A SENSOR BASED FIXTURING SYSTEM TO DETERMINE
THE MINIMUM REQUIRED CLAMPING FORCE FOR UNEDEEDED MACHINING
OPERATIONS

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DEDICATION

To My Parents
ACKNOWLEDGMENTS

I express my sincere appreciation to my adviser Dr. Amit Bagchi and Dr. Ronald L. Lewis for their guidance and insight throughout the research. Special thanks to Shelby Davis and Bob for their assistance in the machine shop.
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CHAPTER I
INTRODUCTION

1.1 ROLE OF FIXTURING IN MANUFACTURING

Workholders are devices that hold, grip or chuck a workpiece to perform a manufacturing operation. Fixture is a workholder which is designed to hold, locate and support the workpiece during a machining cycle and provides a means to reference and align the cutting tool to the workpiece. It must position or locate a workpiece in a definite relation to the cutting tool and must withstand holding and cutting forces while maintaining that precise location [1].

A fixture is made up of several elements, each performing a certain function. The locating elements position the workpiece; the structure or tool body withstands the forces; brackets attach the workholder to the machine and clamps; screws and jaws apply the holding forces. Each of these elements may have manual or power activation, and the functions must be performed with the required firmness of holding, accuracy of positioning and with a high degree of safety for the operator and equipment [1].

Conventional fixtures are currently designed for a specific part geometry. Therefore, there is limited flexibility in using the same fixture for different part shapes and sizes and is often difficult to use for other operations. In this era mass produced workpieces account for less than twenty-five percent of the total volume of metal working production in all industrialized nations. Of the remaining seventy-five percent, nearly one-
half is produced in batch sizes of less than fifty parts[2]. Social and technological trends, such as demands for customized products, shorter product life cycles, higher reliability, closer component tolerances and a wide variety of work materials are leading to increasing requirement for smaller batch sizes [3]. Due to a greater demand for smaller batch sizes, flexibility, versatility and higher productivity, a flexible fixturing system will be more appropriate than conventional fixtures which are tied to specific products and operations. Such a system should be able to accommodate a wide variety of part sizes, shapes and weights. As Thompson [4] suggests, a fixture should be capable of accommodating parts of any geometrical configuration within a given part family if it is to be considered truly “flexible”.

Presently, there are more than 150 Flexible Manufacturing System (FMS) installations and many more stand-alone workcells worldwide [5]. Hartley [6] suggests that FMS, not robotics, will lead the manufacturing industry to attain the present levels of automation in other processing industries. Portyrator [7] suggests that implementation of FMS can lead to an improvement of productivity of as much as 240% as compared to conventional manufacturing. This improvement comes from reduced use of manual labor for support functions in FMS. A new flexible fixturing system needs to be developed, which can handle a variety of parts where the fixtures can be assembled by a robotic manipulator based on product geometry and the required sequence of processing operations.

The main concern of a tool designer is to design a fixture sufficiently rigid to withstand the cutting forces and torques and to absorb the
machining induced vibrations. Fixtures are designed based on a set of standard rules for clamping which have evolved over the years [8]. The clamping rules that need to be satisfied are:

1. Clamping provided by the work holding device should hold part deflection and damage to a minimum.
2. Clamping should be rapid and positive.
3. Clamping should be located with respect to a bearing point on the workpiece so as to minimize part distortion.
4. Clamping design should be kept as simple as possible to minimize down time and for ease of maintenance.
5. Locating points should be far away from each other for ease of cleaning.
6. The workpiece must be held rigidly while the cutting tools are in operation.

All relevant details such as location surfaces, clamping surfaces, clamping methods, the amount of machining required must also be considered in the initial phase of the fixture design. The effect of design decisions on the overall function and operation of the tool is always considered. It is important to determine the faces on the fixture to be used as the datum surfaces. The location of these datum surfaces dictate the type of clamping necessary. For example if proper care is not taken in designing the clamping arrangement, the holes in a typical drilling and reaming operation, may become non circular during a subsequent machining operation, due to the elastic deformation of the material due to clamping.
1.2 **TYPES OF FIXTURES**

Fixtures are classified either by the machine they are used on, or by the process they perform on a particular machine tool. However, fixtures also may be identified by their basic construction features. While many fixtures use a combination of different features, almost all can be divided into five distinct groups. These are plate fixtures, angle plate fixtures, vise jaw fixtures, indexing fixtures and multi-part fixtures [1]. Each of these fixtures will be briefly discussed here.

1.2.1 **Plate fixtures**

As the name implies, plate fixtures are constructed from a plate with a variety of locators and clamps. These fixtures are the most common. Their versatility makes them adaptable for a wide range of machine tools. The material used for the fixtures is determined by the part being machined and the process being performed. A plate fixture is shown in Fig. 1.1 [1].

1.2.2 **Angle Plate Fixture**

This is a modified form of the plate fixture. Rather than having a reference surface parallel to the mounting surface, the angle plate fixture has a reference surface perpendicular to its mounting surface shown in Fig. 1.2 [1]. This fixture is useful for machining operations which are performed perpendicular to the primary reference surface of the fixture. Modified angle plate fixture can accommodate angles other than 90 degrees.
Figure 1.1: Plate Fixture[1]
Figure 1.2: Angle Plate Fixture [1]
1.2.3 Vise Jaw Fixtures

Vise jaw fixtures are basically modified vise jaw inserts which are machined to suit a particular workpiece as shown in Fig. 1.3 [1]. These are the least expensive type of fixtures to produce and the simplest to modify. Their limitations are in part size and the capacities of the available vises.

Figure 1.3: Vise Jaw Fixture [1]
1.2.4 Indexing Fixtures

Indexing fixtures are used to reference workpieces which must have machine details located at prescribed spacings. A typical indexing will normally divide a part into any number of equal spacings, such as those used for geometric shapes or gears. The fixture must have a positive means to accurately locate and maintain the indexed position, for instance the indexing pin. An example of an indexing fixture is shown in Fig. 1.4 [1].

Figure 1.4: Indexing Fixture [1]
1.2.5 Multi Part Fixtures

Multi part fixtures are normally used for one of two purposes: either to machine multiple parts in a single setting, or to machine individual parts in sequence, performing different operations at each station. A typical multi part fixture is shown in Fig 1.5 below [1].

![Figure 1.5: Multipart fixture](image-url)
1.3 PROBLEM STATEMENT

The preceding description of common fixtures in use today suggests that fixtures are currently designed for a specific task on a specific part geometry. There is only limited flexibility in using the same fixture for different part shapes and sizes. In order to comply with the needs of smaller batch sizes of the future [9] fixtures should also be redesigned with a view to making them flexible and versatile to increase productivity. The goal of the fixture designer today is to make them modular so that these modules can be used for a wide variety of part sizes, shapes, materials and weights. In this research, a subset of this problem has been addressed - the characterization of "proper" clamping forces for a family of machining processes.

The effect of different machining parameters on clamping forces, and machining forces and torque are very important in developing a flexible fixturing system. In this study a fixture is designed using a few modules, such as vee blocks and flat plates. Force and slip sensors are incorporated in the fixture to measure the clamping forces, thrust forces and torque. From the data obtained the mechanics of prehension and its effects on the dimensional and geometrical tolerances are appraised. The important issues that are studied are:

1. What is the minimum force necessary for clamping any part.

2. Can the minimum required clamping force be directly related to the machining forces.
Is there a unique method of clamping a family of parts, in order to provide "optimum" clamping force without any appreciable slippage or loss of rigidity.

The results from this work will be useful in the development of a methodology for design of flexible fixtures for untended machining which will provide adequate clamping forces for the family of machining operations considered.

This research was divided into three parts. In the first part, an instrumented fixture was designed to measure the clamping forces, machining forces and the torque during a machining operation. Secondly, a slip sensor was designed to detect the slip of the workpiece. And in the last part of the research, tests and analysis of the mechanics of prehension were carried out using the instrumented fixture. From the data obtained and the experiments performed, parameters affecting clamping force will be determined, and a model will be developed for a fixturing system to hold a part with minimum clamping force.

1.4 ORGANIZATION OF THESIS

This thesis is organized into 6 chapters. Chapter 1 introduces the importance of a flexible fixturing system compared to conventional fixturing and also states the objective of this research. Chapter 2 presents a detailed literature review of previous work done on flexible fixturing systems and workholding devices. Chapter 3 describes the experimental design and the methodology of the research performed. Chapter 4 contains the experimental results and analyses, of the proposed model. Chapter 5
discusses the results in detail. Finally, Chapter 6 concludes the thesis and suggests topics for further research...
The workholding industry has lagged behind other segments of the machine tool industry [10]. According to an expert in the workholding field, the industry is still using nineteenth century workholding concepts. Regardless of batch the size, conventional fixturing has been the norm in most production environments.

2.1 **CONVENTIONAL FIXTURING**

Fixtures are traditionally single purpose workholding devices which are designed and manufactured for specific processes and products. It is a labor intensive and time consuming job to design and set up the fixtures. It is also a serious problem to store and maintain a large number of different fixtures. Fixture storage space is sometimes much larger than the space for the machine tool itself [11]. Many corporations, depending on their size, have a group of specialists whose sole task is tool engineering. They design, specify and select necessary jigs and fixtures for each of the manufacturing operations [12]. At present workholding is often the least automated component of a flexible manufacturing system and may be the source of a potential bottleneck in the production process [13]. An approach that has been taken to solve this problem is the development of a flexible fixturing system.
2.2 FLEXIBLE FIXTURING

For greater flexibility and versatility and higher productivity, machinists, designers and engineers, have been challenged to develop flexible fixturing techniques. The industry wants to develop workholding that is sturdy, precise, universal, and can be made and maintained at a relatively low cost.

