	2.4
氧化铝	2.3-5
氧化硅	1.14
有机玻璃 PMMA	0.7-1.6
聚苯乙烯 Polystyrene	0.7-1.1
钠钙玻璃 Soda-lime glass	0.7-0.8
混凝土	0.2-1.4

2.1.4. 磨蚀速率

当物料互相摩擦时，两者都会损耗。较强的材料一般磨损得较慢；磨损机制是一一们相当复杂的科学，所以也经常有不少例外。

当材料与尖锐和坚硬的氧化铝或碳化硅摩擦时，磨损率可以很高。当然，磨损率也受摩擦压力影响。表 2.4 列出些常用材料于 30kPa 压力下的磨损率。

表 2.4　用 P240 号碳化矽砂纸在不同材料的磨损率

材料	屈服强度 [a] (MPa)	HV[a]	磨蚀速率 (μ m/m)
铅，Pb	8	6	1.2
锡，Sn	14	10	3.5
铝，Al	70	17	2.5
金，Au	79	22	0.08
银，Ag	83	26	1.1
铜，Cu	130	37	0.6
镍，Ni	170	130	0.1
铁，Fe	28[a]	30-80	0.1
钛，Ti	120	99	0.05
铬，Cr	--	108	0.05
钨，W	411	350	<0.05

a　部份纯金属的力学性能对成份非常敏感，因此不能确认其准确性

2.2. 金属和合金的物理学

日常生活的主观判断可能使我们以为较重的东西会较强。但当我们很发现金和铅都很重却不强，便知道这种观念是错误的了。

材料的强度源于组原子间的原子键强度。原子键主要分为共价键、离子键和金属键三种。陶瓷材料通常由共价键和离子键组合成，一般强度较高。组成金属和合金的金属键强度略低，但金属键的特性却使金属的延展性更，可加工度更高。金属的可延展性，除了与金属键有关外，还受很多其他因素影响，最重要的可算晶体结构。

2.2.1. 晶体结构

在金属溶点以下，金属多数处于结晶状态，即有规律的三围 (3D) 排列。此 3D 晶体结构决定了金属和合金的众多独特性能。

铁碳合金钢在高温时为面心立方相 (FCC)，强度相对较弱，便于锻造加工变形。此 FCC 相亦称为奥氏体。当奥氏体慢慢地冷却至低温，便会转化成体心立方相 (BCC)，变得坚硬了，并且不再容易被塑造成不同的形状。再次提升温度，BCC 又会转化回 FCC 相。加入铬和镍的钢合金，在室温仍保持 FCC 奥氏体相，变得容易加工。常用的 304 及 316 等属于这类不锈钢，称为奥氏体不锈钢。

2.2.2. 金属变形与断裂

在应力下金属键会被拉长、压短或剪切；当应力低于屈服强度时，材料只会弹性变形，会随应力消失而消失。当应力继续增加，晶体会沿著特定的晶面切变滑移，造成塑性变形的效果。

屈服强度的理论值比实验结果大 100 至 10000 倍，这差异是由于晶体中存在使晶滑移的晶体缺陷，最重要的晶体缺陷包括位错。不同的晶体结构受不同的滑移晶面和位错影响，有些晶体有较多的滑移系统，于是变形机率较高，屈服强度较低。

FCC 与 BCC 晶体结构均有 12 个滑移系统，所以较六方密集晶体结构 HCP 容易塑性变形。表 2.5 简列了一些常用金属的晶体结构和强度。通常 FCC 结构的金属材料可塑性较高。

表 2.5　常用金属的晶体结构

材料	**原子比重**	**HV 硬度值 (MPA)**	**晶体结构**
铝 , Al	27	167	FCC
金 , Au	197	216	FCC
银 , Ag	108	251	FCC
铜 , Cu	64	369	FCC
镍 , Ni	59	638	FCC
铁 , Fe	56	608	BCC
钛 , Ti	48	970	HCP
铬 , Cr	52	1060	BCC
钨 , W	184	3430	BCC

晶体中位错错能使金属变形更容易。但当位错沿著不同晶面滑移和相交时，会产生弗兰克-里德位错源(Frank-Read Source)，令位错密度提升。当位错密度随变形而大量提高，位错间的滑移便会变得不易，形成了机械应变硬化(Strain hardening)。同时，材料会变得更强，当应力不断增加时，裂缝会随应力增加而形成，最终导致断裂。

当晶体化的金层缺有效的滑移系统，又缺乏其他的塑性变形机制，便会变得强度高，同时也了脆性材料，可延展性大大降低。

2.3. 金属和合金的热加工

机械加工硬化了的合金材料不容易继续冷加工，因为高强度的材料会提高模具的损和破裂，工件本身也可能断裂。高温退火处理能回复原有的柔软度和可延展性，使工件可再次被机械加工。退火一般可分为三过不同却又重迭的过程，包括回复、再结晶和晶粒长大。

回复发生于较低温，材料的力学性能和位错密度变化较少。最重要的回火过程发生于再结晶阶段，所需退火温稍高于回复温度，材料强度和硬度却会大复度降低，使材料可再次被机械加工。若退火温度过高，晶粒便可能持续长大，强度也会继续下降。100μm或以上的大晶粒材在机械加工后会出现橘子纹，使打磨工序更费力。因此，必须避免不适当的高温退火。

退火可于真空、气体或液体媒介中进行。在大气压力下，液体只能加温至它的沸点，300°C高温的加热器也不能把水温提升至100°C以上；一般120°C火炉，加上搞拌气已能提高其热处理的效率。

热处理的效率按次序简列如下：

液体媒介 > 气体媒介 > 真空
强制对流 > 自然对流 > 静态
高温度 > 底温度
小工件 > 大工件

部份合金可通过适当的热处理而产生沉淀硬化或淬火硬化效果，并不需要机械加工。沉淀硬化又可称为析出硬化、老化硬化或时效硬化。

小部份钢材和合金可通过快速冷却带来淬火硬化效果。淬火硬化的工序分简单，只需将工件提温至固溶温度以上，让原有析出相完全固态溶解，此时若慢速于空气中冷却，材便会变得柔软和容易机械加工；若快速冷却于水中，材料便会转换成非平衡相(如马氏体 martensites)，变得坚硬。钢材中的马氏体非常坚硬，但形状记忆合金中的马氏体却可以较柔软。

老化硬化过程稍为复杂一点。工件需放于固溶温度以上，让原析出相完全溶解，然后慢速空冷至较低强度以便机械加工。加工后再次提温至固溶温度以上，然后快速冷却至低温，达至高强度的性能；跟著再次提温至合适的老化温度及保温段较长时间，让硬化材料的析出相生长形成，材料的强度便会大复度提升，达至硬化强化的效果。

热加工的 序必须小心周周详设计，并且按所需温度和时间准确执行。不恰当的热处会削弱材料的力学和防侵蚀性能，或使材料变得过硬和晶粒粗大，令打磨工序变得困难费时。

甲部：原理篇

第三章

3. 机械打磨机制

机械打磨是利用坚硬的颗粒(研磨料)将工件表面磨平。通过使用一系列的粗磨粉和幼磨粉，工件的表面平滑了，刮痕也变得幼细了，达至最终的镜面如镜的反射效果。研磨料的硬度必须比工件硬 1.5 倍或以上，最好能是工件的硬度 3 或以上。表 3.1 为常用研磨料的硬度。

表 3.1　常用研磨料的 HV 硬度值

研磨料	**硬度 (HV)**
硅石(二氧化硅)	850
氧化锆	1150
金钢砂	1400
氧化铝	2000
碳化硼	2000
碳化矽	2500
立方氮化硼	2750
金刚石	10000

使用越硬的研磨料打磨，可提高打磨的效。最常用的研磨料有氧化铝 (Al2O3)、碳化矽 (SiC) 与金刚石。在打磨的过程中，我们利用研磨料在工件上划出幼细而平均的刮痕，最终达至镜面的效果。

3.1.　金属镜面与粗糙度量度

完美的镜面能反射所有的光线，并且不造成任何影像扭曲。不过，世上并没有完美的镜面。极高级的介质反射镜 99.9% 的光线。当镜面只反射可见光波段中的一部份时，所反射的光波便组成了材料的色泽。

反射面的质素的另一重要指标是漫射光和镜面反射光的比例。不光滑的反射面如石膏墙或反射出接近 100% 的漫射光。光滑的表面如经打磨的白金面可反射出接近 100% 的镜面反射光。

当一个镜面放于显微镜中检视时，不整发现那看似镜面的光滑表面原来布满刮痕。刮痕越多越粗，漫射光的比率越高，反射的影表扭曲度越大。使用更幼细的研磨料来**磨蚀**(磨削)加工，刮痕会变得更浅和幼细，漫射光比率降，镜面反射光比率提高了，便成了更好的镜面，影像扭曲也减少了。

20/20 是人的合理良好视力，但仍不能分辨两条 20cm 外相隔少于 70 μ m(即 0.07mm) 的线条。

120 级砂纸能刮出只 5μm 宽的刮痕；肉眼虽然不能清楚分辨这些微小的刮痕，但这些刮痕却漫射光比率提高至接近 100%，加上分布不均的刮痕，使这等表面不能清晰地反射影像。在显微镜下，那些刮痕却是清晰可见。

测试镜面的反射质素不难。可使用镜面观察一条直线，如笔直的荧光管，并将工件慢地摇晃，若反影像保持不变，即表示镜面反射质素非常高。这方法也能找出不平滑的位置。

较科学和客观的的测试方式是使用表面光度仪或原子力显微镜等接触式仪器来量化表面的粗糙度叁数，非接触式的仪器有光学乾涉仪、角膜共焦显微镜。最常用的表面粗糙度叁数是粗糙幅度叁数 Ra。粗糙度叁数越小，漫射光线率越低，平面的质

3.2. 磨削、打磨与抛光

将材料加工切削和塑性成形后，最后的工序是把表面打磨至所需的光滑度，所有生产程序便完成，可以进行包装了。表面加工包括磨削 (grinding) 和打磨 (polishing) 两部份。

磨削是指利用坚硬的磨削砂轮或粗磨砂纸刮擦工件表面。砂轮磨削的磨蚀速率较快，将工件表面快速磨平。使用粗磨砂纸刮擦表面的目的与砂轮磨削相同，只是速率较慢，适合用于磨蚀毛边芒刺。

打磨、研磨 (lapping) 与抛光 (buffing) 都是机械表面加工光整加工 (finishing cut) 工序，通常使用较幼细的研磨料。打磨和抛光等通常含糊地泛指所有能使工件表面加工成镜面的工艺。从技术角度来分类，砂纸打磨是指使用幼砂纸磨蚀工件的表面，目的是使面光滑如镜；使用粗磨砂纸刮擦工件的目的则是磨削工件至所需尺寸，归类为磨削工序。小心地使用 P1500 级以上的幼砂纸刮擦工件能造出类镜面打磨效果。

表 3.2 列了砂纸上颗粒级别与磨削或打磨效果的粗略分类。当使用 P1500 级以上的砂纸打磨 (sanding) 后，一般肉眼已不能分辨刮痕，可评为初级镜面效果；其实在光学显微镜下，刮痕仍是清晰可见。大部份的优质镜面反射效果，都是通过研磨与抛光工艺完成的。研磨与抛光使用的研磨料没有被固定黏附在磨轮上；研磨用的磨轮一般是坚实的，其形状与工件的最终形状相同，研磨的第一个目标是使工件达至所需的尺寸精度，其次才是得到镜面反射效果；抛光用的抛光抛可以非常柔软，强度很低。

表 3.2　砂纸颗粒级别与 (ISO/FEPA) 表面光整加工工序分类

品质	**ISO /FEPA 单位**	**研磨料颗粒尺寸 (μm)**	**光整加工工序**
极粗糙	P20	1000	去氧化层
粗糙	P50	336	去毛边
中度幼细	P100	162	磨平
幼细	P220	68	磨削
中度幼细	P400	35	磨蚀
超幼细	P800	22	磨削至打磨
极幼细	P1500	13	
极幼细	P2500	8	打磨

