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Robot Automation Systems for Deburring

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1. Introduction

Deburring is a significant area of research for robot application. However, it is difficult to obtain details on this important topic in modern text books and archival journal papers. Therefore, in general, the engineer is subjected to a time consuming decision making process that usually involves trial-and-error procedures. This chapter will attempt to organize important know-how and field experience, in a logical sequence, so that the engineer can use the information in a straightforward manner. The chapter will provide important details on various types of tools, material selections, robots and station concepts, and programming. This information will help reduce the trial-and-error approach, which is a significant drain on time and money. The contents of this chapter will also provide the opportunity to obtain an optimal solution to the problems associated with deburring.

The chapter is arranged as follows. Section 2 defines a burr and presents background information on the automation systems for the deburring process. The process is classified by the types of burr and the work material. Section 3 gives a brief introduction to robots for the deburring process. Section 4 discusses the tools of a robot deburring system including, the spindle motor, tool holders, and tool selection. Section 5 focuses on the rotation-type burr tool; i.e., deburring by a solid rotating file. The rotating file is the most commonly used at the present time. Section 6 focuses on the deburring operation and includes a discussion of potential problems in the deburring process. Section 7 presents a discussion of the selection of tools for different applications. Finally, Section 8 addresses the problems associated with the cutting and deburring of polymers and die castings.

The material in this chapter is based on the reports and experiences of experts in Europe, the United States of America, Japan, and Korea.

2. Burrs and Deburring

A burr is defined as an undesirable effect generated at the edge of a work piece after the machining process. In a broader sense, burrs can also be generated during casting, forging, sintering, welding, cutting, plating, and painting. Usually, a burr is harder than the parent metal due to work hardening. Sometimes a burr is considered to be different from a flash but both are common in affecting the processes that follow. For example, a burr can be a

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major hindrance in assembly work and the sharp edge of a burr can cut a workers hand. Also, in general, burrs give the appearance of a poorly finished product.

Deburring can occupy as much as five to ten percent of total man hours, yet in many cases, it is generally regarded as a minor problem or just a bothersome phenomenon. As the demand for quality becomes more rigorous, and the role of process automation becomes more important, it is necessary to devise a substantial and systematic prescription against burrs and flashes. The best solution is that a burr should not be generated in the first place, or the effects of a burr should be minimal. Also, the direction of a burr should be controlled in the process planning stage so that it does not affect the upcoming processes. Finally, the burrs that are generated must be removed, in which case, a deburring methodology, automation, process planning, and justification of the financial implications must be thoroughly investigated.

Robot automation systems for the deburring process have been developed primarily for the automotive industry, kitchen products, and the manufacture of plastics. The motivation is due to the reduction in the available work force, industrial environmental problems such as dust, and the demand for cycle time reduction. The latter issue is very important in applications such as the production of crankshafts. The deburring process, however, is a relatively undeveloped process and it is difficult to obtain a comprehensive list of the literature on the subject. In general, information on deburring automation is not readily available, it has remained as the know-how of the experts in the field and in the reports of system houses. The robot automation system of deburring is composed of a robot (see Section 3) and peripheral equipment. The most important peripheral equipment is the fixture device of the work piece. This device may be a simple clamping table, an indexing table, or a sophisticated manipulator depending on the geometry of the work piece and conditions such as cycle time. When the size of the work piece is bigger than the robot work envelope then robot track motion should be used.

The selection of the correct deburring tool is very critical for the success of the process and, therefore, is an essential part of the deburring process. Also, more than thirty-five methods have been reported for the deburring process. The most important criterion in choosing one method over another is the minimization of total manufacturing cost. Primary items that must be considered are the production volume, the cycle time, the material properties, tolerances, geometry, and dimensions. Secondary items are the investigation of the process that generates a burr and the purpose of burr removal. The best solution can only be obtained when all of these conditions are thoroughly investigated.

3. Robots for the Deburring Process

In the robot automation of machining processes, robots are performing operations such as deburring, polishing, grinding, and light duty cutting. The robots for these processes require a higher stiffness and rigidity, especially in the wrist area, compared to robots for applications such as arc welding. Industrial robots, however, have a limited rigidity especially at the wrist and, therefore, are not suited to process applications. Different from applications such as arc welding, the robots are in direct contact with the work piece and have to sustain reaction forces and torques, and withstand undesirable vibrations. Usually, industrial robots designed at low cost prices are for less challenging applications using timing belts, harmonic drives, and cycloids. Sturdier robots are typically designed with speed reducers, made of gear assemblies that can be used for machining processes. In some cases, dedicated robots are developed for this specific purpose. These robots are generally designed to withstand the inevitable dust and chips.

The major application areas of industrial robots include:

- Deburring of automotive engine blocks, crankshafts, and camshafts.
- Deburring and finishing of die casting products.
- Polishing and buffing of kitchen products.
- Cutting and drilling of plastics.

4. The Tools of a Robot Deburring System

A robot deburring system is composed of a spindle motor, a deburring tool, and a tool holder. Peripheral devices for the robot and the work piece such as a manipulator, and a robot track, are based on the same principle as for arc welding robot automation (see the chapter on arc welding robot automation systems).

(A) The Spindle Motor for Deburring

A spindle motor rotates the deburring tool, oscillates the tool in the axial direction, and occasionally rotates the work piece when it is small and lightweight. The motors are classified by speed as follows: (i) a high speed motor (15,000 rpm and higher) for rotating files; (ii) middle speed motor (10,000 - 15,000 rpm) for operation by brush with 60 mm diameter or less; and (iii) low speed motor (500 - 1,500 rpm) for tools for special applications such as deburring the inside of a hole.