Flexible fixtures are designed to position and hold one or more families of workpieces, and will eliminate the expense of storing libraries of standard fixtures and outdated dedicated fixtures. Flexible fixturing, in general, attempts to combine the flexibility and economy of standard fixturing devices with the speed and accuracy of dedicated fixturing.

According to Thompson[4] the advantages to be gained by the development of a flexible fixturing system would be threefold. Firstly, it would reduce the lead-time and effort necessary in designing special fixtures. Secondly, it would reduce the overhead cost of storing a multiplicity of fixtures required to effect rapid changeovers between different assembly/machining tasks. And thirdly, it would simplify the programming requirements. The field of flexible fixturing is still very new and has not been fully developed by any means. Researchers have been able to develop fixtures that are flexible in nature, some more flexible than others.

A detailed background study on flexible fixturing systems has been done by Bagchi and Lewis [12]. The paper describes the role and importance of flexible fixturing in the manufacturing industry today and
compares and contrasts the difference between the requirements for conventional fixturing systems, with those utilized in fully untended factories. A Computer Aided Fixturing System has been proposed which can truly automate the fixture design process by integrating Computer Aided Manufacturing, Computer Aided Process Planning, Computer Aided Engineering and Data Base Management.

2.3 FLEXIBLE FIXTURING: SOME SOLUTIONS
A number of flexible fixtures have been developed and a number of solutions have been proposed for resolving the issue of how to locate and hold a wide variety of parts of different geometry. Some of the flexible fixturing systems will now be discussed in the next section.

2.3.1 Fluidized Bed Vise
In 1984, the Industrial Technology Institute (ITI) in Ann Arbor, MI launched a drive to develop a workable flexible fixturing system[14]. This system uses the two-phase nature of a gas-particle fluidized bed to accommodate and hold irregularly shaped parts as shown in Figure 2.1[4]. Many small steel spheres are retained in a container with a porous floor through which air flow is maintained at a carefully controlled rate. Under these conditions the spheres behave as a fluid in which the workpiece is partially immersed. Upon switching off the air supply the balls are compacted downwards under the influence of gravitational loading to form a solid mass which secures the workpiece. The principal characteristic of the vise is the ability of the spheres to behave as a solid or a liquid.
According to Thomas and Gandhi [14], this fluidized bed fixture can cut 75% off the time needed for fixture assembly, reduce fixture design time from days to hours, and lower inventory costs. Also, it permits a wide variety of different part geometries to be clamped because a liquid provides the ultimate conformable surface. In addition, since this device has only a few critical moving parts, the mode of operation is expected to be more reliable than units requiring extensive manipulation of a number of moving parts.

There are a number of drawbacks to the system as well. Vacuum compaction permits the vise to resist forces of about 13N only, exerted on a
workpiece immersed in the bed to a depth of 50mm[4]. This is considerably less than the weights of most commercially manufactured parts or the forces associated with metal cutting and forming. Hence, it would appear that this concept would be most appropriate for clamping parts during the assembly of small components, such as electronic assembly or, tool changes but not machining.

Another design of a conformable clamp developed by Wright, Kurokawa and Cutkosky [15]. The clamping device is capable of accommodating a variety of turbine blade shapes produced in an automated forging cell. These clamps eliminate the need to design and fabricate a specialized fixture for each of a possible set of several hundred blade styles. The design is limited for turbine blades only.

2.3.2 Petal Collet

The petal collet clamping device is an assemblage of petals each of tetrahedral shape with a large aspect ratio which are connected at a common joint as shown in Figure 2.2[4]. The workpiece is positioned on the axis of symmetry of the device and then the encircling clamping ring is moved vertically upwards, thereby clamping the workpiece[4].

A similar concept is used in designing the multi-leaf vise [4]. This device comprises a movable jaw of constant geometry and a fixed jaw which is a multi-leaf arrangement as shown in Figure 2.3[4]. Each leaf has one degree of freedom - rotation about one axis - which is restrained by torsional springs and this permits parts of different geometries to be grasped.
Both clamping devices mentioned above are inexpensive and simple to setup. But the inherent geometrical nature of the devices impose limitations on the size and shapes of parts that can be grasped. Since the device does not optimally grasp all workpieces, it has the potential for not constraining the part adequately and, furthermore, the surface finish of the part may be damaged by the clamps.
2.3.3 Modular Fixturing

Modular Fixturing is the most recent concept in the flexible workholding industry. It is an extension of the traditional mode of fixturing and was introduced by a German organization in 1984 [4]. The existing modular fixturing systems generally consist of a universal grid plate on which the fixture components are built up [8]. Riser blocks are included for assembling the fixture and strap clamps are often utilized for clamping. Modular fixturing is the means of locating parts which employs standard components that can be easily built up for one machining job and then reused for other tasks later. It accelerates the setup process and enables shorter production runs to be economical.

The commercially available modular fixturing systems can be categorized into the following two basic styles:

1. The T-slot system and
2. The Dowel-Pin system

The T-slot system (Figure 2.4[16]) utilizes a baseplate in which T-slots are machined in a grid pattern. Regardless of the baseplate shape, the T-slots are machined exactly perpendicular and parallel to each other to ensure accurate and precise alignment of the fixture elements. Each component is assembled by inserting T-clamping blocks in the slots which are then firmly mounted by a screw and bolt.
Two-way clamp adjustment:
Clamps slide parallel and perpendicular to T-slots.

Figure 2.4: An Example of a T-Slot Fixture [16]
An example of a T-slot fixture is the Modular Fixture System (MFS). It is assembled directly from a set of ready-made reusable standardized elements (Figure 2.5) [17]. This system is being strongly supported by the Chinese government, and nearly 10 million MFS elements are now in use in aviation, machinery, transportation, instrument, electrical, textile machinery, and light engineering industry in China. The China National Aero-Technology Import and Export Corporation (CATIC) compared dedicated fixturing to MFS and found that MFS can minimize fixture design work, reduce jig and fixture manufacturing time by 90% and lead time by 85%, achieve an 80% reduction in fixture manufacturing cost, save 95% on fixture material cost, and reduce fixture storage area.

Another very popular T-slot fixturing system is the Halder modular jig and fixture system [18]. It is very productive for small batch sizes and compared to a dedicated fixture, the setup time for the Halder system is a lot shorter.

Dowel-Pin systems also utilize a baseplate containing a grid pattern of holes which provide numerous locating combinations for positioning pins and studs. The system utilizes a series of precisely positioned dowel holes along with tapped holes to accurately mount and secure the fixture elements. A schematic of a Dowel-Pin modular fixture is shown in Figure 2.6 [19].
Figure 2.5: A Set of Ready Made Reusable Standardized Elements of a Modular Fixturing System [17]
Figure 2.6: An Example of a Dowel Pin Fixture [19]
Colbert, Manessa and DeVries [20] have developed a dowel-pin modular fixture for prismatic parts. This system can indicate when a workpiece is loaded, initiate a clamping sequence and then release the workpiece after it is processed. The design has been integrated into 3 basic modules: Fixture Base Plate, Tool Point Unit and the Clamp Unit. It can be loaded and unloaded by a robot for locating and clamping the prismatic workpieces. The fixture shows good repeatability, but there is much room for improvement. The fixture only uses the minimum requirement of 3-2-1 locating point concept, therefore it might have rigidity problems. Furthermore, the clamps are set in such a way that if a cut needs to be made all around the workpiece, sequential clamping and unclamping needs to be done. This may prove to be tedious and time consuming for some part shapes and sizes.

The feasibility of modular fixturing systems has been highly debated in the industrial community. There are several users [13,21,22] who strongly favor the design, development and use of the MFS. On the other hand, there are others [13,22] who show skepticism towards its flexibility and implementability in an industry with several thousand part shapes and sizes. Since, no state of the art MFS has yet been deployed and tested, it may be premature to conjecture on its true performance.

The move from conventional to flexible fixturing system has been fairly encouraging and beneficial overall to the workholding industry in terms of cost and time. Although they show feasibility of some hardware innovations, they have not revealed much information on where to put clamps around an arbitrary part. Consequently, new research is underway
to consider the geometrical constraints in workholding, correct part setup and reduction of non productive time in the system, partly from the viewpoint of traditional engineering mechanics and partly from the viewpoint of the more craft-oriented knowledge that is acquired from many years of knowledge. A traceable approach of developing an expert fixtureing system is the area of concentration in this era now.

2.4 EXPERT SYSTEM FOR FIXTURE DESIGN

Feasibility of an expert system for designing fixtures for workpieces which have to be machined is the latest development in the workholding industry. What some researchers want an expert system to be capable of achieving is, given the raw material description (might be obtained from a CAD database), the machine description and the list of operations to be performed on the workpieces, it should be possible, making use of the knowledge of operations, to generate and evaluate various fixture designs. Farreira, Kochar, Liu, Chandru [23] have developed a framework that outlines the basic rules in designing such an expert system,

Similarly, Wright and Englert [24] have also developed an expert framework system. The system plans part setups and clamping on a CNC machine tool. It employs a new production system language, Cell Management Language (CML), and attempts to capture the geometrical considerations in fixtureing, as well as the intuition of the machinist. The device automatically loads the clamps onto the fixture bed, locks it to the table and provides large holding force to the workpiece.
Wright and Hazen [25] are developing a Flexible Clamping System (FLECS). This aims to duplicate the efforts of skilled operators in the area of flexible sensor based clamping. The robot loads the workpiece. Then the sensors detect the coordinates of the piece and accordingly, the NC code is altered so the reference frames are aligned. The clamps are then lowered and pressurized onto the workpiece and the transformed NC code is downloaded and machining commences. FLECS will eventually lead to a new form of a machining center that can, inspect, manipulate, grind, machine, and clear chips.