正确的机械表面光整加工程序如下：

1. 去氧化层、去毛边及磨平 (粗砂纸磨)
2. 磨削 / 磨蚀 (幼砂纸磨)
3. 打磨 (幼细砂纸磨)
4. 抛光或研磨 (镜面效果)

光整表面加工的工艺，包括由粗至幼的砂纸磨工序，主要目的是先去除氧化层和毛边，然后将工件表面磨平，再用超幼细的磨砂纸去除粗糙的刮痕，最后还需用抛光轮稍再抛光。

3.3.　磨损机制

当研磨料被压在工件表面时，坚硬的研磨料陷入了工件表面，移动中的研磨料在工件上划出刮痕，并同时磨蚀材料表面。研磨料通常是单晶硬颗粒，拥有随机的断裂尖角，这些锋利的断裂尖角最能有效地磨蚀金属面。

研磨料的形状和方向都会影响磨蚀的效率，圆形的研磨料不能有效地磨蚀，拥有锐角的研磨料却最为有效。在实际磨蚀过程中，只有部份在砂轮或砂纸上的研磨料能和工件表面接触，其中只有更小部份研磨粒方向适中，是有效的切磨点。表 3.3 列出了常用 SiC 砂纸磨蚀特性。

砂纸磨时施加的压力会加深工件上的的磨痕深度和阔。一般压力应为 20 至 40kPa。表 3.4 简列了不同件大小的适当力度。

表 3.3　SiC 砂纸磨蚀特性

特性	**SiC 砂纸**			
	150	**280**	**400**	**600**
接触点 /cm^2	50	100	400	450
切磨点 /cm^2	10	14	52	55

除了压力以外，刮痕的深度和阔度也会受工件材料的硬度所影响。假设凹陷痕为菱形，利用表 3.3 及以下硬度方程，我们可以推动算出刮痕的阔度。

$$HV = 1.8544\ F_{kgf} / d^2$$

表 3.4　圆形工件砂纸磨需用力度对算表

工件直径 (mm)	**面积 (mm²)**	**压力 (kPa)**	**力度**		
			N	**kg**	**lb**
25.4 (x10 件)	5067	20	101	10	23
	5067	40	203	21	45
25.4 (1 件)	507	20	10	1.0	2.3
	507	40	20	2.1	4.5
12.7 (1 件)	253	20	5	0.5	1.1
	253	40	10	1.1	2.3
6.35 (1 件)	127	20	3	0.26	0.6
	127	40	5	0.52	1.1

表 3.5　刮痕阔度与砂纸磨压力的关系

压力 (kPa)		**20**			
面积 (mm²)		506.7			
力度 (N)		10.13			
力度 (kgf)		1.033			
	砂纸 s	600	400	280	150
	接触点 /(cm²)	450	400	100	50
工件 HV 硬度	**接触点**	2280	2027	304	253
	d²(mm²)	**对角线长度 d (μm)**			
50	0.03831	4	4	9	12
100	0.01916	3	3	6	9
200	0.00958	2	2	4	6
400	0.00479	1	2	3	4
800	0.00239	1	1	2	3
1600	0.00120	1	1	2	2
压力 (kPa)		**40**			
面积 (mm²)		506.7			
力度 (N)		20.27			
力度 (kgf)		2.066			
工件 HV 硬度	**d²(mm²)**	**对角线长度 d (μm)**			
50	0.07663	6	6	12	17
100	0.03831	4	4	9	12
200	0.01916	3	3	6	9
400	0.00958	2	2	4	6
800	0.00479	1	2	3	4
1600	0.00239	1	1	2	3

表 3.5 推算了刮痕的阔度随压力增加而变阔。因为弹性变形的部份回复，实际的刮痕阔度可能更小。实验数据显示表 3.5 的推算甚是可靠。当 160mm 直径的磨砂纸使用了 20-100 转之后，接触点会增加至稳定数目，才会适合用作打磨加工用途。真径较大的磨砂纸会较快达至稳定的打磨效果。

3.4. 变形深度与磨蚀叁数

砂磨、打磨与抛光时所用的压力越小，刮痕的深度越浅。因此，应该使用较低的压力，但缺点是磨蚀速率较慢。表 3.6 列出新旧 SiC 砂纸于 40kP 在 Cu30%Zn 表面所造成的刮痕深度。

表 3.6　列出新旧 SiC 砂纸于 40kP 在 Cu30%Zn 表面所造成的刮痕深度

刮痕最深深度 (μm)	**SiC 砂纸 Grit**	**220**	**400**	**600**
	新砂纸	5	3	1.3
	使用 20m 后	2.4	1.5	0.9

表 3.7　磨削与打磨 Cu30%Zn 所造成的塑性变形层深度

	级别	**切削液**	**μm**		
			花痕 / 刮痕	**D_s**	**D_d**
手锯	18 齿 /in.	无	100	55	750
切断磨轮	氧化铝 16 网	油水乳化液	4	16	700
切断磨轮	金刚石轮	专用液体	1	14	--
锉	粗切削	无	70	55	450
锉	幼切削	无	30	50	370
车床车削	0.001 寸进料速率	油水乳化液	1	15	150
机械表面磨削	氧化铝 28 网	油水乳化液	6	50	350
手工磨削	氧化铝 38 网	无	15	40	170
砂带打磨	氧化铝 100 网	无	15	35	250
	SiC P120	水	5.5	25	19
	SiC P240	水	3.5	15	95
	SiC P400	水	1.2	5	60
砂纸磨	SiC P220	水	2.0	7.5	77
	SiC P400	水	1.5	6.5	43
	SiC P600	水	0.8	5.0	22

表 3.7 及表 3.8 表列了机械切削、磨削和打磨所造成的刮痕阔度和深度，但这些只是我们所能看见在工件表面的痕迹。机械切削、磨削和砂纸打磨都会在工件表面下引起了一层肉眼不能看见的塑性变形层，这变形层又可细分为切变变形层 (亦即 significantly deformed layer, $\mathbf{D_s}$) 和变形层 ($\mathbf{D_d}$)。

D_s 与 D_d 的深度为可见刮痕的 14-50 倍，因此不容忽视。表 3.7 了 *Cu30%Zn* 在加工和打磨时所造成的变形层深度。材料越硬，D_s 与 D_d 变形层的深度越浅； 压力越大，D_s 与 D_d 变形层的深度越深 . 奥氏体不锈钢的硬度比 CuZn 合金高与，变形层也较薄。表 3.8 表列了不同磨削和砂磨对工件所造成的伤痕深度。

表 3.8　磨削与打磨在钢与锌的表面所造成的变形层深度
（压力：30kPa）

	研磨料	Grit	环境状态	D_s（μm）	
				奥氏体不锈钢	锌 Zn
机械表面磨削	氧化铝	38	25 μm 进料速率、使用切削液	35	125
	氧化铝	38	手动、 切削液	43	130
手动砂磨带	氧化铝	100	手动、 切削液	12	85
手动磨蚀纸	SiC	200	手动、 切削液	6	50
	SiC	400		2.5	45
	SiC	600		2.2	15

经过打磨与抛光后，变形层亦被磨蚀和磨平了，表面上不会带来任何不良后果。但这些变形层的抗腐蚀工功能一般较低，若工件被暴露于腐蚀气氛中，将会被快速侵蚀，表面光整度将会大复度降低。

再者，若工件需要作 PVC、CVD 或化学研磨的话，表面的光整度将会变坏，不能达至镜面的反射效果。因此，在生产高质量耐用品时，必须确保这层变形层已被去除。

减少变形层的不良影响的最简单方法是降低磨蚀压力，也可使用十字打磨法（即每次转换打磨方向 90 度），以确保变形层被完全去除。

3.5.　磨蚀速率与磨蚀参数

磨蚀的机制十分复杂，因此不容易准确预测，而且常有例外。但一般磨蚀速率与工件硬度成反比。表 3.9 简列了一些常用金属材料的磨蚀速率及其硬度。

磨蚀速率和研磨料的颗粒直径约成线性正比，大颗粒研磨料能达至高磨蚀速率。但值得注意的是，使用直径约 100μm 的研磨料（即 220 至与 150 级）的磨蚀速率最高。表 3.10 简列了一些磨蚀速率和 研磨料的资料。

表 3.9　　不用砂纸应用在常金属材料的磨蚀率

	硬度 (HV)	磨蚀速率（μm/m）		
		SiC P240	氧化铝 P240	金刚石 220
铝：				
高纯度，退火	24	2.61	1.93	1.76
合金，热加工	105	1.29	0.85	0.65
铬：				
高纯度，退火	200	0.25	0.20	0.16
铜：				
高纯度，退火	50	0.61	0.28	0.19
黄铜 30%Zn 退火	45	0.81	0.72	0.40
黄铜 40%Zn 含铅	155	2.06	1.48	0.77
金：				
高纯度，退火	22	0.26	0.16	0.08
镍：				
工业纯度，退火	130	0.08	0.17	0.14
钢：				
奥氏体不锈钢，304	155	0.09	0.36	--
钛：				
工业纯度，退火	200	0.25	0.15	0.11
Ti-6Al-4V, 热加工 ed	295	0.25	0.15	0.07

表 3.10　研磨料于已退火 Cu30%Zn 对磨蚀速率的影响
(压力：~40kPa)

研磨料 grit	平均颗粒直径 (μm)	磨蚀速率 (μm/m)
P1200	15.3	0.25
P800	21.8	0.37
P240	58.5	0.75
220	63	0.95
150	90	1.00
100	150	0.90
80	180	0.70

较高的压力可提高磨蚀速率和生产力，但也会加快砂纸的损耗，还会产生更深的塑性变形层，降低产品的质素，因此应尽量避免。

3.6.　打磨、研磨与抛光

磨削与打磨的分别并不明显。使用 SiCP600 砂纸磨会在工件上留下微细的磨削刮痕，因此应定性为磨削； 使用 SiCP1500 砂纸磨会在工件上留下极微细的磨削刮痕，甚至肉眼难于察觉，但这应归类为打磨抛光吗？那麽 P800、P1000、P1200 这等又如何呢？

这些表面加工工序实际上能制造出相近或重迭的品质，因此单用制成品的光整度来衡量，很难清楚介定甚麽是打磨，甚麽是抛光。不过，我们可以考虑不同加工工序的目标作分类，表 3.1 列出了一些常用表面加工处理工序的主要目的。

表 3.11　常用表面加工处理工序及其主要目的

工序：	**成形**	**磨削，磨蚀**	**打磨**
目的：	*制造成所需形状*	*准确尺寸* *表面纹理*	*表面光整加工*
	Cutting Turning Boring Milling Drilling Lathing	珩磨 砂磨 (50-1000)	砂磨 (1500-2500)* 抛光 研磨 电化学抛光

* *"幼细 磨削"*

要制成好的镜面，所反射的光线是平衡的，结果形成了没有扭曲的反射影像。若反射面由很多细小的坑纹组成，而坑纹粗幼大小完全相同，又完全平均地分布的话，肉眼便很难察觉坑纹的存在。

若研磨料被固定在砂纸或磨轮上，因着研磨料的不平均分布，磨蚀出的坑便会很不均匀地分布所以砂磨轮和砂磨纸很难磨蚀出镜面。砂纸磨极其量只是一种超幼细的磨削。

当同样大小的研磨料使用在研磨轮上时，研磨料可随机地与工件表面摩擦，但却被研磨轮的形状所限制，使工件通过研磨获取了研磨轮的形状，得到了非常准确的尺寸精度。若研磨压力较低，配合使用幼细的研磨料，同时更可获取高光整度的镜面；这完全