A pneumatic spindle is typically used on a low speed motor, and an electric motor and a high frequency motor are used for the higher speeds. The pneumatic spindle is the most commonly used. The maximum speed is 30,000 rpm with no load and the net power can be as high as 550 Watts. This spindle is relatively cheap, reliable, and a high power versus weight ratio. A high frequency motor is controlled by a converter to vary the speed between 5,000 rpm and 12,000 rpm with a maximum horsepower of 0.74 kW and a maximum torque of 0.15 Nm. For reciprocating oscillating files, special reciprocating motors are used, which operate at 2,000 ~ 4,000 strokes per minute with an amplitude of 1 ~ 9 mm.

For a brushing application, two different concepts can be used. The first concept is for the robot to hold the work piece and approach the brush wheel mounted on the floor. The second concept is for the robot to hold the spindle and brush unit and approach the work piece which is fixed on a clamp as shown in Fig. 1(a). In this case, the brush wheel usually has a diameter less than 60 mm and the speed of the motor does not exceed 15,000 rpm. When burrs are easily accessible, such as burrs on the outside edges or on the corners of a work piece, then small belt grinders attached to the robot, see Fig. 1(b) for example, will give good results.



(a) A Brush Grinder Tool.



(b) A Belt Grinder Tool.

Fig. 1. Two Types of Grinder Tools.

For deburring the inside of a hole, there are two different cases. First, when the hole diameter is larger than 25 mm, then general rotating tools with high speeds (15,000 rpm and greater) may be used. Second, when the hole diameter is smaller than 25 mm then special tools, or counter sinking tools, with low speeds (30 - 60 m/min) are used. Figure 2 illustrates the procedure for deburring the inside of a hole.

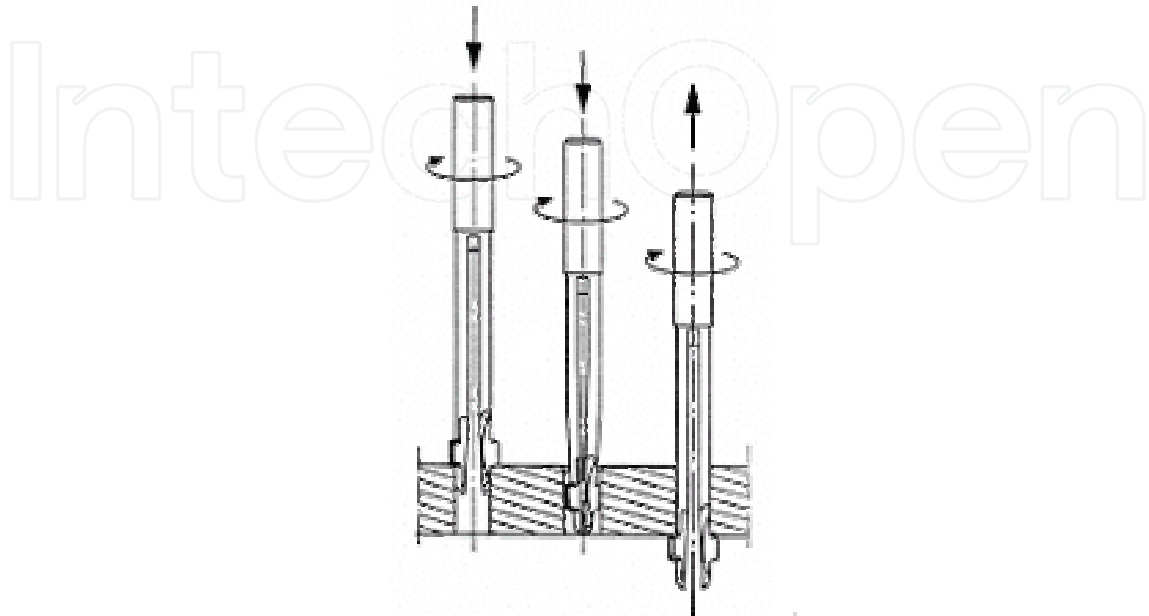


Fig. 2. Deburring the Inside of a Hole.

When selecting a spindle, the pneumatic spindle should be given first consideration since it is the most economic and reliable tool. When various speeds are required for several tools then a high frequency motor and a tool adapter with an automatic tool changer should be used. The high frequency motor is controlled by a converter and changes speed easily across broad range with quick response. However, the high frequency motors are expensive and if only two speeds not variable speed are required then the concept based on high frequency motors should be compared with using two cheaper pneumatic spindles.

(B) A Deburring Tool

The most common tools for robot deburring automation are flexible tools, solid burrs (rotating files), oscillating files, and internal deburring tools. There are belts and brushes in the category of flexible tools. The belts are made of coated abrasives with backing paper or cloth, or abrasive non-woven webs. The brushes are made of aluminum oxide or silicon carbide impregnated on nylon, or steel. The most effective work is at the tip of the brush. Generally, a belt is efficient for straight line edges and a brush is efficient for corners.

The most widely used tools in robot deburring automation are solid deburring tools which will be discussed in some detail in Section 2.3. Solid deburring tools are rotary files made from various materials that have many different shapes. The selection of the correct tools is based on geometry, material property, location, and the volume of the burrs to be removed. Oscillating files are used for small and slender burrs. There are files with various profiles as shown in Figure 3. The appropriate profiles are chosen

based on speed. The stroke is based on the burr geometry and conditions such as oscillating tool performance.