Some work towards the development of an expert system is also being done by Toumi, Bausch, Blacker [26]. They want to integrate automation of modular fixturing with automated planning. Guidelines for automatic setup and reconfiguration of modular fixtures are developed. These guidelines include requirements for proper design, determining the layout requirements by examining the task, workpiece and system information. The assembly tasks are extremely difficult with the present technology but has been successful for simple prismatic parts and sheet metal fixturing.

The growth and development of the Flexible Manufacturing Systems suggest that the FMS of the future will be capable of planning the process in detail, develop a fixture, clamp, machine and unload the workpiece automatically. In other words, the expert system is being developed to perform all steps to manufacture a workpiece in a FMS without human intervention. But there are loop holes in the framework and guidelines. For example, none of the systems has considered the optimal design of the
system which minimizes the total work done on the workpiece, the clamping force and the deformation of the material.

2.5 SUMMARY

Industry has started leaning towards developing flexible fixturing systems to meet the demand for smaller batch sizes and the increasing requirements of productivity improvement. A number of different flexible fixtures have been designed, developed and implemented for workpieces of different shapes, sizes and weights. Among all the fixtures developed, modular fixturing system seems to be the most flexible and versatile.

Recent research has concentrated on developing an expert system for fixture design. The primary strategy towards this goal is the introduction to knowledge based system for machining and workholding. However, none of these systems utilize the actual clamping stresses necessary for holding the part without slippage, and thus are unsuitable for computer integrated manufacturing systems.

There is a need to study the effect of part location and clamping of a workpiece. This thesis considers this problem and proposes a relationship which minimizes the total work done and clamping force required without slippage or loss of rigidity during a machining operation. The next chapter describes the experimental design of the fixture, and the tests required and performed to develop the model.
CHAPTER III
EXPERIMENTAL DESIGN

In this research the effect of clamping forces, machining forces and torques is studied for simple machining operations such as drilling and milling. Fixtures with suitable force transducers were developed to measure clamping forces and machining torques and a sensor to detect the workpiece slippage. The data obtained will be useful in designing fixtures to hold a part with minimum clamping force and torque without allowing any slippage or loss of rigidity. The implication of this work will be the development of a methodology for design of flexible fixtures for untended machining operations.

The research is divided into three main parts:

- Design of the instrumented fixture.
- Design of a slip sensor to detect the slippage of the workpiece during a machining operation.
- Test and analysis of data using the instrumented fixture.

In this chapter the design of the instrumented fixture and the slip sensor are described first. The experiment details are then discussed.

3.1 DESIGN REQUIREMENTS FOR THE INSTRUMENTED FIXTURE

The main concern of the designer is that the fixture should be rigid enough to withstand the cutting forces and torques and also absorb most of the machining induced vibrations. A flexible fixture should be designed to
accommodate a wide variety of part shapes and sizes under different machining conditions for better flexibility and versatility.

There are a number of requirements needed in a design consideration for a fixture system. They are:

1. Locating of the workpiece: The locating of a workpiece in a fixture requires a three-two-one (3-2-1) principle [8]. This means that at least three locating points are required to locate the workpiece in the first plane, at least two locating pins in the second plane, and at least one locating pin to locate it in the third plane.

2. Clamping of the workpiece: The clamping elements should be enough to provide enough clamping forces to hold the workpiece in place during machining operations. However, the clamping forces must be applied as directly as possible without causing any elastic or plastic deformation of the workpiece. Clamping can induce some stresses that may tend to cause some distortion of the workpiece. If the distortion is significant, it will affect the accuracy in final dimensions of the workpiece after machining.

3. Support of the workpiece: The locators only provide sufficient support to secure the geometrical stability of the workpiece with respect to the machine tool, and this may not be sufficient to handle the forces without causing elastic deformation or slippage of the part. The supports add extra rigidity to the fixture to handle all the acting loads. But, they must not interfere with the locating of the workpiece already established.
3.2 DESIGN OF THE INSTRUMENTED FIXTURE

The fixture designed is subject to the limitations of complexity of shape and dimensions of the workpieces. It is suitable for cylindrical, rectangular, or square workpiece of different materials and lengths.

The workpiece can be held in the vise in two ways. The first method is to employ two flat plates as the clamping jaws of the fixture (Fig. 3.1). The advantage of using the flat jaws is that the workpiece can be mounted at any angle in the vise. However, if the size of the cylindrical bars increase the metal removal rate and the cutting forces exerted will also increase, and the flat jaw plates will not be able to hold the workpiece securely. Therefore, another fixture was designed to accommodate one movable and one fixed 90 degree vee jaws for better holding and locating of cylindrical parts (Fig. 3.2). The faces of one of the vee blocks provides the 3-2 portion of the 3-2-1 location principle used in standard fixture design, as mentioned in Section 3.1, while the other vee block constrains the workpiece completely for accurate and safe machining.

The fixed vee block is mounted on a platform of a 3 axis Kistler piezoelectric dynamometer (see Appendix A). The mounting surface of the jaw plate is ground to ensure that there are no gaps between the jaw plate and the dynamometer. A manual clamping screw is attached to the movable vee block to control the clamping action of the workpiece. This system is assembled on a flat base plate to support the workpiece. The bottom of the base plate is mounted on a four axis Kistler piezoelectric drilling
Figure 3.1: Flat Jaw Plates on the Fixture

Figure 3.2: Vee Jaw Plates of a Fixture
Figure 3.3: Schematic of the Instrumented Fixture
dynamometer (see Appendix A). The schematic of the fixture is shown in Fig. 3.3. The entire fixture is then clamped to the table of a CNC Bridgeport Series I vertical milling machine.

3.3 DESIGN OF THE SLIP SENSOR

In a drilling operation, slipping of a workpiece clamped in the vise may occur due to insufficient clamping force and/or excessive cutting forces and tool feed. Slipping of the workpiece results in poor dimensional accuracy, damage to the workpiece, reduced tool life and can be hazardous. Therefore, it is necessary to have a monitoring system to detect workpiece slippage during machining. The slip sensor was designed and implemented in the fixturing system for this purpose. This slip sensor is believed to be the first of its kind to be used in conjunction with a fixturing system.

The requirements for the slip sensing device for this work were:

a. It must be capable of detecting the smallest part slippage (1° or less rotation) during drilling.

b. It must be simple to setup and dismantle so that it can be easily transported.

c. It must be independent of the machine tool operation and control.

d. It must give a clean (visible or otherwise) signal to the operator of the machine tool.

Whenever slipping occurs, the slip monitoring system can sense it so that corrective actions can be taken immediately. Several designs were
considered, of which three most applicable are described below. Design #3 was the only design implemented in this research.

3.3.1 Design #1

In the first design a very small hole is drilled on the vertical surface of the workpiece and a straight thin metal connecting rod is snug fit into the hole as shown in Fig. 3.4. At the end of the rod a dial gage is placed. The feeler of the dial gage is rested against the rod and the dial setting is then set to zero. As the part slips the connecting rod will rotate and push against the feeler, and the dial indicator will measure its magnitude. The longer the rod is the more sensitive the slip will be.

Though this design was very simple, it was not implemented because it was

1. cumbersome to drill holes in each workpiece;
2. difficult to keep the slender rod absolutely rigid and straight for every experiment, especially if it had slipped and hit the vee blocks earlier on;
3. dependent on the sensitivity of the dial gage and thus would not be able to record the initiation of workpiece slippage;
4. difficult for the operator to machine and read the small dial indicator at the same time.
3.3.2 Design #2

In this design a GE Optomation vision camera would be used to detect the slip of the workpiece. The slip would be amplified and displayed on a CRT screen. This design would be a very good choice if the objective was to use the sensor data to modify the clamping forces and/or machining parameters in an untended manufacturing environment, but this design was not considered because,

1. it would be computationally slow - possibly non real time.
2. it was too sophisticated for implementation.
3. it will pick up rigid body motions such as vibrations of the workpiece and which could be mistaken for slippage.
4. it was too complex to implement in a laboratory environment.

Figure 3.4: Dial Gage Slip Sensor
3.3.3 Design #3

This is the design that was used in this research. In this design a very low power visible laser beam is shined onto the workpiece at a certain angle (Fig. 3.5). The light beam is reflected off the workpiece onto a stationary white opaque screen, set parallel to the fixture at a known distance. If the workpiece slips during the machining operation, so does the reflected beam, which is easily observed on the screen. As soon as the reflected beam shifts on the screen the machining operation should be stopped as the applied clamping force is too small. For ensuring repeatability the laser beam is always kept horizontal by using a spirit level, and a constant distance is maintained between the workpiece and the screen in all cases. Figure 3.5 shows the schematic of the slip sensor.