有赖研磨料的随机游动。明显可见，研磨与砂磨的基本原理大不相同。

所有机械打工序都会产生表面刮痕，刮痕的大小在光学显微镜或电子显微镜中清晰可见，分别只是这表面刮痕的粗幼大小和分布特性而已。

研磨与抛光的独特之处，在于使用没有固定位置的研磨粒，随机地和更均匀地刮削材料表面，造成了更平滑的反射面，减少了对反射影像的扭曲。研磨轮是有固定形状的，研磨料可在研磨轮和工件之间自由游动；抛光轮有别于研磨轮，它没有一坚硬的固定形状，一般是以布料、皮革或纤维材料造成。

研磨与抛光均通过让松散地黏在轮上的研磨料与工件摩擦而产生作用。研磨料除了刮削工件表面外，还会在其上滚动加压。研磨料还可能在压力碎裂成更细小的颗粒，这种「滚动 - 破碎 - 磨蚀」的复杂过程，最终产生了非常理想的平滑镜面。

研磨与抛光可以达至平均粗糙度约 0.4-0.05 μ m 的效果。当然，必须使用较幼细的研磨料，否则，过多的磨蚀会使工件表面粗糙。常用的研磨料包：

- 氧化铝
- 金刚石
- 氧化镁
- 二氧化矽

3.7. 摩擦力与润滑剂（黏结剂）

磨蚀与打磨必须于摩擦力略条件下进行。高摩擦力会打磨速不稳定，导致表面粗糙起波纹。

表 3.12　润滑剂对磨蚀速率的影响

润滑剂	相对磨蚀速率
流动清水	1.0
矽油	1.0
高压润滑油	0.7
无润滑剂	0.5
固态蜡	0.4
停滞水	0.4

P240 SiC 砂纸，已退火 Cu30% Zn

适当的润滑剂（黏结剂）能使研磨抛光面光滑平正，同时也会改变磨蚀速率。表 3.12 的资料显示了正确选择润滑剂的重要性。液态的润滑剂还有冷却剂、蚀刻剂和扩散剂的作用：

冷却剂：　流动的液体可将摩擦所产生的热能带走，减低过高温度对工件的损坏和对磨轮的损耗。

蚀刻剂：　添加小量的低消浓度化学侵蚀品，可提高磨蚀速率，能使光整表面更光滑。不过化学磨蚀学必须彻底清洗工件，以免残馀化学学物继续侵蚀工件。

扩散剂： 局部磨蚀会破坏表面的平滑度，好的扩散剂使研磨粒均匀分布，产生镜面打磨的抛光效果。使用煤油 kerosene 作扩散剂，比用清水打磨效果更好，磨蚀速率更可提升 5 至 10 倍。

在抛光过程中，抛光剂在工件摩擦发热时快速升温融化，流动性大大提高。藏于抛光剂内的研磨粒自由随机地磨蚀工件，造成了均均匀而轻轻柔磨蚀效果，工件表面变得平正光亮。若温度太低，研磨粒不能平均分布，会使抛光不平均。若抛光温度因压力太大而升温过高，可能导致抛剂过热分解，黏在抛光轮上，破坏抛光效果。

3.8. 保护已打磨的表面

打磨工场内的磨轮和抛光轮，应按研磨粒的粗幼度顺序排列，不同粗幼度的磨轮和工具应分类分区摆放，以免粗研磨粒污染幼细的精磨抛光工序。

不同的磨轮应使用于不同的工件材料，不同的抛光剂也不应使用于一个磨轮上，避免粗糙磨料和金属屑刮花精磨抛光工件。

减低打磨工场内的气流速度，气流方向从上而下，从幼磨向粗磨，不可使用强力风扇，避免把微尘吹起，造成污染。每个磨轮最好能配备独立抽风器，地上尘屑要经常清理，减少尘屑累积于工场内。

已打磨好工件的必须彻底清洁，烘乾后存放于清洁的环境，应用柔软的包装物料，并固定于胶盒内，免受震荡和撞击。

乙部：技术篇

第四章

4. 磨蚀、打磨与抛光技术

磨削的主目的是制成尺寸精确的件。小心选择的精磨削序产生理想的表面加工效果，使表面接近光滑如镜，可减低后期接打磨抛光的成本和困难度，提高产品的光整度。

直接使用粗研磨料抛光去除厚厚的氧化层，不单浪费时间，还会使工件大量变形，失去原设计的线条美感，工件的尺寸精确度大复降低。

机械磨削 (grinding) 是金属制过程的课程范围，很多教科书都有详细资料，在这里不再重复。采用幼砂纸磨削的工序，以及使用抛光轮和抛光剂的光整工艺，是经常被钟表制造业采用于技术，都是本章的重点内容。

1. 机械成形 (Forming)
2. 切割加工 (Cutting)
3. 磨削 (Grinding)
4. 除毛刺 (De-burring, Section 4.2)

5. 除氧化层 (Oxide Removal, Section 4.3)
6. 砂纸磨 (Sanding, Section 4.4)
7. 研磨 (Lapping, Section 4.5)
8. 抛光 (Buffing, Section 4.6)

4.1. 磨削、打磨与抛光前的准备

在设计打磨工序之前，必须搜集以下资料：

- 材料成份
- 所受的热加工处理和硬度
- 所受的机械加工处理
- 期望达到的硬抛光光整度

运用以上资料，加上从供应商、材料加工手册和文献的资料，可以推算下磨削与打磨叁数：

- 几种不同的磨削与打磨方法的磨蚀速率
- 所选择的磨削与打磨方法将会造成的变形层厚度
- 所选择的磨削与打磨方法的成本效益

磨削与打磨方案应反复分析评估修正，以减低加工时间和成本为目标。必须考虑塑性切变变形层会否影响产品质素，如塑性变形层可能导致锈蚀，便需考虑是否需要用电化学抛光去除掉这塑性变形层。

所有机械切削所产生的碎屑必须于磨削与打磨前彻底清除。油性的切削润滑剂可能影响磨削的速率和质素，也应清洗乾净。要确保粗糙的研磨料和金属屑被冲走，才可进行更幼细的打磨抛光工序。要将可磁化材料消磁，减少因碎屑被吸在金属表面而导致的刮痕。

4.2. 除毛刺 (De-burring)

去除毛刺的方法包括锉、钢丝刷清理、砂带磨削、磨料喷流。量产的除毛刺工艺包括滚筒光磨、振动研磨等。自动化的工艺能使表面光整加工的质素更稳定可靠。

抛光工艺是一个效率较低的工艺，不宜用于除毛刺；选用粗糙抛光轮除毛刺会使工件的尖角被大量磨蚀，令工件变形。可考虑采用砂纸磨工艺去除毛刺。

4.3. 除氧化层

热处理后的工件表面可能有厚厚的氧化层，可按其厚度及硬度选择合适的磨削或打磨抛光工序去除氧化层。热处理过的表面成份可能有变，也需考虑是否需要磨掉。热加工后的结晶粒度、防腐蚀性都可能被改变了，亦需注意。

很多金属氧化物都金属本身坚硬，不容易磨蚀，应选择砂带磨等高效率磨削工艺去除氧化物。磨砂轮可用于又硬又厚的氧

化物，既可省时，又可省去耗费大量的磨砂纸，减低加工成本。

氧化层除掉后，必须彻底清理所有残留的氧化物碎屑，避免坚硬的氧化物刮花金属表面。

表 4.1　使用不同级别的研磨料磨削氧化层

工艺		研磨料改级别
剥皮		12-20
切削	**重**	24-40
	中	50-80
	轻	100-150
整光		180-240
打磨		280-600

应使用不同级别的研磨料来去除氧化层。表 4.1 简列了砂带磨机上的研磨料选择。砂带磨的刮痕较深，建议使用砂纸磨去除这些粗糙刮痕。

4.4.　砂纸磨 (Sanding)

经过机械加工、成形、清除氧化层后，应估计塑性变形层的厚度，然后选择合适的砂纸磨作进一步的光整加工。要得到高品质和耐用的金属表面，便需要完全磨掉切变变形层 (D_s)；若所有塑性变形层都都被磨走，表工件的防腐性能便会更好。表 3.7 及 3.8 简列了塑性变形层的厚度。

研磨料的颗粒越粗糙，SiC 砂纸的磨蚀速率便越高；但研究却发现现磨蚀速率最高的是 150 至 P240 级 SiC 砂纸。 P240 或更幼细 (egP600) 的磨砂纸被分类为微网类，比 P200 级所选用的砂粒不但更小，粒度分布也更窄，有助于磨蚀出更均匀的刮痕。因此必须选用 P240 级以上的磨砂纸打磨。

要用磨砂纸做出打磨的细纹效果，压力要保持在 20kPa 至 40kPa 之间。过高的压力使刮痕又阔又深，亦加快砂纸的消耗；压力太低令磨蚀效率降低。表 3.4 提供了圆形工件砂纸磨需用力度的对算表以供叁考。

使用 P240 砂纸磨时，加载压力为 40kPa，并用流动清水作冷却润滑剂，所得的磨蚀速率约为为 ~0.8μm/m 。若缺乏润滑剂，工件可能会产生过热而损坏磨砂纸。要磨蚀 50μm 的切变变形层，磨蚀距离为 62.5m。使用圆周 0.5m 的磨轮时，假定转速为 1000rpm，磨轮每分钟运行 500m，运行 62.5m 将塑性变形层只需 7.5 秒。

磨蚀速率与压力的平方根约成正比。当压力倍增时 (2)，磨蚀速率会增加 $\sqrt{2}$（即约 1.4)。当压力减半时 (0.5)，磨蚀速率会只得 70%。

表 4.2　磨蚀塑性变形层 (Cu-30%Zn)

工艺	**磨蚀速率 (μm/m)**	**前工序**	**前工序产生之 $_{Ds}$ 切变变形层 (μm)**	**需磨蚀距离 (m)**	**估计所需磨蚀时间 * (sec.)**
P240 SiC	0.8	机械表面磨削	50	62.5	7.5
P800SiC	0.4	P240 SiC	9	22.5	2.7
P1200SiC	0.25	P800 SiC	5	20	2.4
P2500SiC	0.1	P1200 SiC	4	40	4.8
6μm 金刚石研磨	~0.05	P2500 SiC	3	60	7.2
1μm 金刚石研磨	<0.01	6μm 金刚石打磨	~1	>100	>12

** 磨轮速度 = 500m/min, 压力 =40kPa, HV45*

P240 SiC 砂纸磨削新形成的切变变形层 D_s 约 ~7μm，加上刮痕深度约 2μm，下一工序便需磨掉 9μm 的的物料。若使用 P800 级 SiC 磨砂纸，磨蚀速率约 ~0.4μm/m，所需磨蚀距离为 22.5m。以同类磨轮打磨，约需时 2.7sec。留下的刮痕约 0.7μm 阔，切变变形层约 4μm 厚。

可以继续用 P1200 或更幼细的 SiC 砂纸打磨表面，直至获得所需的光整效果。提高磨轮速度可缩短磨蚀时间，但可能使工件和磨砂纸过热，必须小心考虑。

若磨蚀速率加快十倍，磨蚀时间可能过短而难于准确控制。磨蚀速率与工件硬度约成反比。打磨较硬的材料时，应增加磨蚀压力或磨轮速度，并要确保有适当和充足的冷却润滑剂。表 4.2 简列了一个打磨工序的叁数推算表以作叁考。若整层塑性变形层必须磨掉，所需磨蚀时间便要倍增。

4.5.　研磨 (Lapping)

研磨的主要目的是按研磨模具制造尺寸精准的光亮表面，模具的形状可以是平面或弯曲面。研磨过程很慢，所用压力要较低，要将工件轻压在模具上，模具与工件间加入研磨料，也可放上薄而的绒布。

砂纸磨利用刮削除掉磨削所引起的粗刮痕，取而代之的是幼细的学刮痕。研磨和抛光的效果比砂纸磨轻柔，应用于磨削与砂纸磨之后，避免使用粗抛光，减少工因抛光而导致的变形。研磨适用于制造尺寸精确和高光整度的工件，抛光则只能制造高光整度的工件。

研磨料混合在黏结剂里，黏结剂可以是水、油、油脂、蜡或水溶制剂。黏结剂的作用包括减低研磨料的流失浪费、保持分布均匀、避免研磨料过份黏结和使研磨料能轻轻附在工件或绒布上。