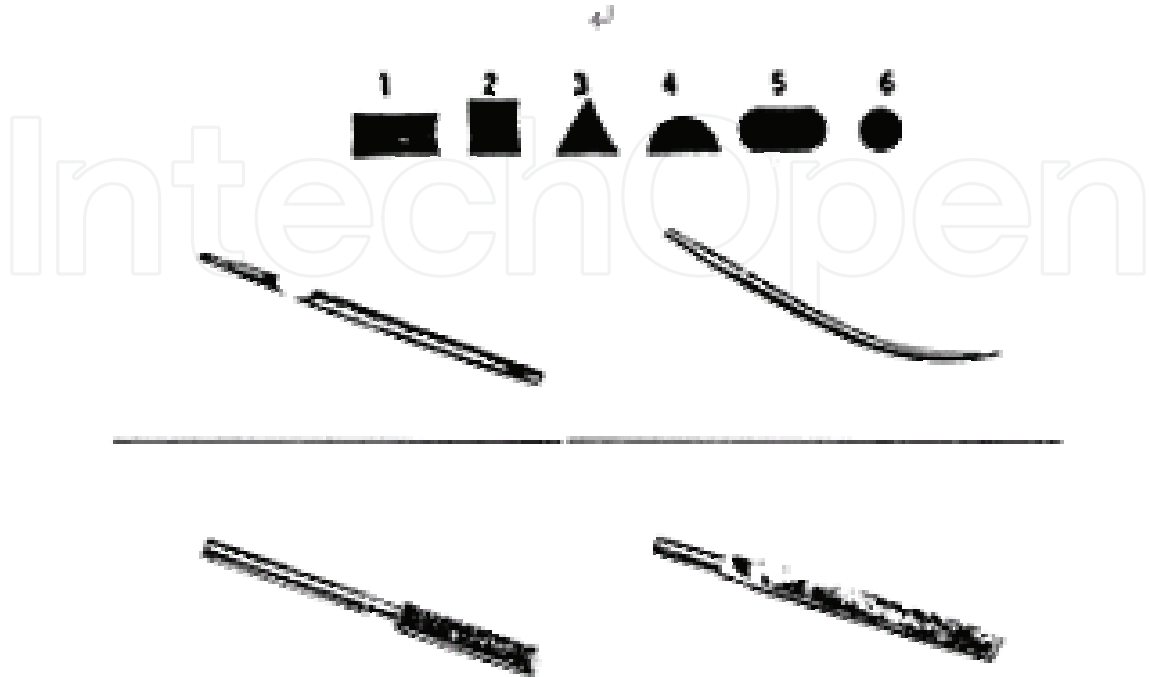


Fig. 3. An Oscillating File and a File Profile.

A tool for deburring the inside of a hole is shown in Fig. 2. The tool should have radial compliance so that the diameter can be extended inside the hole. A description of the spindle was presented in section (A).

(C) Tool Holders

Solid burrs do not absorb the reaction during the burr removing operation. Also, the volume and the hardness of the burrs are not uniform. Therefore, the results may not be uniform and the robot and spindle are exposed to unexpected shock. In such cases, the robot may stop running and provide an error message. To protect the system from this situation, tool holders should be provided with certain compliance functions. A simple solution is to use basic compliance function provided by the tool holder itself while a sophisticated system may use a specially designed integrated spindle and tool holder system.

General overviews of simple solutions to tool holder compliances are illustrated in Fig. 4. The figure shows that there are four types of tool holder compliance:

- (i) Multi-directional compliance, see Fig. 4(a). The spindle is wrapped in an elastic material such as rubber. This concept is used when the spindle is under axial direction thrust but does not provide precision due to slow elastic recovery.
- (ii) Two-directional compliance, see Fig. 4(b). The spindle holder is loaded with a spring for compliances in two directions perpendicular to the spindle axis.
- (iii) One-directional compliance, see Fig. 4 (c). The spindle holder is loaded with a spring for compliance a direction perpendicular to the spindle axis.

- (iv) No compliance, see Fig. 4(d). The spindle holder is rigidly fixed without compliance for soft material deburring.

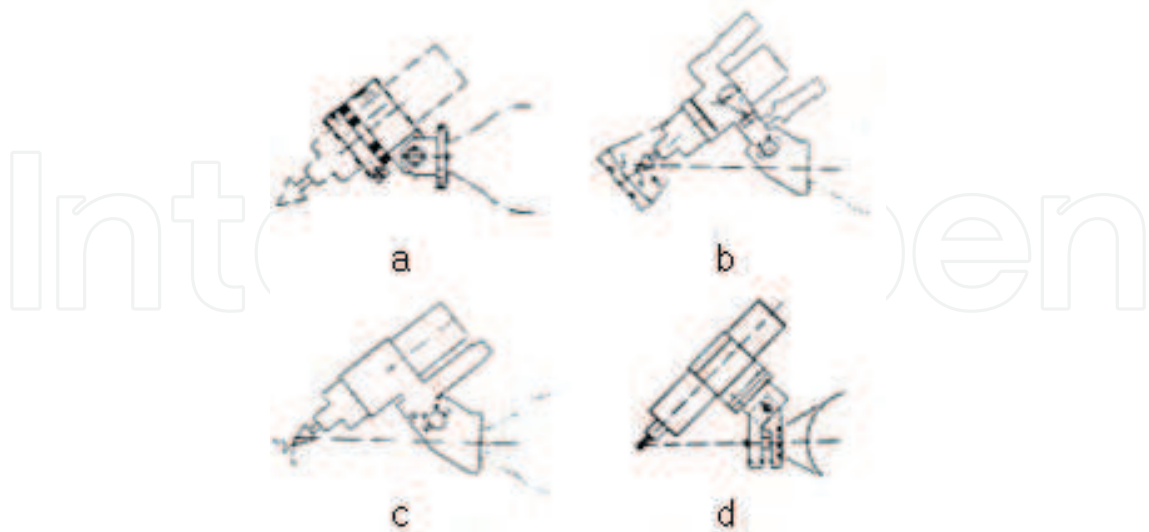


Fig. 4. Four Types of Tool Holder Compliance.