To analyze the angle of reflection as the workpiece slips a ray of light $\Delta O$ is considered. $\Delta O$ is incident at $O$ on the shiny surface $M_1$, $\alpha$ being the glancing angle with respect to $M_1$ as shown in Fig. 3.6. $O\Delta B$ is the reflected ray, the angle of deviation being $\angle COB=2\alpha$. If the workpiece slips, the shiny surface is rotated through an angle $\theta$ to a new position $M_2$. The incident ray is now reflected from $M_2$, in a direction $O\Delta P$ and the glancing angle of deviation $L\Delta COP$ will be $2(\alpha-\theta)$. The reflected ray has thus been rotated though an angle $BOP$ when the shiny surface is rotated

$$\angle BOP = \angle COB - \angle COP$$
$$\angle BOP = 2\alpha - 2(\alpha-\theta) = 2\theta$$
Thus, if the direction of an incident ray is unchanged, the angle of rotation of the reflected ray is twice the angle of rotation of the *shiny* surface [27]. For example, if the workpiece slips by 4 degrees, the reflected ray turns through 8 degrees.
Calibration of the Slip Sensor

In the design of the slip sensor it was important to calibrate the screen for several reasons:

1. Starting the experiments at the same initial point of the reflected ray makes replication of experiments much easier and accurate.

2. By quantification of slip the magnitude of the workpiece skippage can be quantified.

3. Setting a limit on the maximum slip is permissible in a future work.

4. Reproducibility of experiments is easier.
A horizontal light beam of light is reflected off the workpiece and hit the screen at an initial point B as shown in Fig 3.7. The screen in the slip sensor is calibrated 1° of slip apart. This was because it is the smallest slip that is clearly visible on the screen. When the workpiece slips 1°, it rotates from position \( W_1 W_2 \) to position \( W_1' W_2' \) and the light beam hits the screen at \( B' \), similarly if the workpiece slips another 1°, the surface of the workpiece rotates to \( W_1'' W_2'' \) and the light beam hits the screen at \( B'' \) and so on. To calibrate the points \( B', B'' \) etc. the angle of reflection \( \theta \) would need to be known. This is done by measuring a perpendicular distance \( Y \) from the screen to the workpiece (A to 0) and the horizontal distance \( X \) from A to the initial B. Using simple trigonometry, \( \tan \theta = X/Y \), \( \theta \) is calculated. Once \( \theta \) is known, subsequent markings are determined by increasing \( \theta \) by \( \Delta \theta (1°) \) and the distance \( Y \) is kept constant. An example of the markings on the screen are shown in Fig. 3.8.

### 3.4 PRODUCTION OF SPECIMENS

Each specimen was cut 3.0mm longer than the required length using a parting tool on a turret lathe. Then 1.5mm was faced off on each side of the material using a carbide cutting tool on an engine lathe. In the facing operation the same spindle speed and feed rate (automatic feed) was used for each specimen. The last step was to produce the reflecting flat surface at the side of the specimen for the laser beam to reflect off and detect slippage. This was done by grinding a consistent flat surface using a belt sander. Every specimen was made on the same setup to ensure a small tolerance.
band. A typical specimen is shown in Fig. 3.9 and its dimensions in Table 3.1.

Figure 3.7: Calibration of the Screen for the Slip Sensor

Markings 2 degrees apart

Figure 3.8: An Example of Calibration Markings on the Screen
Table 3.1: Dimensions of the Specimens

<table>
<thead>
<tr>
<th>A (mm)</th>
<th>B (mm)</th>
<th>C (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.7</td>
<td>38.0</td>
<td>5</td>
</tr>
<tr>
<td>12.7</td>
<td>25.4</td>
<td>5</td>
</tr>
<tr>
<td>12.7</td>
<td>12.7</td>
<td>5</td>
</tr>
</tbody>
</table>

3.5 EXPERIMENTAL WORK

Experiments were performed using the instrumented fixture with an assortment of parts, sizes and part materials in a drilling operation on a CNC vertical milling machine. The objective was to determine the
relationship between the clamping force and the thrust force and torque as the machining parameters are changed.

In the experiments the independent variables were:

1. feed rate
2. spindlespeed
3. drill size
4. workpiece size
5. workpiece material

The dependent variables were:

1. minimum clamping force
2. machining force
3. torque
4. slip

For each experiment an NC program (see Appendix C) was written, so that the drilling was performed in the same area in each workpiece and the depth of the hole drilled was constant. During drilling the clamping forces were decreased periodically until they became too small and/or the specimen slipped. The data were recorded just before the workpiece slipped to determine the minimum required clamping force (MRCF) prior to slippage.

The experiment was divided into five major steps. Initially, 1018 plain carbon steel workpiece of 38mm height and 25.4mm diameter was drilled to a depth of 12.7mm using a 9.5mm HSS drill. From the data obtained by varying the spindle speed and feed rate a relationship between
the clamping force and thrust force and torque was established. Four more sets of experiments were then performed and in each case one of the following parameters was changed to study its effect on MRCF:

1. Length of the specimen.
2. Drill diameter.
3. Friction at workpiece

3.5.1 Reduction in Length of the Specimen
This set of experiments was performed to test the effect of the length of contact between the workpiece and the clamps on clamping force. Firstly, the specimen length was reduced from 38mm to 25.4mm and then, the length was reduced further to 12.7mm. Drilling was carried out for each specimen length for several speeds and feed rates but with a fixed drill diameter.

To avoid non uniform forces acting on the workpiece, it was loaded in the middle of the vee blocks. This was done by raising the workpiece using appropriate height of the bottom supports, so that the vise was loaded symmetrically.

3.5.2 Different Drill Sizes
In this test the effect on clamping was studied as the drill size was changed. In the first sequence, the drill diameter was increased from 9.5mm to 12.7mm and in the second set the drill size was reduced to 8mm. The speed
and feed rate were varied but the frictional conditions and the workpiece length were kept constant.

3.5.3 Reduction of Friction
In this case, the frictional condition between the bottom support and the workpiece was reduced to examine its effect on the minimum required clamping force. The friction was reduced firstly by grinding the bottom surface of the workpiece to make it smoother and secondly, by using a set of lubricated ball bearings to support the piece as shown in Fig. 3.10. Twelve ball bearings of 0.2 cm diameter were lubricated using light machining oil. The feed rate and spindle speed were varied, but the drill size and part length were kept constant.

Figure 3.10: Lubricated Ball Bearings on the Bottom Support of the Fixture.
3.5.4 Change of Work Material
Experiments were also performed with 2024 aluminum (124 BHN) and free machining 12L14 steel (164 BHN) specimens, in addition to 1018 plain carbon steel (164 BHN) specimens used initially. The chemical composition and physical properties are shown in Appendix B. For these experiments the feed rate and spindle speed were varied but frictional forces, drill size and part length were kept constant.

3.5.5 Other Machining Parameters
Parameters like workpiece diameter, fixture material, depth of cut and presence or absence of cutting fluid were also some of the parameters considered in determining the effect an clamping force, but from experience and past studies[28,29] it appears that the parameters that were be tested in sections 3.5.1 to 3.5.4 contributed to the effect on clamping force the most. Also, due to the limitation of the size of the project and the design of the fixture parameters like part shape and change in jaw angles were not studied.

3.6 SUMMARY
In this chapter an instrumented fixture was designed to measure the clamping forces and machining forces of a workpiece during a drilling operation. To monitor and recognize the slip, a sensitive, easy to implement slip sensor using a laser beam was developed. The last part of the chapter discusses the details of the experimental work performed on the sensor
based fixture. Results from the experiments carried out are followed in the next chapter.
4.1 RELATIONSHIP OF MINIMUM REQUIRED CLAMPING FORCE WITH THRUST FORCE AND TORQUE

The relationship of minimum required clamping force with thrust force and torque is derived for cylindrical 1018 steel specimens 38mm in length and 25.4mm in diameter using a 9.5mm HSS drill. In each experiment the spindle speed and feed rate were set and the minimum required clamping force, thrust force and torque were recorded on a strip chart recorder. The results are presented in Table 4.1.

The relationship of thrust force and torque with feedrate for drilling has been well established by scientists before [29]. This relationship is supported by the results in the Table 4.1. It was found that as the spindle speed increases the thrust force and torque decrease whereas, as the feedrate increases the thrust and torque increase.

These results obtained lead us to believe that required clamping force is related to the thrust force and torque in some way. Therefore, firstly the minimum required clamping force as a function of thrust force and then minimum required clamping force as a function of torque will be investigated. Subsequently a relationship of minimum required clamping force as a function of both thrust force and torque will be considered.
Table 4.1: Data from Machining 38mm Long 1018 Steel Specimen with a 9.5mm HSS Drill

<table>
<thead>
<tr>
<th>No.</th>
<th>Spindle Speed (rpm)</th>
<th>Feed Rate mm/min</th>
<th>Thrust Force (N)</th>
<th>Torque N-cm</th>
<th>Minimum Clamping Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1000</td>
<td>12.7</td>
<td>110</td>
<td>25</td>
<td>75</td>
</tr>
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<td>125</td>
</tr>
<tr>
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<td>135</td>
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<tr>
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<td>700</td>
<td>12.7</td>
<td>340</td>
<td>65</td>
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<td>480</td>
<td>75</td>
<td>200</td>
</tr>
<tr>
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<td>1000</td>
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<td>125</td>
<td>250</td>
</tr>
<tr>
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<tr>
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<td>500</td>
<td>76.0</td>
<td>1850</td>
<td>450</td>
<td>800</td>
</tr>
</tbody>
</table>
4.1.1 **Minimum Required Clamping Force as a Function of Thrust Force**

A graph of minimum required clamping force vs. thrust force is plotted in Fig. 4.1. The analysis of the data was accomplished by using the statistical analysis package Minitab [30]. The data are summarized in Table 4.2.