表 4.3(a)　不同表面加工工序所用之磨料及工具

工序	磨轮 / 带	研磨料	研磨料黏附强度
磨削	坚硬	黏附在磨削轮上	高
砂磨带，砂磨纸	柔韧易弯	黏附在研磨料带上	低
研磨	带柔软外层之硬轮	没有黏附	松散
抛光	柔韧易弯	没有黏附	松散

研磨工序一般较为昂贵缓慢，不适应于大批量生产，一般钟表制造业不会采用。机械抛光通常被采纳为光整加工的最后加工工序，但缺点是容易令工件失去精确度。

研磨与抛光能使表面粗糙度 Ra 降低至 0.4-0.05 μm。使用粗研磨料当然会使表面粗糙，因此必须小心选择研磨料。表 4.3(a)&(b) 列举了一些常用的表面加工工艺与其光整度的关系。

4.6.　抛光 (Buffing)

抛光的工作原理与研磨差不多，都是理用自由松散的研磨料随机地滚动磨平工件。抛光过程没有坚硬的模具，研磨料被涂于轻柔的转轮上。动物油脂是常用的黏结剂和扩散剂，用不同级别的研磨料颗粒抛光可达至不同质素的表面光整度。

表 4.3(b)　表面加工的光整度和尺寸精度

	研磨料颗粒	研磨料黏附力	光整度	尺寸精度
磨削	粗糙	高	不良	粗糙
打磨	中等	低	良好	良好
研磨	幼细	松散	优越	优越
抛光	幼细	松散	优越	变形

适当的抛可使表面光亮如镜。研磨料随机地、轻柔地刮磨工件表面是高品质镜面成形的主因。重点如下：

(1) 柔韧易弯的抛光轮限制了刮磨压力，使刮痕又浅又细，减少漫射光的比例；

(2) 软抛光轮随机摆动，使刮痕更平均分布；

(3) 金属碎屑被吹走，减少所造成的花痕；

(4) 抛光亮绒毛柔软，不容易加深原有刮痕，使表面平滑。

表 4.4 列举了几种常用的抛光技术。

表 4.4　常用抛光技术

	目标	**抛光剂 / 轮**	**光整度**
硬抛光	切削为主、打磨	硬抛光轮、粗研磨料、快速	平滑 与 半光泽
接触抛光	自动化	硬抛光轮、粗研磨料、快速	平滑 与 半光泽
光泽抛光	幼细	软抛光轮、幼研磨料、慢速	光亮如镜
磨菇抛光	自动化、 慢速、比接触抛光光滑	软抛光轮、幼研磨料、慢速	光亮如镜

下列因素对抛光结果有重要影响：

1. 抛光轮的硬度 (柔软度)
2. 抛光剂 (蜡、研磨料)
3. 抛光压力
4. 抛光速度
5. 抛光时间

硬抛光轮的削磨速率较高，若压力过高使工件线条变得模糊，应使用合适的压力；但准确控制压力不易，所以一般不会使用硬抛光轮作最后的抛光。另外，也可将抛光轮削切成特定形状，使抛光制品尺寸较精准。

使用柔软的抛光轮及幼细抛光剂可制成光滑镜面，易弯曲的、松散的布质抛光轮都能使表面更光滑。不过，代价是抛光速度慢，不适用于磨削加工或去毛刺、磨蚀塑性变形层。

切削抛光：　切削抛光目的是要把材料磨掉，要将工件逆向推向抛光轮，同时加大压力，提高抛光速率，结果可制成半光亮平面。

色泽抛光：　减低压力，并将工件顺著抛光轮转动方向移走，可造成更闪亮抛光表面。

抛光前先用 P600 至 P1000 级砂纸磨将表面磨平效会更好更有效率，因为砂纸磨削的速度比较快，也较少令线条模糊。当然，若工件没有细线条，接触抛光还可接受。

抛光剂 (蜡) 用油脂将研磨料黏牢。抛光剂是**润滑剂**、**冷却剂**、也是扩散剂，研磨料负责刮磨，而油脂黏结剂则不侵蚀工件及具。脂肪酸与润湿剂都是抛光剂内的主要成份。抛光剂必须在电镀前彻底清除。

抛光剂应随著抛光时温度上升而融化，瞬间变成液态油剂，让研磨粒能较自由游动；当抛光摩擦停止，**抛光剂**很快风冷凝固。抛光剂的适当温度与黏稠度对抛光质影响重大。

表 4.5　常用抛光剂 (蜡)

颜色	**成份与应用**
黑	石榴石、粗研磨料用作削磨 (磨蚀) 及除掉刮痕、硬抛光用
棕	Tripoli/ 二氧化硅、中级粗磨、一般**削磨抛光至色泽抛光用**、用于软金属和塑料
绿	绿色氧化铬粉粒、用于**不锈钢光泽**抛光、也可用于塑料、黄铜、铝、镍与铬、被认为是最全面的抛光剂
白	白色方解石 (calcite)、氧化铝、幼细研磨料、用作小量削磨、通常用于铬、镍、不锈钢与普通钢材的色泽**抛光**
红	珠宝商用的红蜡、红色的氧化铁、用于金、银、镍与贵金属的抛光、配合松散软绒布轮使用、超平滑光泽抛光表面、让金属微红反光
蓝	较乾身、不含油脂、用途与红蜡相同、适用于大部份材料包括塑胶和木、使用白蜡后使用

黏结剂黏稠度过高时，研磨料不能平均扩散，在工件表面刮磨出密集刮痕，形成低质素光整效果。若黏结剂黏稠度过低，研磨粒锐流向磨轮外围并飞脱，造成浪费。抛光剂以颜色分类，用途各有不同。表 4.5 列举常用的抛光剂，表 4.6 按粗幼度列出各抛光剂的用途。

表 4.6　按粗幼度列出各抛光剂的用途

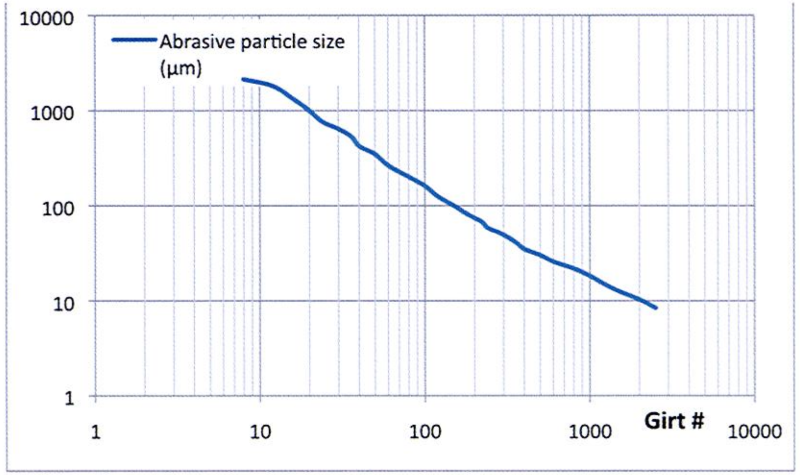
用途	
削磨	黑，棕
抛光	灰
色泽抛光	黄，白，绿
超幼细抛光	蓝，红 (1-5 μ m)

抛光剂的幼细度取决于所含研磨料的颗粒大小。不同供应商虽然使用同一颜色白代号，但质素不一，必须测试使用后才大批量使用。表 4.7 及图 4.1 提供了研磨颗粒的应用资料。

表 4.7　常用抛光剂所含研磨料的不同用途

用途	**相对粗幼度**	**Grit #**	**颗粒直径 (μ m)**	**粗糙度 (~Ra μ m)**
粗削磨	粗糙	8-24	800-2000	--
削磨	平坦	30-60	250-650	>3.5
预打磨	平顺	70-180	80-230	0.5-3.5
砂纸磨	光滑	220-1200	15-68	0.1-0.5
研磨与抛光	镜面	>1200	<15	<0.1

图 4.1　研磨料 Grit 与颗粒直径的关系



抛光时不要将过多的抛光剂涂在抛光轮上。使用过多的棕色抛光剂，会使抛光剂积聚在抛光轮和工件上，结果是要花功夫去除抛光剂，否则残馀的抛光剂会导致局部位置留有粗糙刮纹。

4.7.　清除抛光剂

残馀在工件表面的抛光剂，可使用除蜡水清理。除蜡水内含表面表面活化剂、清洁剂、乳化剂和水；通常要在 80°C 高温才能发挥去除抛光剂的工效，但必需按照供应商的温度使用。

若粗抛光可以用幼磨砂纸取代，便可省却一次除蜡的工序。选择容易清除的抛光剂也可提高效率。况且错误地白使用粗抛光会引至不必要的工件变形。

若工件还需继续表面加工，除蜡便是一个麻烦但必须的工序。若不需再加工，可以涂上蜡层防止氧化，对铜合金来说，这是非常重要的。过量的抛光剂当然要去除，但却不一定要百分百去除；因为抛光剂内的油脂本身就是一层好的防护膜。但必须确保抛光剂内不含腐蚀成份。

以下是一般的除蜡程序：

1. 按产品说明稀释除蜡水
2. 按指示提升除蜡水温度
3. 开动搞拌器
4. 用超声波让除蜡水内气泡 10 分钟
5. 将工件放于除蜡水内
6. 用清水彻底清洗工件
7. 烘乾或吹乾工

不少除蜡水是轻微酸性或轻微硷性的，因此必须于以上步骤 6 先中和除蜡水，然再彻底清洗。若清洗不完善，工件便会被侵蚀，降低产品质素。使用于不锈钢的除蜡水不一一定适用于铜合金，所以必须小心选择否则会在铜合金表面留下瑕疵。抛光后的工件，可以用高温蒸气、碳酸钙或白粉笔清洁。

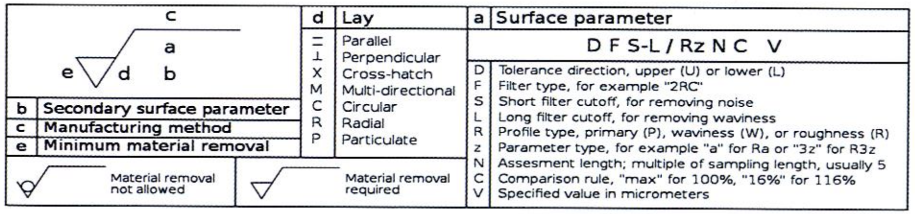
乙部：技术篇

第五章

5. 选择砂磨抛光工具

5.1. 光整加工的规

光整加工的规格需清楚订明于合约内。可叁考 ASME Y14.36M or ISO 1302 标准。



b	Secondary surface parameter
c	Manufacturing method
e	Minimum material removal

d	Lay
=	Parallel
⊥	Perpendicular
X	Cross-hatch
M	Multi-directional
C	Circular
R	Radial
P	Particulate

a	Surface parameter
	D F S-L / Rz N C V
D	Tolerance direction, upper (U) or lower (L)
F	Filter type, for example "2RC"
S	Short filter cutoff, for removing noise
L	Long filter cutoff, for removing waviness
R	Profile type, primary (P), waviness (W), or roughness (R)
z	Parameter type, for example "a" for Ra or "3z" for R3z
N	Assesment length; multiple of sampling length, usually 5
C	Comparison rule, "max" for 100%, "16%" for 116%
V	Specified value in micrometers