- (a) A Rubber Suspended Holder. (b) A Two-Way Spring-Loaded Holder.
 (c) A One-Way Spring-Loaded Holder. (d) A Rigid Holder.

(D) Tool Selection for Robot Deburring

The selection of robot deburring tools is based on the following criteria:

- (i) The selection of tool profile based on geometric accessibility to burrs.
- (ii) A decision of the correct tool compliance based on burr size and location.
- (iii) A study of tool cutting data considering cutting force and speed, tool RPM, and material property.
- (iv) A selection of spindle type and specification based on the cycle time and the manufacturing cost.

5.The Rotation-Type Burr Tool (A Solid rotating file)

The most common tools for robot deburring are rotating burrs. A rotating burr gives precise and predictable results. Also, the tool is small, has a long life, and various shapes and materials are readily available. Therefore, right selection of tools is very important.

(A) The Geometrical Shape of the Tools

Figure 5 shows the typical structure of a rotating burr. It consists of a tool body, a tooth and fluting pattern, and a shank.

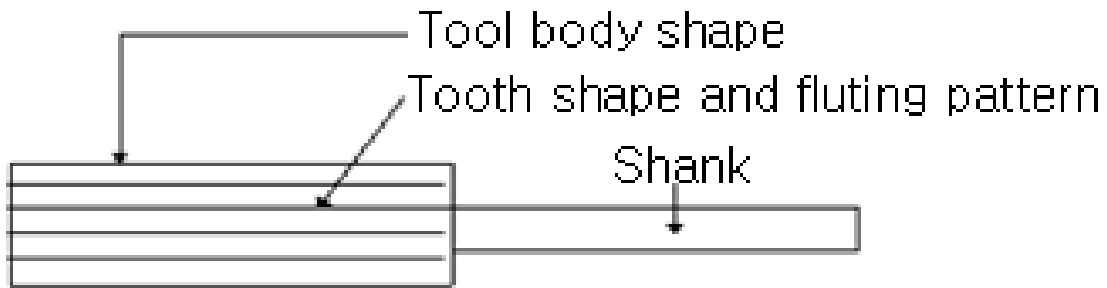


Fig. 5. A Rotating Burr.

The tool body has various shapes, such as wheels of cylinder, cone, and sphere, and saw type cutter depending on the direction and type of compliances. Figures 6, 7, and 8 illustrate various rotating burrs depending on the concept of compliance. When attaching a rotating burr to a robot, it is important to program the robot to apply power to the tool in the direction coincident with the direction of compliance. Figure 6 shows cylindrical shapes for radial direction compliance. The conical cutter with the straight ends offers an advantage in that it requires no dressing.

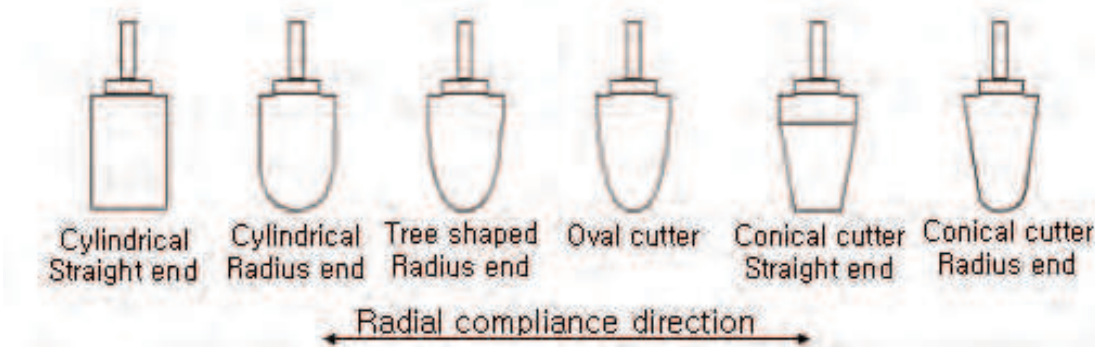


Fig. 6. Cylindrical Shapes for Radial Direction Compliance.

Figure 7 shows conical shapes for axial direction compliance. The cone cutter offers an advantage because the robot does not need to be reprogrammed to modify the tool center point, even after it is worn down.

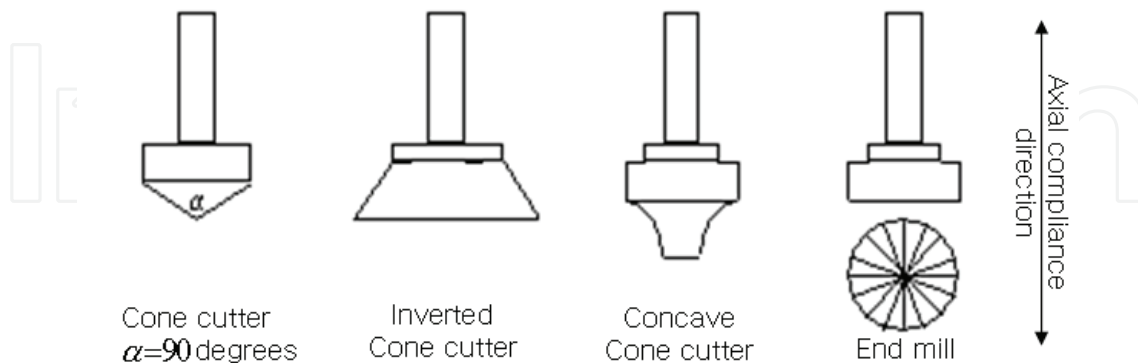


Fig. 7. Conical Shapes for Axial Direction Compliance.