(a) **Statistical Analysis**

Based on the data in Table 4.1, the regression equation is

\[
\text{Minimum required clamping force} = 18.1 + 6.394 \times \text{Thrust Force}
\]

**Table 4.2**: Analysis of **Minimum** Required Clamping Force vs. Thrust Force

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficient</th>
<th>StDev.</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>18.06</td>
<td>10.44</td>
<td>.05</td>
</tr>
<tr>
<td>Thrust</td>
<td>0.39419</td>
<td>0.01108</td>
<td>&lt; .0005</td>
</tr>
</tbody>
</table>

given

\[N = \text{No. of tests performed} = 28\]

\[\text{MSE} = \text{Mean Square Error} = 770\]

Standard deviation = 27

\[R^2 = \text{Coefficient of determination} = 98\%\]
Figure 3: Variation of Clamping Force with Thrust Force;

38mm long 1018 Steel Specimen, 9.5mm diameter HSS Drill
(b) Significance of Thrust Force

To test whether there is a linear relationship between minimum required clamping force and thrust force using the regression model obtained above, the t-test was carried out. The two alternative hypothesis that were considered were [31]:

\[ \begin{align*}
H_O & : \text{Thrust Force} = 0 \\
H_I & : \text{Thrust Force} \neq 0
\end{align*} \]

Explicit tests of the alternatives are based on the t-test where

\[ t = \frac{\text{Thrust Force}}{s(\text{Thrust Force})} \]

The decision rule with this test statistics when controlling the level of significance at \( a \) is:

- If \( |t| \leq t(1-\alpha/2; n-2) \), conclude \( H_O \)
- If \( |t| > t(1-\alpha/2; n-2) \), conclude \( H_I \)

where \( a = 0.05 \),

Thrust Force = 0.394,

\( s(\text{Thrust Force}) = 0.01108 \)

the \( t(0.975; 26) = 2.056 \)

Thus, the decision rule for testing alternatives is

- If \( |t| \leq 2.056 \), conclude \( H_O \)
- If \( |t| > 2.056 \), conclude \( H_I \)

Since, \( |t| = 10.394/0.01108 = 35.56 > 2.056 \) it is concluded that thrust is not zero and there is a linear association between minimum required clamping force and thrust force.

The 95% Confidence Interval of the thrust force is:
Thrust Force \( \pm t(1-\alpha/2; n-2) s(\text{Thrust Force}) \)

\[ 0.317 \leq \text{Thrust Force} \leq 0.417 \]

(c) Significance of the Constant

The hypothesis and Confidence Interval for the constant value are derived in the same manner as for the thrust force. From Table 4.2 the T-Ratio for the constant is 1.98 and at \( \alpha = 0.05 \), \( t(0.975, 26) = 2.056 \). Therefore, as \( t = 1.73 < 2.056 \) concludes, the fact cannot be rejected that the constant is zero 95% of the time.

The 95% Confidence Interval of the constant is:

\[ -3.4 \leq \text{Constant} \leq 39.52 \]

The significance of the constant and thrust force is summarized in Table 4.3

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Hypothesis</th>
<th>95% C.I.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>Const = 0</td>
<td>Not Significant</td>
</tr>
<tr>
<td>Thrust</td>
<td>'Thrust \neq 0'</td>
<td>Significant</td>
</tr>
</tbody>
</table>

The degree of linear association between minimum required clamping force and thrust is calculated by R2. It is known as the coefficient of determination and can be interpreted as the proportionate reduction of total variation in minimum required clamping force associated with the use of
thrust force [32]. The larger the $R^2$ the higher the correlation between minimum required clamping force and thrust force which can be seen in the linear relationship between the two variables.

4.1.2 Minimum Required Clamping Force as a Function of Torque

A plot of minimum required clamping force vs. torque is shown in Fig. 4.2 and the analysis is summarized in Table 4.4. The resulting regression equation is

$$\text{Minimum required clamping force} = 57.6 + 1.52(\text{Torque})$$

Table 4.4: Analysis of Minimum Required Clamping Force with Torque

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficient</th>
<th>StDev.</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>57.59</td>
<td>13.52</td>
<td>&lt; .0005</td>
</tr>
<tr>
<td>Torque</td>
<td>1.5173</td>
<td>0.06095</td>
<td>&lt; .0005</td>
</tr>
</tbody>
</table>

given,

$N=28$

$\text{MSE} = 1539$

$\text{Standard Deviation} = 39.24$

$R^2 = 95.8\%$

The significance of the constant and torque is summarized in Table 4.5
Figure 4.2: Variation of Clamping Force with Torque; 38mm long 1018 Steel Specimen, 9.5mm diameter HSS Drill
From the results in the table above it is shown that both the constant value and torque are significant in determining the minimum required clamping forces. The results in sections 4.1.1 and 4.1.2 lead us to believe that minimum required clamping force is a function of both thrust force and torque. The next section will investigate this relationship.

4.1.3 Minimum Required Clamping Force as a Function of Thrust Force and Torque

The results above show that minimum required clamping force is a function of the thrust force and torque separately. Therefore combining both the variables obtained in Table 4.1 the regression equation of minimum required clamping force as a function of thrust force and torque is

Minimum required clamping force = 20 + 0.372(Thrust Force) + 0.0886(Torque)

The analysis and results of the relationship are summarized in Tables 4.6 & 4.7.
Table 4.6: Analysis of Clamping Force with Thrust Force and Torque

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficient</th>
<th>StDev.</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>19.95</td>
<td>12.29</td>
<td>.1</td>
</tr>
<tr>
<td>Thrust</td>
<td>0.3717</td>
<td>0.8741</td>
<td>&lt; .0005</td>
</tr>
<tr>
<td>Torque</td>
<td>0.0886</td>
<td>0.2881</td>
<td>.3</td>
</tr>
</tbody>
</table>

Given,

\[ N = 28 \]

\[ \text{MSE} = 720 \]

Standard Deviation = 26.8

\[ R^2 = 98\% \]

Table 4.7: Inferences Concerning Constant, Thrust Force and Torque

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Hypothesis</th>
<th>95% C.I.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>Const = 0</td>
<td>Not Significant</td>
</tr>
<tr>
<td>Thrust</td>
<td>Thrust ≠ 0</td>
<td>Significant</td>
</tr>
<tr>
<td>Torque</td>
<td>Torque = 0</td>
<td>Not Significant</td>
</tr>
</tbody>
</table>
Thrust force and torque are highly correlated with each other. The multicollinearity and the high correlation between the two variables explains the reason the estimated regression coefficients are individually significant but are not so when related together [31].

The Confidence Interval at $a = 0.05$ for thrust force has been determined separately. But to analyze the correctness of the entire set of data points, the results are combined together and the confidence band of the whole curve is developed.

4.1.4 Confidence Band for the Regression Line

To see in what region the entire regression line lies, the confidence band for the regression line of minimum required clamping force vs. thrust force is analyzed.

Working and Hotelling [31] derived the formula for the $1-a$ hyperbolic confidence band for the regression line. At any level $X_n$, the two boundary values of the confidence band are:

$$Y_n + Ws(Y_n)$$

where

$$W^2 = 2F(1-a, 2, n-2)$$

$$Y_n = B_0 + B_1X_n$$

The equation of the regression line is:

Minimum Required Clamping Force = 18.1 + 0.394(Thrust Force)

given,

$N=28$
\[ \text{MSE} = 770 \]

Mean of X = 814.46

\[ F(0.95, 2, 26) = 3.37 \]

\[ W = 2.6 \]

The data are summarized in Table 4.8 and the confidence band of the regression line is plotted in Figure 4.3.

Table 4.8: Data for 95% Confidence Interval of Minimum Required Clamping Force as a Function of Thrust Force

<table>
<thead>
<tr>
<th>Thrust Force ( X_0 ) (N)</th>
<th>Minimum Clamping Force ( Y_0 ) (N)</th>
<th>( W s(Yn) )</th>
<th>95% Confidence Interval (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>96.9</td>
<td>22.4</td>
<td>(74.5, 119.3)</td>
</tr>
<tr>
<td>400</td>
<td>175.7</td>
<td>18.1</td>
<td>(157.6, 193.8)</td>
</tr>
<tr>
<td>600</td>
<td>254.5</td>
<td>15.0</td>
<td>(239.5, 269.5)</td>
</tr>
<tr>
<td>800</td>
<td>333.3</td>
<td>13.6</td>
<td>(319.7, 346.9)</td>
</tr>
<tr>
<td>1000</td>
<td>412.1</td>
<td>14.6</td>
<td>(397.5, 426.7)</td>
</tr>
<tr>
<td>1200</td>
<td>490.9</td>
<td>17.6</td>
<td>(473.3, 508.5)</td>
</tr>
<tr>
<td>1400</td>
<td>569.7</td>
<td>21.1</td>
<td>(548.0, 591.4)</td>
</tr>
<tr>
<td>1600</td>
<td>648.5</td>
<td>26.4</td>
<td>(622.1, 674.9)</td>
</tr>
<tr>
<td>1800</td>
<td>727.3</td>
<td>31.5</td>
<td>(695.8, 758.8)</td>
</tr>
<tr>
<td>2000</td>
<td>806.1</td>
<td>36.8</td>
<td>(769.3, 842.9)</td>
</tr>
</tbody>
</table>
The confidence band was developed by taking a number of values of $X_0$ and determining the boundary points. A pair of boundary curves were drawn by joining these points. The boundary points of the confidence band are not very much farther apart than the confidence limits for a single response $E(Y_n)$ at a given $X_n$ value. With a somewhat wider limit for the entire regression line, one is able to draw conclusions about any and all mean responses for the entire regression line and not just about the mean response at a given $X$ level.