表面加工的规格，可以通过检视不同的表面特徵来订定标准，包括粗糙度、花纹 (lay)、波纹 (waviness) 和缺陷 (flaws) 的特性：

粗糙度最常用 Ra 叁数 (平均刮痕深度波幅叁数) 来表达，可叁考本手册 3.1 节。

花纹包括不同的磨痕方向交织所组成的图案，可以是垂直的、水平的、幅射状的、交叉线画的、圆形的、迷向的等多种类变化，是通过不同的打磨表面处理而成。

波浪纹幅度是指表面高低不平的特性，会使所反射的影像变形，是肉眼能见的表面不平滑缺陷。主要成因是过度抛光或工件振荡所引起。

缺陷包括表面裂痕、微小凹陷、局部的粗刮痕等加工缺陷。此外，还可以表 5.1 的方式分类

表 5.1　常用的钢材表面特性标准

未经打磨表面	加工工艺
未经打磨表面	
1a	热轧 + 退火 + 除氧化层
2D	光亮的冷轧 + 退火 + 除氧化层
2B	光亮冷轧 + 最后磨光滚轮冷轧
2BA	冷轧 + 光亮退火 (真空或保护气氛) + 最后精磨光滚轮冷轧 (建筑材料用)
经打磨表面	
3	100 网级 (~150 μ m) 研磨料磨削
4	120-150 网级 (~105-125 μ m) 研磨料磨削 (厨具)
6	将经 4 号表面处理表面用研磨料与油再钢丝擦擦处理、表面比 4 号稍逊
7	初步打磨处，稍作抛光，表面仍留有刮痕 (建筑材料用)
8	精磨与抛光、镜面效果

同一打磨工艺可达至不同的光整度，受到加工条件的影响。表 5.2 列举了部份工艺可达至的光整度效果，一般以粗糙度 Ra 表示。使用幼细的磨砂纸，可得到非常光滑的表面。表 4.2 与表 5.3 简列砂纸磨与 Ra 的对比作参考。

表 5.2　不同工艺可达至的光整度 a(粗糙度 Ra, μ m)

Ra (μ m)	50	25	12.5	6.3	3.2	1.6	.8	.4	.2	.1	0.05	0.025
铸造												
砂模铸造		■	■									
Investment casting					■	■						
die						■	■					
成形												
热轧		■	■									
锻造			■	■	■							
冷轧					■	■	■					
burnish								■	■			
金属切削												
sawing		■	■	■	■	■						
drilling			■	■	■	■						
milling				■	■	■	■					
turning				■	■	■	■	■				
磨蚀												
磨削						■	■	■	■	■		
滚筒磨							■	■	■			
砂磨								■	■	■	@	
抛光								■	■	■	■	@
研磨								■	■	■	■	@

@ 当小心使用超幼细研磨料作砂纸磨、研磨与抛光，可达至更光滑表面。

表 5.3　砂纸研磨料与粗糙度的关系

研磨料 grit	**平均粗糙度，Ra（μm）**
500	0.1-0.25
320	0.15-0.38
240	0.2-0.51
180	<0.64
120	<1.14
60	<3.56

P500 级的磨砂粒只会留下 Ra0.2μm 的刮痕，但仍不能制造镜面反射。这些磨削工艺所造成的刮痕虽然肉眼不能分辨，但却分布不匀，影响反光度反射影像质素。平面的波浪纹决定了镜面的质素。表 5.4 总结了一些工艺所能得出的效果。

表 5.4　砂磨带表面加工效果

工艺	**磨砂料**	**加工状态 / 效果**
脱皮	12-20	除氧化层
粗切割	24-40	磨蚀速率高
一般切割	50-80	一般磨蚀速率、达至平面
花纹	100-240	已达一般尺寸精度
表面平整	180-240	可作表面电镀
打磨	280-600	光滑表面，可作 CVD 、PVD、抛光国处理
抛光		镜面

5.2.　磨砂轮与抛光轮

砂纸磨与抛光工艺都需使用工具桌、高速电动轮等。电动轮必须固定减少振动，速度稳定和马力充足，轮轴越短越稳定，但加工时可能变得不方便。振动是打磨抛光的致命用伤，必须小心处理。

也可考虑使用磨砂带。使用砂带磨有以下优点：

- 磨蚀速率高
- 不需平衡磨轮
- 砂带面积大、可作大量加工
- 容易使用
- 设备简单

砂带磨特别适用于大面积磨削，选用较幼细研磨料砂带，也可生产高质量产品。不过，砂带的最大优点还是效率。

磨蚀速率为于 30m/s 下与砂磨轮速度成正比，常用砂磨速度为 18-40m/s，快速削磨时速度为 30-40m/s。砂磨软合金应用慢速 (18-20m/s)。速度越慢，质素越高。

磨速与磨轮直径成正比，直径越大，磨速越高，砂磨速率越快。但过大的磨轮会使磨轮失平衡及振动，影响打磨质素。砂纸磨的优点是可以在同一磨轮上运用不同直径打磨，得出不同的磨蚀速率和打磨质素，但需要仔细陪训砂技术人员。

表 5.5　砂磨速度与砂磨轮直径的关系（两种不同转速的）

砂磨直径		圆周 (m)	磨速 (m/s)	
英寸	**mm**		**2000 rpm**	**3000 rpm**
4	102	0.32	11	*16*
6	152	0.48	*16*	*24*
8	203	0.64	*21*	*32*
10	254	0.80	*27*	40
12	305	0.96	*32*	48
14	356	1.12	37	56
16	406	1.28	43	64

rpm 每分钟转数

磨速越低，质素越好。表 5.5 提供了砂磨速度与砂磨轮直径的关系以作参考。2000rpm 的磨轮一般已经足够，高磨速如 40m/s 容易引至过热，因此要小心使用。高抛光速度会提升工件温度，甚至热坏抛光剂，要小心处理，更不应用高速抛磨塑胶。

可选择使用砂纸磨的边缘砂磨，将可黏贴的砂纸带黏在磨轮圆周，然后砂磨，优点是磨速保持高速而不变，品质只受压力、温度、时间和技工力度的稳定性所控制，可以比较稳定。

磨轮必须马力足够，在压力下速度保持不变。不稳定的或磨速会出现磨蚀不均的波浪纹现像。表 5.6 列举了一些选择磨轮马达的建议。

表 5.6　选择磨轮马达

砂磨直径	**英寸**					**mm**				
	4	6	8	10	12	10	7.5	20	25	30
马力 H.P.	**最大容许磨轮厚度（边缘）**									
	英寸					**mm**				
1/8	0.5	x	x	x	x	15	x	x	x	x
1/6	1	0.5	x	x	x	25	15	x	x	x
1/4	1.5	1	0.5	x	x	40	25	15	x	x
1/3	2.5	2	1	0.5	x	65	50	25	15	x
1/2	3.5	2.5	2	1	0.5	90	65	50	25	15
3/4	5	3.5	2.5	2	1	125	90	65	50	25
2	9	6	4.5	3	1.5	230	150	115	75	40

**1 H.P. = 746W 输出，　x = 马力不足*

必须选用马力足够的马达作砂纸磨。1/8H.P. 通常已足够，重点是转不会过快而磨坏工件，1200-1800rpm 已经足够；至于马力不足的问题，只要不用过大的力度便可。况且，慢速和低压力都是质素的保证。若摩擦力过高，可考虑使石蜡作润滑剂。

5.3. 抛光轮 s selection 与 usage

抛光轮的选择则可考虑以下建议

1. 使用 30mm 直径可变速抛光轮作磨削抛光
2. 使用 20mm 直径中度柔软抛光轮作初步抛光、去除刮痕
3. 使用 10mm 直径中度柔抛光轮作色泽抛光

尽可能减少使用多抛光轮和抛光剂，这样便可以减少除蜡工序的次数，提高生产力。抛光是一个需要技术工人操作的工艺，要技巧地使用同一抛光轮作磨削抛光和色泽抛光，便可提高质素，又同时减省成本。抛光的效率与质素，受以下因素影响：

1. 抛光轮的密度、硬度(越柔软越好、但越慢)
2. 抛光轮的平衡度越高越好
3. 压力越低质素越好、但速度慢
4. 轮速越慢质素越高、但效率低
5. 研磨料越幼细越好，但较昂贵

选择抛光轮可叁考下列原则：

1. 硬轮用于硬材料，软轮用于软材料
2. 硬轮用作磨削抛光，软轮用作光泽抛光
3. 柔软幼细的抛光轮使质量更高
4. 使用同一抛光轮作二步软抛光(磨削 + 色泽)，提高效率

常用的抛光轮简列于表 5.7。

表 5.7　抛光轮的不同应用范围

抛光轮	**磨削**	**色泽**	**简述**
翼片轮	粗	无效	含磨砂粒的砂纸，用作除氧化层
尼龙轮	粗	无效	用作除氧化层、木材
洗擦轮	粗	无效	含研磨料的柔软接触木抛光轮、快速磨削
指轮	粗至幼	无效	用于不规则形状、薄片
麻质	粗	低	硬轮用于粗糙前期磨削、质素低、变形量大、用作除氧化层
螺旋日连结	粗	无效	初步粗抛光
螺旋牛仔布	粗	无效	较棉质在轮耐用
透气轮	中速	中度	细磨、不易扇过热
软垫轮	慢速	幼细	精抛光
松散绵布	慢速	幼细	精抛光
软垫轮	无效	幼细	不规则形状抛光
软棉花轮	无效	幼细	平面抛光、铝合金用
软棉布轮	无效	超幼细	幼细抛光
绳丝轮	无效	超幼细	幼细抛光、塑料用
绒球	中速	中度	不规则形状
绒布	无效	超幼细	不规则形状

抛光时应注意以下程序：

1. 先砂磨至 P600-P1000 级然后抛光
2. 只使用少量抛光剂，轻涂于转动中的抛光轮上(约 1 秒)，数秒后才抛光
3. 紧握工件
4. 使用最低的压力，若抛光轮减慢，再减低压力
5. 抛光塑料时使用低压慢速
6. 把工件慢慢左右摇晃，使抛光更均匀
7. 将工件逆向移动，加快磨蚀(磨削抛光)

8. 将工件顺向抽离，做出色泽抛光效果
9. 经常清洁抛光轮，耙走积聚的抛光剂，用刀剪齐抛光轮
10. 用压缩气流吹走碎屑，重新加添抛光剂
11. 若抛光轮直径太小，更换抛光轮
12. 使用同抛光剂于大小不同、硬度不同的抛光轮上，减少清洗抛光剂的需要
13. 每一抛光工人只用种抛光剂、每一抛光轮只用种抛光剂
14. 曾用作粗糙抛光的抛光轮不能用作幼细的抛光，除非已彻底清除碎屑
15. 用直径大但柔软的抛光轮提高抛光效率，品质还可以
16. 除蜡
17. 若需进一步抛光，用更幼细抛光轮重复步骤 2 加工
18. 已镀上涂层工件只稍色泽抛光
19. 彻底清洗工件
20. 烘乾工件
21. 上蜡（如需要）及包装

5.4. 选择抛光剂

最好只选用一种抛光剂，减低除蜡的需要。只需轻涂小量的抛光剂于抛光轮上便足够。摩擦所产生的热力已能融化抛光剂，不必使用水和其他热力使之软化。表 5.8 列举了选择抛光剂的建议，以供叁考。蓝色抛光剂不含油脂，较容易清洗。

表 5.8　选择抛光剂

	粗糙 ← 抛光剂→ 幼细					
材料	**黑**	**棕 Tripoli**	**白**	**绿（不锈钢）**	**红**	**蓝**
丙烯酸树脂 PMMA						X
Ni,Cr 膜					X	X
白金			X	X		X
硬胶		X				X
木料		X				X
热固树脂		X	X		X	X
银		X	X			X
金		X	X		X	X
黄铜，铜片		X	X		X	X
锡	X	X			X	X
铁	X			X		X
镍	X			X		X
钢	X			X		X
铝	X	X	X	X		X
铜	X	X	X	X	X	X
黄铜	X	X	X	X	X	X
不锈钢	X	X	X	X		X