Figure 8 shows the ball shaped cutter for multi-directional compliance and cutters for the case of no compliance.

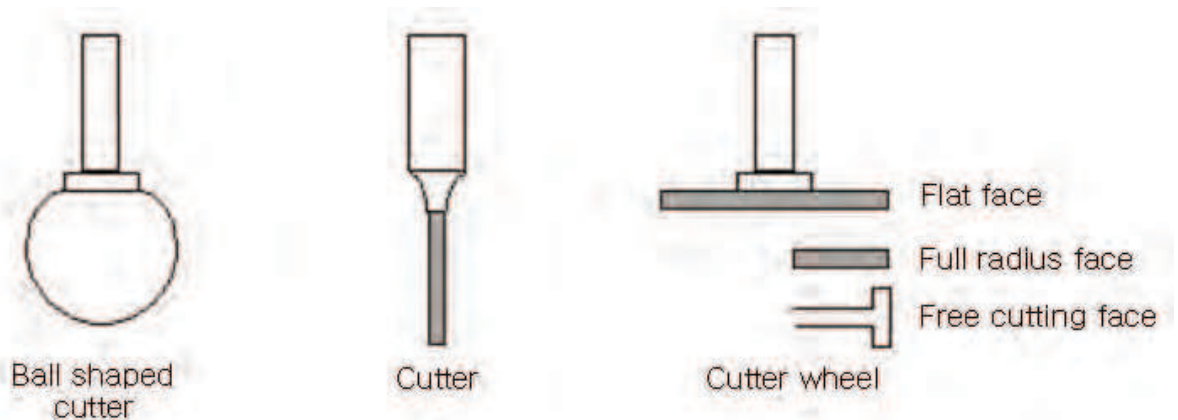


Fig. 8. The Ball Shaped Cutter for Multi-Directional Compliance and Cutters for No Compliance Applications.

The spherical shape of the ball shaped cutter is very efficient for deburring along smooth curves. The cutter wheels and the straight cutters are good for mild materials (such as plastics and aluminum) but need a device to protect them from the vibrations.

The fluting patterns and cutting edges shown in Fig. 5 may be classified as in Fig. 9. The patterns are categorized by the blade angle relative to rotation axis, number and size of blades, and cut mechanisms. It is important to choose right concept of the pattern to the size and hardness, and material of burrs. The standard concept is spiral cut, standard cut, and medium number and size of blades. It should be the starting point when designing a system. In the case where diamond cut, double cut, or chip breaker is used in deburring, then the chip from the process becomes different. The chip generation mechanism is the same as that of machining processes and, for more details, the reader is referred to books on the theory of machining.

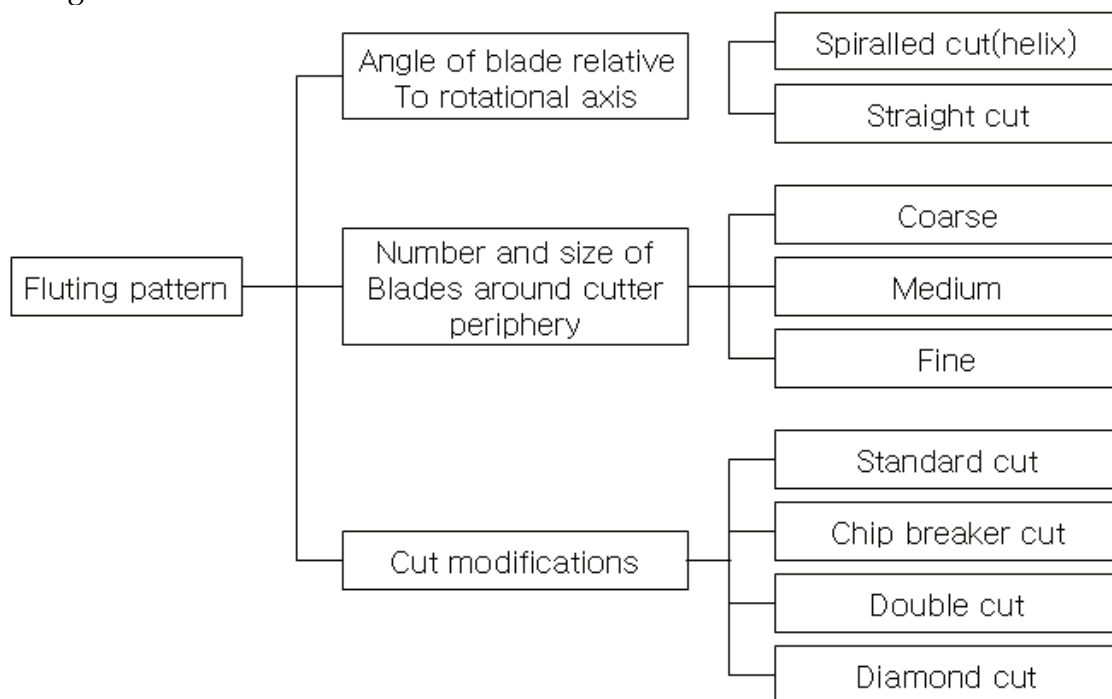


Fig. 9. Hierarchy of Fluting Pattern.