The above analysis shows that thrust force and torque contribute in determining the minimum required clamping forces. They are both highly correlated with each other and one cannot be expressed in terms of minimum required clamping force without the other.

### 4.2 Dependence of Clamping Force on Process Variables and Workpiece Specifications

#### 4.2.1 Change in Length of Specimen

Experiments were performed using 25.4mm and 12.7mm 1018 steel specimens to study the influence of specimen length on the minimum required clamping force. The other variables were kept exactly the same as before. The results for the 25.4mm specimens are presented in Table 4.9, and those for 12.7mm specimens in Table 4.10. The curves for these experiments are shown in Fig. 4.4 & 4.5 respectively.
Figure 4.3: Confidence Band for the Regression Line; Clamping Force as a function of Thrust Force

\[ y = 44.4717 + 0.3662x + 1.6688 \times 10^{-5}x^2 \quad R = 0.00 \]

\[ y = -8.2717 + 0.4213x - 1.6688 \times 10^{-5}x^2 \quad R = 1.00 \]
Table 4.9: Data from Drilling 25.4mm Long 1018 Steel Specimen with a 9.5mm Drill

<table>
<thead>
<tr>
<th>No.</th>
<th>Spindle Speed (rpm)</th>
<th>Feed Rate mm/min</th>
<th>Thrust Force (N)</th>
<th>Torque N-cm</th>
<th>Clamping Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>850</td>
<td>12.7</td>
<td>325</td>
<td>75</td>
<td>165</td>
</tr>
<tr>
<td>2</td>
<td>850</td>
<td>12.7</td>
<td>325</td>
<td>75</td>
<td>170</td>
</tr>
<tr>
<td>3</td>
<td>500</td>
<td>12.7</td>
<td>500</td>
<td>125</td>
<td>215</td>
</tr>
<tr>
<td>4</td>
<td>500</td>
<td>12.7</td>
<td>500</td>
<td>150</td>
<td>235</td>
</tr>
<tr>
<td>5</td>
<td>1000</td>
<td>76.0</td>
<td>1000</td>
<td>250</td>
<td>450</td>
</tr>
<tr>
<td>6</td>
<td>850</td>
<td>76.0</td>
<td>1150</td>
<td>250</td>
<td>465</td>
</tr>
<tr>
<td>7</td>
<td>500</td>
<td>76.0</td>
<td>1600</td>
<td>250</td>
<td>465</td>
</tr>
</tbody>
</table>

Table 4.9: Data from Drilling 12.7mm Long 1018 Steel Specimen with a 9.5mm HSS Drill

<table>
<thead>
<tr>
<th>No.</th>
<th>Spindle Speed (rpm)</th>
<th>Feed Rate mm/min</th>
<th>Thrust Force (N)</th>
<th>Torque N-cm</th>
<th>Clamping Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1000</td>
<td>12.7</td>
<td>300</td>
<td>50</td>
<td>175</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>12.7</td>
<td>450</td>
<td>80</td>
<td>250</td>
</tr>
<tr>
<td>3</td>
<td>1000</td>
<td>38.0</td>
<td>600</td>
<td>125</td>
<td>325</td>
</tr>
<tr>
<td>4</td>
<td>1000</td>
<td>76.0</td>
<td>1000</td>
<td>300</td>
<td>300</td>
</tr>
</tbody>
</table>

Statistical Analysis was done to determine the significance of the length of the material on minimum required clamping force. The results are summarized in Table 4.1. The high significance value shows that the length does not contribute to the clamping force.
Table 4.1: Analysis of Minimum Required Clamping Force with Thrust

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficient</th>
<th>StDev.</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>40.65</td>
<td>29.13</td>
<td>0.1</td>
</tr>
<tr>
<td>Thrust</td>
<td>0.2563</td>
<td>0.0575</td>
<td>&lt; .0005</td>
</tr>
<tr>
<td>Length</td>
<td>0.4505</td>
<td>0.2317</td>
<td>0.025</td>
</tr>
<tr>
<td>Length</td>
<td>0.1350</td>
<td>0.8254</td>
<td>&gt; 0.4</td>
</tr>
</tbody>
</table>

From the results it is seen that a change in length does not affect the required clamping force shown in Tables 4.1, 4.9, 4.10 and 4.11 for 12.7mm, 25.4mm, 38mm long specimens. Thus the clamping force appears to be independent of the length of the material.

Effect of Clamping Force per Unit Length

Changing the length of the specimen has no effect on the minimum required clamping force as shown and discussed in Section 4.2.1 earlier. However a distinct relationship seems to exist between thrust force and torque and the clamping force per unit length. The results are presented in Table 4.12 below and the graph is represented in Fig. 4.6.
Figure 4.4: Variation of Clamping Force with Thrust Force; 25.5mm long 1018 Steel Specimens, 9.5mm diameter HSS Drill.
Figure 4.6: Variation of Clamping Force Per Unit Length with Thrust Force
Figure 4.5: Effect of Length of Specimen on Clamping Force; 12.7mm long 1018 Steel Specimens, 9.5mm diameter HSS Drill
From the results presented above it can be seen that clamping force per unit length increases as the length of the specimen decreases. This was a new finding and will be discussed in Chapter 5.

4.2.2 Reduction of Friction

Experiments were also performed by reducing friction between the workpiece and the bottom support as discussed in Section 3.4.2. All other process and workpiece variables were kept constant. The results are presented in Table 4.13 below and are plotted in Fig. 4.7.
Table 4.13: Data from Drilling 38 mm Long 1018 Steel Specimen with 9.5 mm HSS Drill: Reduced Friction Condition

<table>
<thead>
<tr>
<th>No.</th>
<th>Spindle speed (rpm)</th>
<th>Feed Rate mm/min</th>
<th>Thrust Force (N)</th>
<th>Torque N-cm</th>
<th>clamping Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>850</td>
<td>12.7</td>
<td>200</td>
<td>60</td>
<td>150</td>
</tr>
<tr>
<td>2</td>
<td>850</td>
<td>12.7</td>
<td>200</td>
<td>70</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>500</td>
<td>12.7</td>
<td>240</td>
<td>110</td>
<td>380</td>
</tr>
<tr>
<td>4</td>
<td>500</td>
<td>12.7</td>
<td>250</td>
<td>120</td>
<td>350</td>
</tr>
<tr>
<td>5</td>
<td>1000</td>
<td>38.0</td>
<td>500</td>
<td>225</td>
<td>600</td>
</tr>
<tr>
<td>6</td>
<td>850</td>
<td>76.0</td>
<td>650</td>
<td>300</td>
<td>950</td>
</tr>
</tbody>
</table>

From the curve it was observed that a reduction in friction between the bottom support and the workpiece increases the required clamping force during machining. It was to be expected that when the bottom friction was reduced, the machining torque was balanced by the friction force in the circumferential direction on the workpiece by the vertical surface (that is, between the vee blocks and the workpiece). Therefore to resist the slip, higher clamping forces were required.
Figure 4.7: Effect on Clamping Force on Friction
4.2.3 Change in Drill Size

These experiments were similar to the other experiments except that a larger drill (12.7 mm diameter) was used. The drill size was too big for the small workpiece and fixture and caused a lot of chatter and vibration. No deductions could therefore be drawn from this experiment. When a 8.0 mm drill diameter was used the original relationship between minimum required clamping force and thrust force and torque was found to be valid (the results are presented in the Table 4.14 and Fig. 4.8). Clamping force was thus found to be independent of drill size.

Table 4.14: Data from Drilling 38 mm Long 1018 Steel Specimen with an 8 mm HSS Drill.