无油蓝色抛光剂适用于多种的用途

若真的需要使用不同的抛光剂提高磨削效率，可叁考以下的抛光三步骤：

第 1 步：　粗糙磨削

第 2 步：　磨削抛光 与 预打磨抛光

第 3 步：　色泽抛光

每一步可再分开运用 (A) 接触抛光与 (B) 色泽抛光来提高效率。抛光剂密封并储存于凉快的地方。表 5.9 是对三步抛光法的一些建议。

表 5.9　选择抛光剂的指引

材料	**塑胶**			**Al, Ag, Au 及薄片**			**Ni 及 Cr 薄片**			**Cu, 黄铜，及软金属**			**钢铁**			**不锈钢**		
步骤	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
抛光轮																		
麻轮										x			x			x		
螺旋连结								x			x			x			x	
松散绵布												x			x			x
绒布轮						x			x									
绳丝轮	x	x	x															
抛光剂																		
黑										x			x			x		
棕											x							
白								x				x		x				
绿																		
蓝	x	x	x			x			x						x		x	x
红						x			x						x			

5.5.　砂纸磨与抛光叁数：力度、温度与时间

砂纸磨时必须选用适当的润滑剂和冷却剂，以确保不会过热。建议压力为 20-40kPa。选用水、煤油或其他润滑液不单可降低温度，更能使研磨料分布均匀，比乾磨优胜。表 5.10 简列了不同工件大小所需力度。

用硬抛光轮粗抛光所用的压力和砂纸磨基本相同。精细抛光时选用柔软易弯布轮，压力不可能提升很多，所以压力调控不重要，反而温度控制才重要。高压引至高温，会在工件上烧出黑纹，其实是烧坏了的抛光剂。抛光力度越低越好。

表 5.10　工件面积与砂磨及抛光力度对算表 (压力 :20-40kPa)

		砂磨 / 抛光压力			
正方形工件		**20kPa**	**40kPa**	**20kPa**	**40kPa**
边长 (mm)	**面积 (mm^2)**	**kgf**	**kgf**	**lb**	**lb**
1	1	0.002	0.004	0.0009	0.002
5	25	0.051	0.10	0.023	0.046
10	100	0.20	0.41	0.093	0.19
1	1	0.002	0.004	0.0009	0.002
40	1600	3.26	6.52	1.48	2.97
100	10000	20.4	40.8	9.27	18.5

一般表面抛光用作光整平面，抛光轮不会触及凹陷位置。常用转速为 1500rpm。工件不应陷入软抛光轮超 10mm，以确保平均抛光。

磨菇抛光适用于复杂形状。使用的磨菇抛光轮非常柔软，不会磨走仔细线条。轮速应低 1200rpm，直径越大越好，让工件能被推进松软的磨菇轮 15-40mm 内。

连续长时间抛光会导致过热。抛光时间般只应于 10 秒内完成，若仍要继续抛光，应先工件冷却后再进行。长时间、高压力抛光也会因技工疲劳而导致质素下降。因此，要好好设计抛光工序。

5.6. 夹具

适当地运用简单的夹具，可减低对技工工艺的依赖，使抛光打磨品质更高更稳定。当中主要原因是更能准确地控制压力和角度，只馀下打磨时间这一因素由技工控制，序变得简单容易，错误也可大大减低。

夹具可让工件直线移动或自转，让不同部份都获得足够的打磨，用于砂纸磨时更可确保尺寸的精准度，亦减少工件振动所引起的问题。砂纸磨和抛光时使用夹具，也使整套打磨工序的数据更详尽，方便进一步进行自动化打磨。

5.7. 砂纸磨与抛光前后的处理

磨削用的润滑冷却液，通常都会影响砂纸磨和抛光的质素和效率因此必须彻底清除；应考虑使用无油或水溶磨削液以便清理。同理，应使用无油砂纸磨润滑剂和抛光剂。

大多磨砂纸都能防水，可选用清水为砂磨液，让流动清水带走碎屑，成本较低又环保。加入少小少量氨水可减低腐蚀机会；相反，加入小量微酸可加快研磨速率，但必须确保彻底清洗乾净，没有留下碎屑和酸性液体。砂纸磨后的工件比较容易清洗，若有凹陷位置，应利用水流带走所有杂质，并中和清洗液，然后烘乾。

抛光后清洗比较困难，可叁考本手册 4.7 节处理。抛光时产生的黑纹，可能是高温分解了的抛光剂，不容易清除；可尝试机械抛光移除。

乙部：技术篇

第六章

6. 打磨的缺陷：杂质、刮痕

材料的缺陷可源于不良的冶炼、铸造、成形、锻造、轧链、分末冶金等工艺，机械加工也会增加缺陷。内部缺陷分布于工件的每一部份，不能轻易用打磨及表面处理去移除。局部的表面缺陷有机会藉表面处理移除或掩饰。

6.1. 内部缺陷

局部的内部表面缺陷，可用磨削除掉。这些缺陷不少是早于铸造时已存在，或后期错误加工而形成，问题不能在最后的加时有效处理。以下为部份常见内部缺陷：

1. 成份分布不均 (Segregation)
2. 孔洞
3. 收缩变形
4. 杂质
5. 收缩孔与冷收缩拉裂
6. 裂纹

7. 残馀应力
8. 含氧量过高（如钛合金）
9. …

成形与加工时也会产生缺陷，包括：

1. 裂纹（锻造、冷轧）
2. 层离 (e.g. 因杂质所引起变形）
3. 氢脆化
4. 挤压裂纹
5. 深冲皱褶
6. 高热影响区（焊接缺陷）
7. 速冷裂纹
8. …

6.2. 表面缺陷

部份表面缺陷可以用磨削或粗砂磨除去。若这些缺陷不移除，将会影响表面光整度。以下为一些常见表面缺陷：

1. 表面铸造气泡、砂眼
2. 热轧引入氧化物杂质 (Laps, feather like laps, oxide inclusion)
3. 热轧引入金属 (Seams, scabs)
4. 挤压引至裂纹 (Hot tears)
5. 热加工时气泡膨胀 (Blisters)
6. 大颗粒所引至的橘子纹
7. 烧痕（加工温度过高）

6.3. 研磨与抛光所造成的缺陷

以下是部份打磨过程中常见的缺陷，缺陷的详细分类和论述，可叁考 BS EN ISO 8785: 1999 “Geometrical product specification (GPS), Surface imperfections, Terms, definitions and parameters” .

6.3.1. 橘子皮纹 (橙皮纹)

橘子纹效应成因为工件果颗粒粗大 (>50 μ m)。因不同颗粒或金属相硬度有别，产生不平均磨蚀现像，外表好像橘子皮。当抛光时间过长或压力过高时，此现像不更为明显。

6.3.2. 模糊 (Haze)

模糊的表面可能是抛光剂与金属起化学反应并产生薄薄的氧化层而生。可选用 pH 度中性的抛光剂，降低抛光压力也可减低模糊度。

6.3.3. 点蚀 (Pitting)

点蚀是很多小孔出现于金属表面。成因是金属被外来化学品污染侵蚀，或被抛光剂侵蚀所造成。应使用不会侵蚀金属的抛光剂和清洗液，工件必须彻底清洗中和才烘乾，并保存在乾爽的环境里。

6.3.4. 不均 (Relief)

不均匀的材料特性，成因可能是成份不均、积构不同、晶体相结构不同所引至。不同的硬度令磨蚀速率有异，使用硬抛光能减低此现像。软抛光时间不可过长。

6.3.5. 边沿效应 (Edge effect)

边沿的磨蚀速率特快，导致边沿快速凹陷。应使用较平较硬的磨轮轮，减低压力和缩短打磨时间，只用软抛光轮作色泽抛光。

6.3.6. 波浪纹 (Waviness)

波浪纹是 mm 至 μ m 级的不平坦表面，肉眼能容易看见。成因包括抛光压力不稳定，研磨料分布不均，或抛光轮过份摆动等。

6.3.7. 坑纹 (Grooves)

坑纹是平衡的线纹，比平均粗糙度 Ra 深。坑纹不一定和抛光方向相同，但却与砂纸磨或粗抛光的方向相同，源于上一磨削工序的的塑性变形层未被完全磨掉这通常表示砂纸磨的研磨料颗粒过大，或粗磨的压力过高。

6.3.8. 裂痕 (Cracks)

裂痕般不是错误打磨工艺的结果。裂纹应该是铸造、冷轧、热处理、快速冷却等加工工艺出错所带来的后果，此类缺陷不能藉打磨改善。

6.3.9. 拉孔 (Pull out holes)

打孔不规则地分布于金属内。成因是金属本身含有很多非金属杂质、氧化物或碳化物等，打磨抛光时被拉出成为凹孔，继续抛光时凹孔再被扩大。降低打磨抛光压力可减少杂质被拉出，使用不否氟化物的抛光剂于钢材亦可减低问题的严重性，转用更均匀的材料才能根本解决问题。

6.3.10. 磨峰 (Peaks)

磨峰是不平均的高点。成因是高磨削或抛光压力下的不平均磨蚀速度。使用低而低的磨削抛光压力可减轻问题的严重性，亦可改用黏稠度更高的研磨液。

6.3.11. 彗星尾巴 (Comet tails)

因杂质被拉出而形成形孔洞，继续研磨或抛光时便在孔洞后形成彗星尾巴。快的抛光速度可减少彗星尾巴的严重性。

6.3.12. 污染物 (Foreign material)

外来污染物的存在是因抛光时前后没有把工件清洁好，抛光又未能把污染物移除。

6.3.13. 腐蚀 (Corrosion)

腐蚀是工件未被彻底清洁的后果。用清洁后没有完全烘乾工件也会带来这类问题。打磨工作间和储藏室个度潮湿也是成因。

6.3.14. 烧痕 (Burn marks)

烧痕因抛光温度过高而成。因抛光压力高而引至摩擦力太大，工件温度大复上升。抛光剂不足、砂磨冷却剂不足、过长抛磨时间都可能是成因。可减低抛光压力、使用通气 (vented) 或更柔软有弹性的抛光轮可解决。

6.3.15. 退色 (Discoloration)

退色现像是局部位置受化学品侵蚀的结果。

6.3.16. 狐尾巴 (Foxtail)

狐尾巴成因为位于工件边沿的不规则或孔洞所引至。是在边沿的彗星尾巴。边沿的不规则应先用除毛刺的方法先除掉。

6.3.17. 不当抛光程序

不当的抛光行为包括：

- *使用太多抛光剂：*
  - 太量抛光剂积聚于某处
  - 需要很长的除蜡工序
  - 很厚的抛光剂残留工件表面
  - 抛光留下黑纹
- *抛光剂含侵蚀性黏结剂*
  - 表面被侵蚀露出微观结构 (e.g. 橘子纹)

- *砂磨太粗糙，未及 grit #P 600 而进行抛光*
    - 抛光时间过长
    - 磨削与机械加工磨削刮痕不能藉抛光除去
    - 长时间抛光令工件幼细线条被除去

- *砂磨压力过高*
    - 明砂磨刮痕不易被磨掉
    - 砂磨刮痕不能藉抛光除去

6.3.18. 错误的除蜡程序

错误的除蜡（抛光剂）程序

- *除蜡水温度过高：*
    - 金属被侵蚀
    - 晶界被显露、不同晶粒或不同相被侵蚀显露 (e.g. 橘子皮纹）
    - 除蜡水被分解、除蜡能力下降