(B) Compliance of Tools

Compliance is the elastic deformation of the tool holder of the spindle due to the external forces that are exerted during the process. Since the active control of forces is not used, force on the tool is considered uniform regardless of robot position. There may be simple solutions to give compliance to tool holders. There are also more sophisticated solutions where spindle, tool, and suspension are integrated as a system.

The directions of compliance for the suspension axis may be classified as radial, axial, two-directional, three-directional, and semi-rigid, as shown in Fig. 10. There is also rigid suspension which are cutters with no compliance, see Fig. 8. An appropriate concept for the compliance may be chosen from the tool holders shown in Fig. 4.

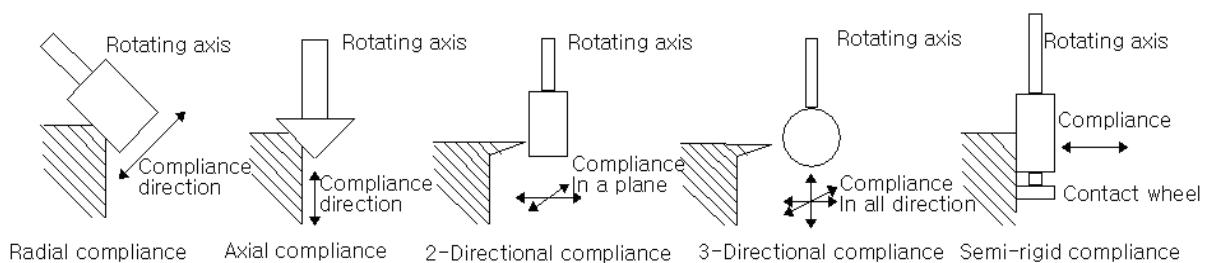


Fig. 10. Directions of Compliance for the Suspension Axis.

The most common compliance in robot deburring is radial compliance. It has a simple structure and it is easy to obtain the correct balance. Radial compliance is commonly useful for robots with six degrees of freedom. The sixth axis of the robot must be aligned such that the axis of compliance is perpendicular to the direction of burrs. A typical example is the deburring of the edge of a hole.

Axial compliance is a new concept which is experiencing an increase in applications. In the conventional concept, the entire motor and tool are moving in the axial direction, which makes the system heavy. In order for the contact force not to be affected by gravity, the system is used for deburring on the same plane. However, new integrated systems such as the tool system proposed by a company, Njuma Hiac [1], have been developed especially for axial compliance with very low weight and high maneuverability.

Two-directional and three-directional compliance are easy to use since they provide the robot with more directions to move, which saves much programming work. However, it is at a cost of potentially more oscillation. Therefore, robot programming speed is usually reduced. Also, if the burr size is uneven along the path the result could be uneven and, therefore, appropriate precautions are necessary such as preloading the tension to a certain value. In the case of semi-rigid compliance, the wheel is always in contact with work. This will give a good result when there are large unexpected burrs. The system is good for castings or machined parts.

Compliance may also be categorized by the elements. Common elements are rubber, pneumatic, spring, and gravitational elements. Rubber is used for two-directional and three-directional compliance. Rubber has a nonlinear characteristic between force and deformation. Also, the rubber must be replaced frequently due to age cracking, and each time the rubber is replaced the robot TCP (tool center point) should be modified. A pneumatic element can control the contact force easily by varying the pressure but attention must be paid to friction in the suspension system. A mechanical spring is a

simple and accurate element, and is good for one directional compliance. The contact force is controlled by a set screw. A preloaded screw can be used for uniform contact force in a limited distance of stroke. A gravitational element is mounted on the floor and the work gripped by the robot approaches the tool so that gravity generates the contact force.

In the performance of the compliance system, the most important factor is the stability of the contact force. It is especially important when the tool position is reversed, and in acceleration or rotation during high speed operation. If the system does not provide sufficient stability then uniform chamfer cannot be obtained during initial contact, at corners, or robot servo lag. The main cause of contact force instability is the low contact force versus inertia ratio. Figure 11 shows the hierarchy of deburring tool systems considering compliance.

(C) Tool Materials

Materials for deburring tools require hardness, toughness, wear resistance, and thermochemical stability. Tungsten carbide, high speed steel, and diamond or CBN coated tools are in common use. Table 1 shows typical materials with hardness data. Aluminum oxide and silicon carbide are brittle and used for coated abrasives and bonded abrasives. Tungsten carbide, tantalum carbide, and titanium carbide are very hard materials with good heat conductivity and may be sintered into various shapes of tools. They also perform very satisfactorily near the melting point. Titanium carbide and titanium nitride are also used to make laminated tools by diffusion bonding on base material. High strength steel is used in the temperature range lower than that of carbide tools, which has lower hardness but higher toughness. It is good for deburring of milder materials with lower strength than carbide tools. Diamond and CBN are known as the hardest materials, as shown in Table 1, and may be used as coated abrasive for solid flexible tools or wheel grinder. These materials have longer life and higher wear resistance than any other tool materials. CBN is next to diamond in hardness and better high temperature stability.