<table>
<thead>
<tr>
<th>No.</th>
<th>Spindle Speed (rpm)</th>
<th>Feed Rate</th>
<th>Thrust Force (N)</th>
<th>Torque Ncm</th>
<th>Clamping Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>500</td>
<td>12.7</td>
<td>380</td>
<td>70</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>38.0</td>
<td>780</td>
<td>165</td>
<td>340</td>
</tr>
<tr>
<td>3</td>
<td>1000</td>
<td>38.0</td>
<td>550</td>
<td>85</td>
<td>220</td>
</tr>
<tr>
<td>4</td>
<td>850</td>
<td>76.0</td>
<td>875</td>
<td>190</td>
<td>350</td>
</tr>
<tr>
<td>5</td>
<td>500</td>
<td>76.0</td>
<td>1250</td>
<td>220</td>
<td>500</td>
</tr>
<tr>
<td>6</td>
<td>500</td>
<td>102.0</td>
<td>1100</td>
<td>250</td>
<td>400</td>
</tr>
</tbody>
</table>

Statistical Analysis was done to determine the significance of the drill diameter on clamping force. The results are summarized in Table 4.15. The high a value shows that the drill diameter does not affect the clamping force.
Table 4.15: Analysis of Minimum Required Clamping Force with Thrust Force, Torque and Drill Size.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficient</th>
<th>StdDev.</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-8.22</td>
<td>89.37</td>
<td>&gt;0.4</td>
</tr>
<tr>
<td>Thrust</td>
<td>0.3665</td>
<td>0.0623</td>
<td>&lt;.0005</td>
</tr>
<tr>
<td>Torque</td>
<td>0.0926</td>
<td>0.2448</td>
<td>.35</td>
</tr>
<tr>
<td>Drill Size</td>
<td>3.331</td>
<td>9.337</td>
<td>.35</td>
</tr>
</tbody>
</table>

4.2.4 Change in Workpiece Material

Experiments were also performed to determine the effect of workpiece material on minimum required clamping force. In the first set of experiments the specimens used were 2024 aluminum alloy, and in the second set of experiments the specimens were 12L14 free machining steel. The results from these experiments are presented in Tables 4.16 & 4.17 and the curves are plotted in Fig. 4.9 & 4.10, respectively. The relationship was found to be independent of the workpiece material.
Table 4.16: Data from Drilling 38mm 2024 Aluminum Specimen with a 9.5mm HSS Drill.

<table>
<thead>
<tr>
<th>No.</th>
<th>Feed Rate mm/min</th>
<th>Thrust Force (N)</th>
<th>Torque N-cm</th>
<th>Clamping Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>850</td>
<td>12.7</td>
<td>380</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>850</td>
<td>38.0</td>
<td>400</td>
<td>70</td>
</tr>
<tr>
<td>3</td>
<td>500</td>
<td>38.0</td>
<td>500</td>
<td>90</td>
</tr>
<tr>
<td>4</td>
<td>850</td>
<td>76.0</td>
<td>725</td>
<td>125</td>
</tr>
<tr>
<td>5</td>
<td>500</td>
<td>76.0</td>
<td>1125</td>
<td>400</td>
</tr>
</tbody>
</table>

Table 4.17: Data from Drilling 38mm Long 12L14 Steel Specimen with a 9.5mm HSS Drill.

<table>
<thead>
<tr>
<th>No.</th>
<th>Spindle Speed (rpm)</th>
<th>Feed Rate mm/min</th>
<th>Thrust Force (N)</th>
<th>Torque N-cm</th>
<th>Clamping Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1000</td>
<td>12.7</td>
<td>120</td>
<td>25</td>
<td>75</td>
</tr>
<tr>
<td>2</td>
<td>850</td>
<td>12.7</td>
<td>150</td>
<td>30</td>
<td>130</td>
</tr>
<tr>
<td>3</td>
<td>700</td>
<td>12.7</td>
<td>160</td>
<td>35</td>
<td>120</td>
</tr>
<tr>
<td>4</td>
<td>500</td>
<td>38.0</td>
<td>425</td>
<td>110</td>
<td>200</td>
</tr>
<tr>
<td>5</td>
<td>500</td>
<td>38.0</td>
<td>475</td>
<td>110</td>
<td>225</td>
</tr>
</tbody>
</table>

Statistical Analysis was performed to determine the significance of the workpiece material on clamping force. The results are summarized in Table 4.18. The high value of the workpiece material shows that the material does not contribute to the minimum required clamping force.
Table 4.18: Analysis of Minimum Required Clamping Force with Thrust Force, Torque and Workpiece Material.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficient</th>
<th>StDev.</th>
<th>( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>7.61</td>
<td>50.41</td>
<td>&gt; 0.4</td>
</tr>
<tr>
<td>Thrust</td>
<td>0.4274</td>
<td>0.0430</td>
<td>&lt; .0005</td>
</tr>
<tr>
<td>Torque</td>
<td>0.1850</td>
<td>0.1614</td>
<td>0.05</td>
</tr>
<tr>
<td>Material</td>
<td>0.1322</td>
<td>0.3199</td>
<td>0.35</td>
</tr>
</tbody>
</table>

From the results presented above it can be inferred that a change in workpiece material had little or no effect on the minimum required clamping force. The mechanical and chemical properties of the materials were different. For example, the hardness of the aluminium alloy was 124 BHN while that for the 1018 steel was 164 BHN. The minimum required clamping forces reduced for softer materials but the linear relationship remained the same.

4.3 Verification of the Model

The model in Section 4.2.3 has been developed for a drilling operation using a simple twist drill. This model will now be tested to for its applicability to other machining operations using the instrumented fixture.
Figure 4.9: Dependence of Clamping Force on Work Material Properties; 38mm long 2024 Aluminum Specimen with a 9.5mm HSS Drill
Figure 4.10: Dependence of Clamping Force on Work Material Properties; 38mm long 12L14 Steel Specimen with a 9.5mm HSS Drill
4.3.1 Center Drilling

Center drilling experiments with the same setup produced the same results as the drilling operation. Since, the center drill was of a smaller diameter than the twist drill, for the same feed rate and spindle speed the thrust force, torque and clamping force were smaller, but the relationship remained the same. The results are shown in Table 4.19 and plotted in Fig.4.11.

Table 4.19: Data from Center Drilling 38mm Long 1018 Steel Specimen

<table>
<thead>
<tr>
<th>No.</th>
<th>Spindle Speed (rpm)</th>
<th>Feed Rate mm/min</th>
<th>Thrust Force N</th>
<th>Torque N-cm</th>
<th>Clamping Force N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1000</td>
<td>12.7</td>
<td>80</td>
<td>25</td>
<td>70</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>12.7</td>
<td>380</td>
<td>70</td>
<td>180</td>
</tr>
<tr>
<td>3</td>
<td>1000</td>
<td>38.0</td>
<td>550</td>
<td>100</td>
<td>250</td>
</tr>
<tr>
<td>4</td>
<td>700</td>
<td>38.0</td>
<td>800</td>
<td>150</td>
<td>300</td>
</tr>
</tbody>
</table>

4.3.2 Reaming

A 9.1mm drilled hole was reamed using a 9.5mm straight flute HSS reamer. The metal removal rate was very small as is to be expected. As a result, the thrust forces were very low. Consequently no significant minimum required clamping forces were required and the workpiece rarely slipped. Because of the limited data, no definite conclusions could be drawn about the applicability of the model to reaming.
4.3.3 Punch Milling

A 9.5mm HSS punch mill was used to mill a 12.7mm deep hole using the same instrumented fixture and the slip sensor. The vibrations were very high because of the flat end of the mill which resulted in high metal removal rate. High vibrations made it difficult to determine the actual machining forces and torques on the strip chart. The approximate values of the forces and torques are listed in Table 4.20 and are shown graphically in Fig. 4.12.

Table 4.20: Data from Punch Milling 38mm Long 2024 Aluminum Specimen with a 9.5mm Cutter.

<table>
<thead>
<tr>
<th>No.</th>
<th>Spindle Speed (rpm)</th>
<th>Feed Rate (mm/min)</th>
<th>Thrust Force (N)</th>
<th>Torque N-cm</th>
<th>Clamping Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>850</td>
<td>12.7</td>
<td>75</td>
<td>40</td>
<td>225</td>
</tr>
<tr>
<td>2</td>
<td>1000</td>
<td>12.7</td>
<td>100</td>
<td>50</td>
<td>225</td>
</tr>
<tr>
<td>3</td>
<td>500</td>
<td>12.7</td>
<td>125</td>
<td>75</td>
<td>325</td>
</tr>
<tr>
<td>4</td>
<td>1000</td>
<td>38.0</td>
<td>175</td>
<td>100</td>
<td>350</td>
</tr>
<tr>
<td>5</td>
<td>700</td>
<td>38.0</td>
<td>225</td>
<td>125</td>
<td>425</td>
</tr>
<tr>
<td>6</td>
<td>500</td>
<td>38.0</td>
<td>300</td>
<td>175</td>
<td>500</td>
</tr>
</tbody>
</table>

The results clearly display that the model does not hold for punch milling. The required clamping forces are substantially higher in punch milling than it is in drilling.
Figure 4.12: Clamping Forces for a Punch Milling Operation;
4.4 SUMMARY

Based on the experimental data, a relationship of minimum required clamping force as a function of thrust force and torque was developed. Change in length of specimen, drill size, and material of specimen did not affect the minimum required clamping force. However, the friction between the bottom support and the workpiece was found to affect it. The smaller the contact friction the higher was the clamping force required. Also, the clamping force per unit length increased as the length of the specimen decreased.