- *除蜡水温度过低：*
    - 除蜡水混沌不清
    - 除蜡能力下降

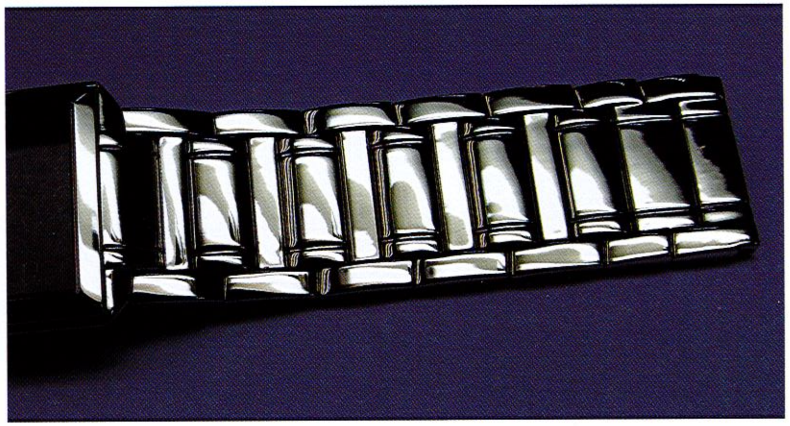
- *除蜡水浓度太低：*
    - 除蜡能力低
    - 清洁时很长

6.4. 个按分析

6.4.1. 波浪纹

图 6.1 显示一已抛光的表带。抛光未能制造镜面效果，波浪纹平衡于抛光方向，有大量的线条被磨削掉，所有边沿都磨钝了。

图 6.1　抛光后表面出现波浪纹（由麦世枝先生提供）



<u>成因：</u>

- 抛光前砂磨不足
- 过量粗抛光
- 抛光压力过高
- 抛光轮不清洁，研磨料与黏结剂积聚在抛光轮上

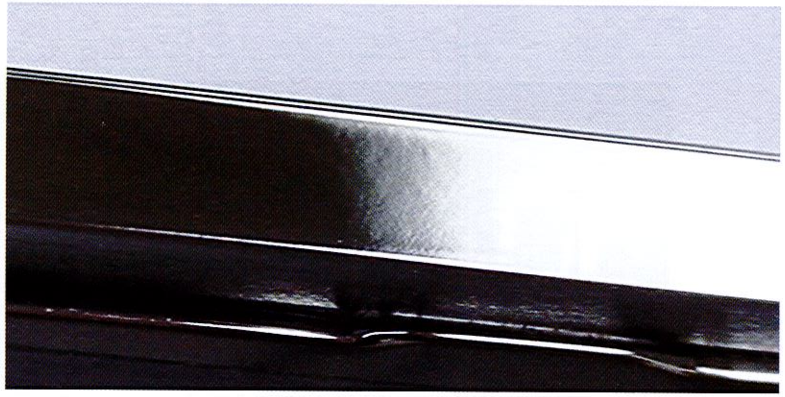
<u>建议：</u>

- 工件应先砂纸磨至 P600 号
- 避免长时间粗抛光
- 善用幼工抛光制造光面

6.4.2. 橘子皮纹

橘子皮纹 (图 6.2) 是反光度不足的表面，与波浪纹不同之处是它没有特定方向

图 6.2　抛光后出现橘子皮纹 (由麦世枝先生提供)



成因：

- 双相合金存在不同成份与硬度
- 加工工序错误引至超大颗粒
- 砂磨与粗抛光不足，未能平整表面
- 抛光压力过高
- 抛光时间过长
- 工件与抛光剂、除蜡水发生化学反应

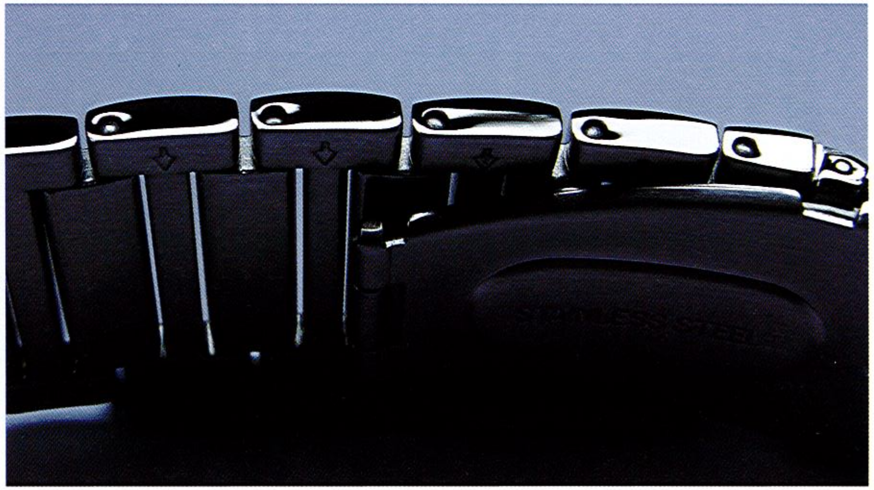
建议：

- 降低热加工温度；减少晶粒长大
- 用砂纸磨磨平表面
- 使用底压力砂磨与抛光
- 使用 pH 中性抛光剂与清洁剂

6.4.3. 孔洞旁的边沿效应

图 6.3 为典型抛光泪孔。孔洞旁大量变形凹陷，研磨料积聚孔内后被拉出，磨削孔边而成。

图 6.3　典型抛光泪孔 (由麦世枝先生提供)



成因：

- 凹陷位积聚磨削碎屑与抛光剂引至彗星尾巴
- 过长研磨与抛光
- 砂磨与粗抛光不足，未能平整表面
- 使用过量研磨料

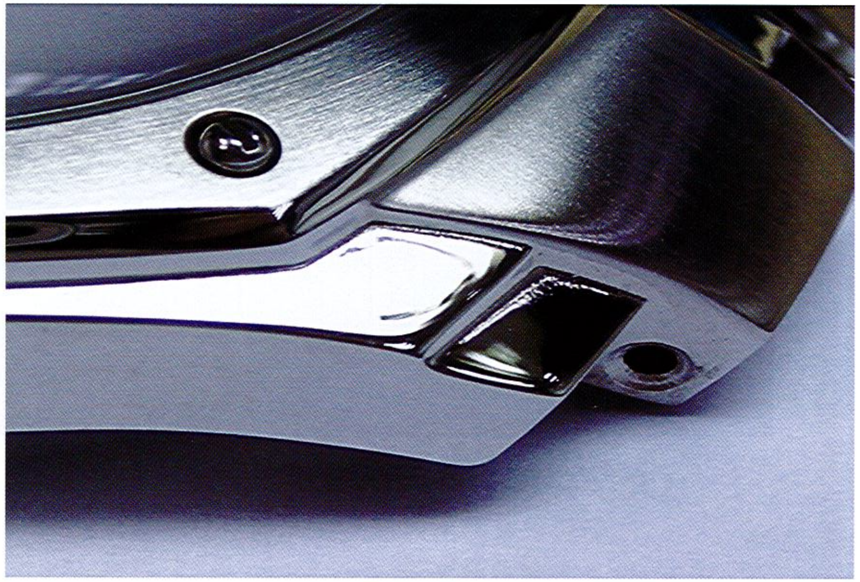
建议：

- 将凹陷位填平
- 使用砂纸磨、减少使用抛光
- 不用粗抛光
- 减少使用抛光剂

6.4.4. 暗角

图 6.4 显示凹陷隐蔽区未能抛光，可采用打磨笔打磨暗角。

图 6.4　暗角 (由麦世枝先生提供)



6.4.5. 内部缺陷

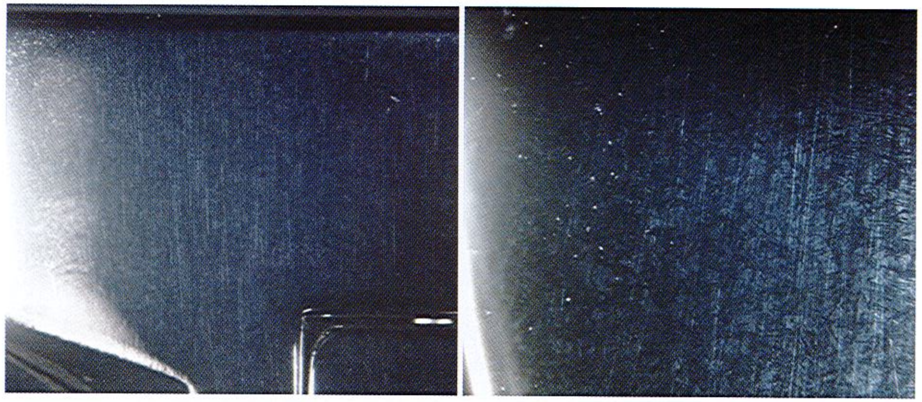
图 6.5 的内部缺陷可能于铸造或机械加工而成，大量微裂纹杂质满布工件，但不能除去。

图 6.5　内部缺陷 (由麦世枝先生提供)

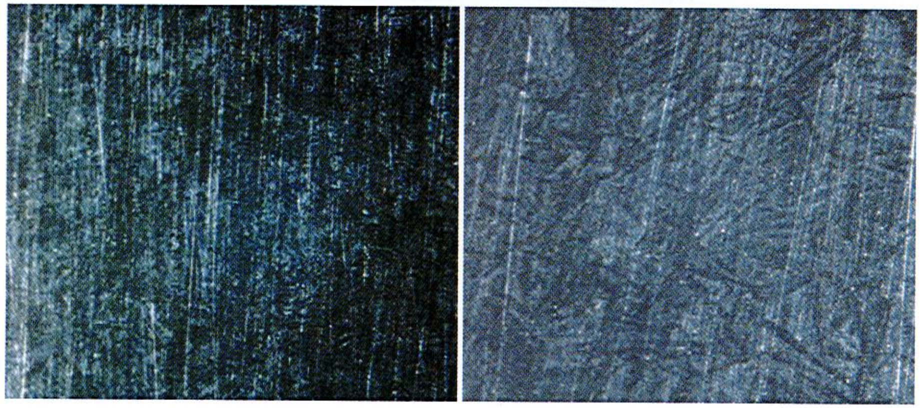
6.4.6. 钛合金的橘子皮纹

图 6.6 中工件 A 和 B 为钛合金，抛光后显视橘子纹。钛合金 A 还勉强可接受。

图 6.6　已抛光的钛合金（由麦世枝先生提供）



(a) 钛 A 100x　　(b) 钛 B 100x



(c) 钛 A 900x (154Hv)　　(d) 钛 B 900x (225Hv)

成因：

- 冷轧后回火温度过高引至晶体颗粒过大，导致橘子纹现象
- 砂磨不足磨平工件

建议：

- 使用较低温度热处理及缩短热处理时间
- 用较长砂磨时间磨表面
- 以幼砂磨代替粗抛光

丙部：经验篇

第七章

7. 打磨 304 / 316 不锈钢

表 7.1　不锈钢的表面加工工艺

工艺	轮	Grit, 研磨料	Finish
粗磨削	硬胶轮	20-30, Al_2O_3, SiC, 干磨	平正
幼磨削	硬胶轮、砂纸带	36-80, Al_2O_3, SiC, 干磨	平正，无深刻刮痕
粗砂磨	砂纸带、砂纸磨	80-100, Al_2O_3, SiC, 干磨	粗磨
中度砂磨	砂纸带、砂纸磨	120-150, Al_2O_3, SiC, 干磨	4 号表面
4 号钢丝擦	钢丝擦	石磨粉	6 号表面
条纹抛光线	硬抛光轮	多种级别、无油抛光剂	条纹
磨削抛光	硬抛光轮	180 级抛光剂	7 号、无刮痕
磨削至色泽抛光	松软布抛光轮	240 级绿色抛光剂	8 号、无刮痕

若钢材所含杂质较多，钢材的不同相硬度差异会较大，应使用较低抛光压力，才能达至高品质抛光面。不锈钢的抗张强度与表面硬度颇高，应选用硬的研磨料。不锈钢的导热性能低，必须注意主抛光温度。磨削与砂纸磨时的压力太大会硬化钢材表面，使抛光效率降低，宜使用较低的磨削及砂纸磨压力。表 7.1 为打磨不锈钢的部份常用工艺。

表 7.2　砂纸磨不锈钢的建议磨速

产品	Grit 级别	砂磨速度 (m/s)	润滑剂
刀锋面	180	28	油脂
餐刀、餐叉	1500	27	油脂
餐匙	150, 200	27	油脂
注射针	320, 400	24	水溶性油
喷射船叶片	120	28	油
线圈	120, 150	17	油
罐装容器、平底镬	220, 320	26	油脂
No. 3 表面光整度	100	21	油脂
No. 4 表面光整度	150	21	油脂
No. 7 表面光整度	180-280	21	油脂