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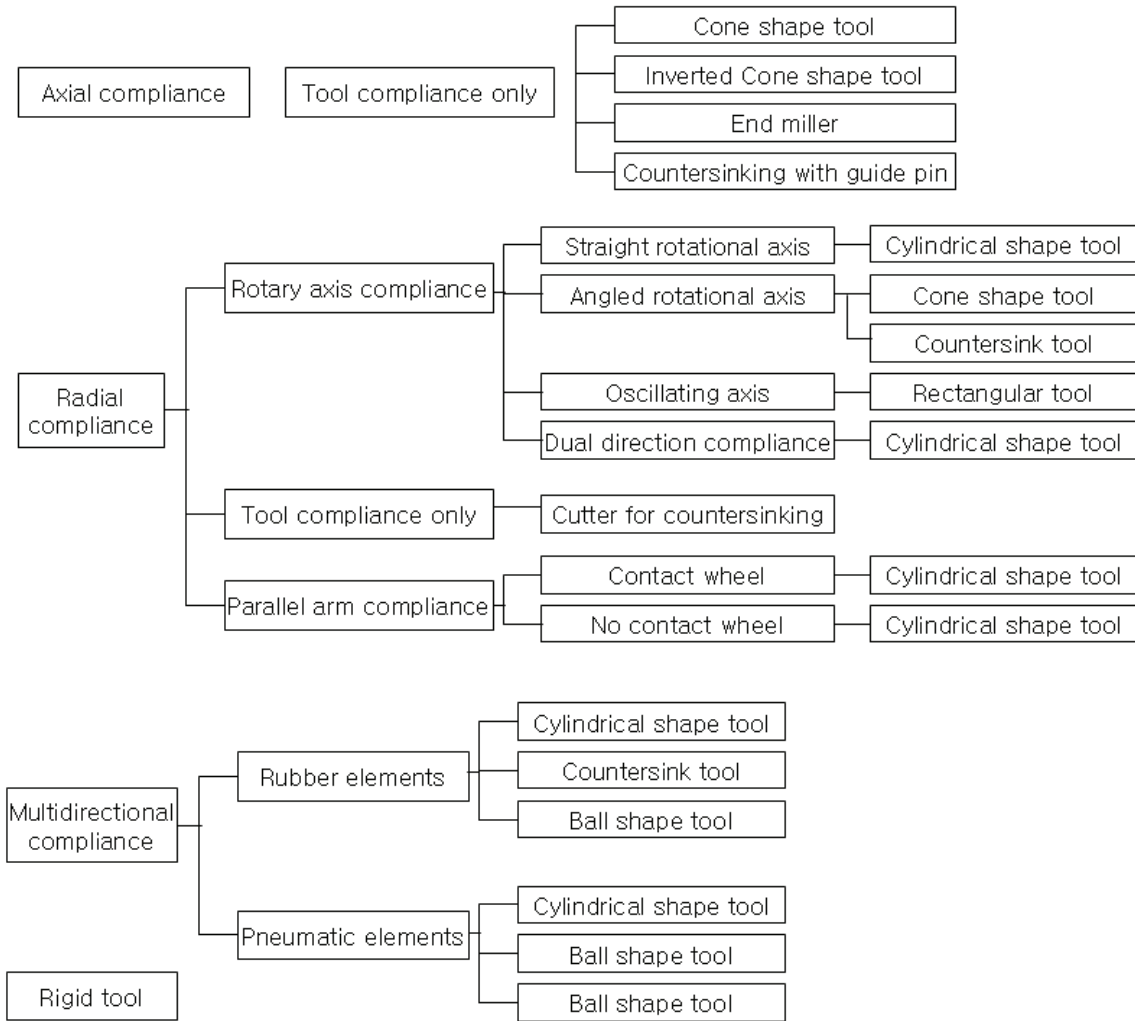


Fig. 11. The Hierarchy of Deburring Tool Systems.

Abrasives Basic elements	Hardness HK, kg/mm^2	Material	Hardness HK, kg/mm^2
Aluminium oxide (Al_2O_3)	2000~3000	Common glass Gray iron 70~30 brass High speed steel (HSS) Hardened steel	300~500 200~300 100~150 800~1100 700~1300
Silicon carbide (SiC)	2100~3000		
Tungsten carbide (WC)	1800~2400		
Tantalum carbide (TaC)	1600~2200		
Titanium carbide (TiC)	1800~3200		
Titanium nitride (TiN)	2000		
Cubic boron nitride	4000~5000		
Diamond	7000~8000		

Table 1. Hardness Properties of Tool Materials.

6. Deburring Operation

After the proper tool has been selected and the station is ready, the robot deburring process can commence. The following is a discussion of the important phases of the robot deburring automation process.

(A) Considerations before operation

The purpose of the deburring operation is to generate round chamfers of a certain radius and breadth. In the case where all the conditions (i.e., width, thickness, and material property) for deburring are uniform, then position control of the tool is the only requirement for a consistent output. However, there are many variables that influence the result; such as:

- The variety of burr size and shape.
- The approaching direction to the burr.
- The repeatability of the robot.

In order to solve the potential problems, the following ideas are proposed:

- Appropriate compliance must be devised.
- Robot speed must be controlled to avoid excessive contact force.
- Adaptive control algorithm of robot path must be applied to variable burr sizes.
- Force control of the robot should be adopted. This, however, is in the research stage.

(B) Potential Problems in the Deburring Process

Important problems in robot deburring process are path inaccuracy, chattering of the tool, proper programming of the robot, and tool wear.

Path Inaccuracy

When the path is not accurate then the chamfer cannot be uniform due to the following reasons.