粗砂纸磨的轮速可以较快，选择 40m/s 的磨速提高除氧化层的速度；若希望提高打磨质素，便应减慢磨速。表 7.2 列举一些常用的砂纸磨叁数以供叁考。抛光时若使用松散的棉布轮，并降低抛光压力，抛光磨速可提升至 50m/s，色泽抛光时应减慢磨速至 35m/s 以下。

幼细的色泽抛光后不一定需要表面钝化或复杂的清洁，因不锈钢表面会在空气自动中钝化；但必须确保碎屑不遗留在不锈钢表面，否则会发生点蚀现像。

7.1. 砂纸磨与抛光前后的处理

适当的热处理可提升不锈钢的机械性能，减低残馀应力，恢复原有的防腐蚀性能。304 与 316 不锈钢都是最常用的奥氏体不锈钢。 很多奥氏体不锈钢都可以通过冷轧和其他冷加工方法硬化，供应商提供的 304 与 316 可能是已冷加工 (较硬) 或已退火的 (较软)，必须验证清楚。不恰当的热处理会引至碳化铬的出现，使钢材容易发生晶界腐蚀断裂；可以提温至固溶温度以上把碳化铬去除。表 7.3 提供了一些退火温度以供叁考。

表 7.3　不同种类的不锈钢的退火温度

不锈钢规格	**温度 (°C)**
201, 202, 301, 302, 303, 304, 304L, 304LN, 305, 308, 316N	1010-1120
254SMO	1150-1205
309, 316	1040-1120
310	1040-1065
316L, 316LN, 317L	1040-1110
317	1065-1120
317LM, 317LX, 317L Plus, 317LMO	1120-1150
321	955-1065
347, 348	980-1065
904L	1075-1125

机械成形工艺会硬化不锈钢工件，使加工困难，但可通过热热处理软化，然后继续机械加工。高温热处理回火快，但会导致晶粒粗大，引起橘子纹现像，要小心考虑。

有害的碳化物会于 425-900°C 形成，冷轧后的 304/316 不锈钢在 425°C 产生碳化铬，必须避免停留在这温度范围。可提温至 ~1090°C 固溶碳化铬，然后快速冷却至 425°C 以下室温以上，减低速冷对工件的伤害。

退火时间不宜过长，避免晶粒粗大，只需保持在所需温度 3-5 分钟 (2.5mm 厚工件) 便已达至退火功文效，较厚工件 (>5mm) 则需延长至 6-10 分钟，再速冷便可以了。

退火温度、退火时间与冷却速率是热处理的三大重要因素，必须小心选择：

- 高退火温度加快固溶碳化铬
  vs.
  低温限制晶粒长大
- 较长退火时间固溶更多碳化铬
  vs.
  短退火时间限制晶粒长大
- 快速冷却减少碳化铬
  vs.
  慢速冷却减低残馀内应力

过长的退火时间使氧化层长厚，加重打磨工序的负担。可于氢气或离解氨中光亮退火，减低氧化的机会；但光亮退火的炉具必须清洁而不存水气，否则工件会变成绿色，很难清除。

7.2. 不锈钢表面硬化与涂层

不锈钢的表面通过氮化或镀上涂层得到适当的表面处理，从而改善硬度、改变色泽、提升抗磨损能力和防腐蚀性能。 所有的抛光表面处理必须于这些表面处理工序之前完成。

在氮化或涂层表面处理之前，最好先将工件磨削、砂磨和抛光，然后用化学物彻底清洗并去除氧化膜，再立即进行涂层或氮化表面加工，将会得到最好的效果。

丙部：经验篇

第八章

8. 打磨钛合金

钛的独特之处，是它的低密度 (4.5g/cm^3) 和高强度 (434MPa)，高抗腐蚀能力也是它的优点。不过，钛的缺点是摩擦系数高、 抗磨损度低及切变强度低。钛合金的低温抗氧化能力很强；不过，于 430°C 以上，钛合金会吸收氧气而脆化。钛合金升温至 260°C 便会失去热稳定性，并可以在 370-540°C 间沉淀硬化。

8.1. 钛合金的清洁和氧化

钛合金的厚厚氧化层可用喷钢砂处理清除，氧化层必须通过磨削彻底磨掉，否则可能在冷加工时引至破裂。冷加工后要以洗涤液清洗乾净，除去油脂，或用 蒸汽去垢。吸收气体而成为杂质是晦影钛合金质素的一大因素。若吸入氧气或氢气，钛合金会变脆。

大多数钛合金会在冷加工时变形硬化，必须退火后才能再机械加工。退火会形成 0.05-0.07mm 厚氧化层，热轧所造成的氧化层可达 0.15-0.2mm。必须用酸蚀或电化学方法除去。

8.2. 钛合金磨削与抛光

因钛金属粉是易燃可爆炸物品，不可用乾砂纸带磨削必须加添 5% K_3PO_4 水溶液或氯化水溶剂作冷却剂，但用后必须彻底清洗。磨带速度不可超过 6-8m/s。80 号砂带可用作磨削 0.07mm 氧化钛表面。以下为打磨程序的建议：

1. 80 号砂磨去除瑕疵和氧化层
2. 100 号砂磨
3. 180 号砂磨
4. P240 号砂磨至 Ra=0.5-0.65μm
5. 用 20% HNO_3 加 2% HF 表面处理，然后彻底清洗
6. 用 SiC 砂纸磨，可配合纸物油作冷却剂及研磨（亦可慢速乾打磨）
7. 用砂纸磨精磨
8. 用喷奖喷磨
9. 用松散的可棉布轮精抛光

对较软的钛合金抛光可能会引至学失去线条，可减低压力，使用适当的抛光剂，否则表面容易出现烧痕。抛光后不一定需要除蜡，可让油脂减慢氧化变暗的速度。

丙部：经验篇

第九章

9. 打磨铝合金（软合金）

铝与铝合金强度较低，比较容易打磨。纯铝的屈服强度约 7-11MPa。铝合金的屈服强度可以被提升至 200-600MPa。纯铝非常轻，密度只有 $2.7g/cm^3$。抛光可用麻轮作粗抛光，用松散布轮作幼细抛光。下列为抛光铝或铝合金的建议叁数：

1. 轮速：180-2000rpm
2. 硬绒布轮直径：350-400mm
3. 油脂润滑剂
4. 磨速：18-40m/s
5. 轻压力

慢速与轻压力都有助获取更好的光面，可用有机溶剂清洁铝合金表面；将有机溶剂加热有利提高清洁效率，使用搞拌器效果更佳。可使用 pH 中性的矿物油除掉抛光剂；也可选用乳化溶剂、碱性清洁剂和稀释酸性液体。

化学抛光也能造出抛光效。可选用含稀释酸性液体如的硫酸、盐酸、磷酸或醋酸来的化学液体作化学抛光。

丙部：经验篇

第十章

10. 其他表面加工技术

表面光整加工技术可分类为**机械研磨类**及**非机械研磨**两大类。上文主要集中讨论机械研磨料类，本章所讨论范围将超越机械研磨类。

10.1. 化学机械打磨

化学机械打磨 (CMP) 为机械打磨和化学侵蚀的混合方法，通过在研磨料里添加小量的腐蚀性化学物，可将磨蚀速率提高；但经打磨的工件必须中和及彻底清洗，然后烘乾后妥善收藏。此方法被广泛应用于半导体制造业，效果优越，但需要小心管理打磨工序，否则残馀化学物会引至应力腐蚀开裂。

高浓度的化学侵蚀物和打磨温度可提高打磨速率，但要小心处理，因为侵蚀速度可能太快。打磨温度不宜高于 100°C。化学侵蚀可能会产生氢气，所以必须有良好的通风系统。

10.2. 滚筒打磨

滚筒打磨利用工件在滚筒内与研磨粒相护摩擦而产生打磨效果，适用于大批量生产。滚筒转动过快会使工件边沿被磨钝，表面光整度也不高。工件与研磨粒的比例，以及材冷却剂的选择都会影响打磨质素。优点是可减少工人数目，品质比较稳定。

10.3. 振动打磨

振动打磨亦是用作大量生产的自动化工艺，通过利工件与研磨粒于振动时互相摩擦而产生打磨效果。可用于去除毛边、除氧化层和清洁较细小的工件。此方法可用于打磨工件的内则，使用越幼细的研磨料，打磨的效果颗越好。因容器没有大幅度转动，所以可以容许随时检视打磨情况与效果。

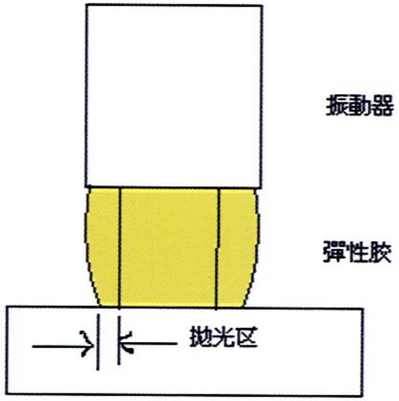
可加入稀释腐蚀剂加快打磨速率。常用的频率为 15-60Hz，振动幅度为 0-5mm。高频率、振幅短会使打磨结果更高。

10.4. 超声波打磨

超声波打磨与振动打磨的原理相似，主要分别为振动频率和振幅。好常用频率为 20kHz 至 GHz。研磨浆含研磨粒因超声波而振动达至打磨效果。此方法适用于全方位的打磨，包括工件内则和暗角位。采用压动传动装置产生高频振动，引起微距摩擦打磨。

工序所产生的温度提升相对少，摩擦压力很低，对工件的伤害极少，减少引至变形量。图 10.1 为超声波打磨用于暗角的示意图。简单的电动雕刻器，也可配上打磨的胶擦进行打磨，分别只是频率较低和速度较慢。高频、大振幅和粗磨料都可提高研磨速度。高频、微距振幅和幼研磨料都可提高打磨质素。研磨浆的黏度越低越好。

图 10.1　超音波打磨 (麦世枝先生提供)



10.5.　研磨料喷射打磨

研磨料喷射打磨使用高速气枪把研磨料 (e.g. 2500 号玻璃珠) 射向工件，产生打磨效果。磨削的比例较少。此方法适用于研磨高硬度或脆性材料。

10.6.　MMP 微抛光

MMP 又称微抛光或超级压光，可磨掉约 1μm 的切变塑性变形层。抛光过程中研磨料于工件表面振荡和转动，速度约 0.1-0.2m/s 的的低速，压力只需 20kPa(磨削速度为 30-60m/s、压力 13-140MPa)。加工精度可达 10nm(0.01μm)。可选用煤油作冷却剂，研磨粒可选用氧化铝、碳化硅、立方氮化硼与金刚石，常用 研磨料颗粒为 5-8μm 。

10.7.　电化学抛光

电化学抛光可用作抛光、钝化和除毛刺，使用于机械打磨之后。此法不会引至机械损坏，无塑性变形层，是一种常用的抛光技术。

丙部：经验篇

第十一章

11. 安全指引

工作環境：

1. 保持工场通风及清洁，经常吸走微尘碎屑，于工人健康及品质都有利。
2. 确保金属与金属氧化物无毒
3. 减少使用挥发性有机化合物(溶剂)
4. 废气、液体、固体经处理后才排出
5. 禁用含 Cd 或 Cr 作表面处理
6. 建立处理微尘的抽风系统

設備設訂：

7. 砂磨轮与抛光轮
8. 确保磨削轮无裂纹，避免粗至命或严重意外

工人服装：

9. 配带安全眼镜
10. 配带安全口罩
11. 脱去松身衣物、指环与手表
12. 带手套保护双手
13. 使用硬皮面防滑的的安全鞋

操作：

14. 紧握工件
15. 集中注意力于工件上
16. 关掉不使用的磨轮
17. 不用手触摸磨轮和抛光轮
18. 磨轮向下转动，用抛光轮的圆心以下部份磨抛光

参考材料：

1. Surface Engineering, Vol 5, ASM Handbook, ASM International, 1994.

2. An Introduction to Buffing and Polishing, by Caswell Inc., Lyons, NY, USA.