- The burr size deviation should not exceed 1 to 4 mm. If the deviation is bigger than this then it should be removed in a previous stage.
- The robot is not securely mounted.
- The work piece is not properly clamped.
- Dust or dirt on the surface of the work piece prevents a tight clamping of the work.
- The tool is dislocated from its original position.
- In corner operation, robot servo lag causes inconsistent chamfer. Simpler tool geometry and slower speed may solve the problem.

Chattering of the Tool

Chattering may damage the deburring tool and break the rotating burr. Chattering can be caused by one of the following reasons.

- Multi-directional compliance such as rubber is used when burrs are not uniformly distributed, speed is too high, or contact angle is not appropriate.
- The robot or the tool is not securely mounted.
- There exist backlashes in the tool holder system.
- The contact force is too small compared with the capacity of compliance system.
- There is a chattering in the tool.
- The wrong concept of compliance is adopted.

Proper Programming of the Robot

The number of tools should be minimized for the robot. Also, the following items are important in robot programming:

- Singularity of the robot should be avoided by maintaining the fourth and sixth axis of robot not parallel. In axial compliance, the sixth axis of robot is oriented perpendicular to tool rotation axis while the sixth axis is parallel to the tool rotation axis in radial compliance.
- The tool center is kept not too far from the robot wrist center.
- Relative motion between robot and the work is utilized for quick and efficient operation.
- Heavy deburring tool is not recommended, which restricts speed, accessibility, and accuracy.

Tool Wear

Important factors to consider when investigating tool wear are:

- The robot should be programmed so as to obtain uniform wear of tool.
- When the file is damaged, it is a sign of poor working conditions. The damage should be investigated and work parameters such as RPM, speed, and contact force and angle should be reviewed. The possibility of tool chattering should be investigated.
- The wear mechanism of the tool material should be studied.

7. The Selection of Tools

The most important factor in tool selection is to decide on the tool that is best suited to the geometry of the burr. The second most important factor is the minimization of the number of tools by choosing the most common type of tools. However, if cycle time reduction is more important than optimal tool selection then proper number of tools may be used. In the reports of system houses, solutions to various situations are proposed based on field experiences over many years.

When addressing a problem, a number of potential solutions should be investigated. In some cases, it is possible to find the optimal solution using different concepts. The first criterion is to find the most common tool in the market. Then the right type of compliance may be proposed depending on the tool. This may not be a unique solution but without this guideline, the system engineer may need to go through a long process of trial-and-error and collecting information. The sections on tool selection in this chapter (see Sections 2.2 and 2.3) may be the first set of guidelines presented in the literature, and it is important to understand these guidelines thoroughly.

8. The Cutting and Deburring of Polymers and Die Casting

(A) Polymers

Plastics with high mechanical strength are formed from composite materials such as SMC (sheet mold compound) through molding processes. In this case, the parts are not finished by the process and must be subjected to a final finishing process. The excessive material should be removed by deburring or cutting. In the automation of plastic cutting, the robot must have a greater load carrying capacity (at least 30 kg), and a net power of 0.7 kW. An

electric motor with a speed of 54,000 rpm is used as the spindle motor. A pneumatic spindle is too weak for cutting with too high speed. When a spindle is attached to robot, it should be aligned with the sixth axis of the robot in order to minimize the moment exerted on the robot wrist. The spindle holder should be sufficiently strong to withstand the strong reaction forces but care must be taken because the spindle bearing might be damaged if it is too tight. The tool length and the diameter are selected first based on the work geometry and accessibility. The pattern of the tool teeth is selected based on the work material. The fixture is tailor made depending on the work shape and size. The fixture should be sufficiently large and rigid to hold the work securely without tool chattering.

(B) Die Casting

A die cast product will have burrs or flash in various locations, which makes finishing operation difficult.

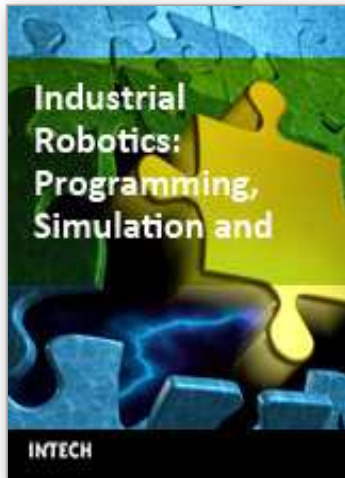
- In die casting, burrs around gate, overflow, and split line. A trimming press is appropriate since the burrs are uniformly distributed and the press can immediately handle the job.
- In the case of robot operation, the robot holds the work piece and approaches the rotary cutting saw mounted on the floor.
- Burrs along the parting line. When burrs are small and thin, the robot system with rotating burr with pneumatic spindle, oscillating files (scaler), or belt sander will be appropriate. If burrs are big and thick, a chisel may also be used. Figure 12 shows two examples of chisels; namely, a flat chisel and a blank chisel. The robot may hold the work and approach the belt sander or grinder that is mounted on the floor.



Fig. 12. A Flat Chisel and a Blank Chisel.

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This book covers a wide range of topics relating to advanced industrial robotics, sensors and automation technologies. Although being highly technical and complex in nature, the papers presented in this book represent some of the latest cutting edge technologies and advancements in industrial robotics technology. This book covers topics such as networking, properties of manipulators, forward and inverse robot arm kinematics, motion path-planning, machine vision and many other practical topics too numerous to list here. The authors and editor of this book wish to inspire people, especially young ones, to get involved with robotic and mechatronic engineering technology and to develop new and exciting practical applications, perhaps using the ideas and concepts presented herein.

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