This model has been satisfactorily tested for drilling operations. An attempt was made to evaluate the suitability of the model for other machining operations, such as center drilling, reaming and punch milling. The model was found to hold for center drilling, but no conclusions could be made for reaming and it did not hold for punch milling. These results will now be discussed in the next chapter.
CHAPTER V
DISCUSSION OF RESULTS

It is very important to determine the optimum clamping force to avoid workpiece slippage due to under-clamping, or deformation of the part due to over-clamping. Generally, machinists tend to overclamp the workpieces significantly more than necessary which very often leads to elastic deformation of the material. A small experiment was performed in this study to verify the concept of over clamping. Experienced machinists were asked to clamp a number of workpieces during a drilling operation. Without inquiring about the drill size or the machining forces being used, they tightened the clamp as tight as they possibly could. Results are shown in Table 5.1. Jaw impressions were left on the workpieces by the sides of the vee blocks of the clamps. The clamping forces in all cases were almost 2 to 3 times higher than the highest clamping forces required during the drilling operation performed. Therefore, it is very important to determine what parameters effect the clamping force and develop a relationship to predict the required clamping force during a machining operation to avoid hazardous or inaccurate machining practice.
Table 5.1: Clamping Force Applied by Machinists

<table>
<thead>
<tr>
<th>operator</th>
<th>Workpiece Length (mm)</th>
<th>Drill Diameter (mm)</th>
<th>Clamping Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>38</td>
<td>12.7</td>
<td>1250</td>
</tr>
<tr>
<td>2</td>
<td>38</td>
<td>12.7</td>
<td>1500</td>
</tr>
<tr>
<td>3</td>
<td>38</td>
<td>12.7</td>
<td>2200</td>
</tr>
<tr>
<td>4</td>
<td>38</td>
<td>12.7</td>
<td>2800</td>
</tr>
<tr>
<td>5</td>
<td>38</td>
<td>12.7</td>
<td>1800</td>
</tr>
</tbody>
</table>

5.1 **INSTRUMENTED FIXTURE**

The instrumented fixture designed and used in this study was simple, compact and versatile. Because the fixture was compact, machining had to be limited to small workpieces using low machining forces. The highest spindle speed the fixture could safely machine at was 1250 rpm and the highest feed rate was 100 mm/min. Above these values, the tool chattered and chipped and caused the fixture to vibrate. Therefore, all the experiments were carried out in the range of safe machining, that is, spindle speeds between 500 rpm and 1000 rpm, and feed rate between 12.7 mm/min and 76 mm/min.

To test the repeatability of the values obtained from the instrumented fixture, two sets of experiments were repeated four times. The results are presented in Table 5.2 and 5.3.
Table 5.2: Data from Drilling a 38mm Long 1018 Steel Specimen, using a 9.5mm HSS Drill: Test for Repeatability of Results (Set No. 1)

<table>
<thead>
<tr>
<th>Spindle Speed rpm</th>
<th>Feed Rate mm/min</th>
<th>Thrust Force N</th>
<th>Torque N-cm</th>
<th>Clamping Force N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>12.7</td>
<td>550</td>
<td>110</td>
<td>225</td>
</tr>
<tr>
<td>1000</td>
<td>12.7</td>
<td>625</td>
<td>140</td>
<td>250</td>
</tr>
<tr>
<td>1000</td>
<td>12.7</td>
<td>600</td>
<td>125</td>
<td>250</td>
</tr>
<tr>
<td>1000</td>
<td>12.7</td>
<td>600</td>
<td>140</td>
<td>280</td>
</tr>
</tbody>
</table>

Table 5.3: Data from Drilling a 38mm Long 1018 Steel Specimen, using a 9.5mm HSS Drill: Test for Repeatability of Data (Set No. 2)

<table>
<thead>
<tr>
<th>Spindle Speed rpm</th>
<th>Feed Rate mm/min</th>
<th>Thrust Force N</th>
<th>Torque N-cm</th>
<th>Clamping Force N</th>
</tr>
</thead>
<tbody>
<tr>
<td>850</td>
<td>12.7</td>
<td>250</td>
<td>50</td>
<td>120</td>
</tr>
<tr>
<td>850</td>
<td>12.7</td>
<td>225</td>
<td>40</td>
<td>130</td>
</tr>
<tr>
<td>850</td>
<td>12.7</td>
<td>300</td>
<td>60</td>
<td>140</td>
</tr>
<tr>
<td>850</td>
<td>12.7</td>
<td>250</td>
<td>50</td>
<td>125</td>
</tr>
</tbody>
</table>

From the results in Table 5.2 the average clamping force is 251N and the maximum deviation is about 12% from the mean. In Table 5.3 the average clamping force is 129N and the values deviate from the mean by only about 8%. The maximum of a 12\% deviation shows good repeatability and
consistency of results. The reasons for such inconsistencies could be because of all or some of the following:

1. Human error.

2. It is not possible for all four vee blocks to be in contact with the workpiece at the same time and apply the same clamping force.

3. The spindle speed was only an approximate value because the dial gage of the machine was not very accurate and a strobe was not used to set the speeds.

4. The strip chart recorder showed some play in recording the forces and torque.

5. Inaccuracy of the milling machine.

Most of the errors mentioned were small enough to be ignored individually, but the cumulative addition of two or more of these errors led to the slight inconsistency of results that was observed. The play in the strip chart recorder was the one to contribute the most to the error in results because it was difficult to quantify. The other sources of error, as mentioned above were fairly consistent throughout the experiment, whereas, in case of the strip chart recorder, over a period of time the amount of error changed. However, fairly accurate deductions are represented from the data obtained.
5.2 SLIP SENSOR

The initial set of experiments were performed by detecting workpiece slippage based on visual observation, using 25.4mm and 12.7mm length 1018 steel specimens with a 9.5mm inch HSS drill. In this case drilling was performed at the same area in each workpiece and the depth of the hole drilled was kept constant. During drilling the clamping forces were decreased periodically till slippage of the workpiece was observed. A scatter plot of the results are shown in Fig 5.1 and 5.2.

Figure 5.1: Results of Minimum Required Clamping Force as a Function of Thrust Force using Visual Detection of Slip.
As seen in these graphs no relationship can be deduced from the results without using a slip sensor. This is because a small slip that takes place at the very onset of slip is too sensitive to be detected by the human eye. A slip sensor that could detect and quantify infinitesimal slip was thus necessary to develop the model. As mentioned in section 3.3 other sensors were considered, but the slip sensor used in this study was the simplest to design, easiest to implement and as sensitive as the others would have been.
The slip sensor would have future potential if the sensor data were to be used to modify the clamping force and/or machining parameters in an untended manufacturing environment. One way to do this is by implementing a feedback loop to control the machining based on part slippage. A flow chart of this design is shown in Fig.5.3. The same concept can be implemented on the design of the slip sensor using the GE Optomation II vision system as mentioned in chapter 3 section 3.3.2.

5.3 PRELIMINARY ANALYSIS OF THE MODEL
The experiments were performed under the assumptions listed below:

1. Thrust force and machining torque are the same in all cases for constant drill size, material, feed rate, spindle speed.
2. The pressure distribution was uniform at all contact lines/surfaces with the vee blocks.
3. Workpiece undergoes no deformation under clamping or supporting forces.
4. There was friction between the bottom surface and the workpiece and also between the vise jaws and the workpiece.

From the experiments it was shown that minimum required clamping force is a linear function of thrust force and torque. The relationship was analyzed to be linear because physically a straight line appeared to be the best fit when the data points were plotted on the graph. Statistically when a straight line was fit through it, the coefficient of determination $R^2$ was extremely high, leading us to believe that a linear function is the best fit.
Figure 5.3: Flow Chart for Automation of Slip Sensor
In both the relationships of minimum required clamping force, as a function of thrust force and minimum required clamping force as a function of torque the curve should pass through the origin. This is because a workpiece does not require any clamping force when the thrust force and/or torque are zero. The original curves did not pass through the origin because at small forces the noise increases, resulting in higher deviations of the readings from the actual data. As a result of these problems it was not possible to obtain any data for very small machining force and torque.

Figure 5.4 A reading of Clamping Force on a Strip Chart Recorder
Fig. 5.4 shows an example of a clamping force reading on a strip chart obtained during drilling. Let the mean reading be $B$ and the error in locating the centerline of the noise $\delta A$ as shown in Fig. 5.5. Where $A$ is the amplitude of the noise. Average value of the signal is then read as $B + 6A$.

So, $\text{error} = \frac{\text{Measured} - \text{Actual}}{\text{Actual}}$

$= \frac{(B + 6A) - B}{B}$

$= \frac{6A}{B}$

As long as the amplitude is very small the error would be small as well. As a result a large amplitude of noise will have a larger deviation from the actual reading.
Due to the high noise to signal ratio at smaller machining forces the error towards the origin of the curve was exaggerated. Despite the inaccuracy of interpretation, the results were still fairly accurate because the 95% Confidence Band obtained in chapter 4 in Fig. 4.3 included the (0,0) point even though the straight line originally did not pass through the point. It is thus inferred that the error in minimum required clamping force that seems to be introduced for very small machining force and torque is not significant at commercial drilling speeds and feed rates.

5.3.1 Machining Parameters

Four machining parameters were changed during drilling to observe their effect on the clamping force. Change in length of the specimen, drill size and workpiece material had no effect on the force. Whereas, a reduction of friction between the workpiece and fixture required higher forces to clamp the workpiece.

The same clamping force is required to resist the workpiece from slipping regardless of the length of the material because thrust force and torque are independent of the length and will not change. The same argument is valid for change in workpiece diameter. Regardless of the diameter of the workpiece the thrust force and torque will not change, as the thrust force and torque are dependent on the drill diameter and not the workpiece diameter. On the other hand the clamping pressure or in this case clamping force per unit length (line contact of workpiece with vise) will
increase as the length of the workpiece decreases to overcome the applied clamping force. This is because as the clamping force remains the same, the change in length of the specimen will have a direct effect on the clamping force/unit length.

The effect of friction on clamping force is obvious because if the friction between two surfaces increase the tendency for the piece to rotate or slip will reduce and clamping force to resist the slip of the piece will also reduce. In this research the frictional force was reduced between the surface of the workpiece and the bottom support. This reduction in friction lessened the hold between the bottom surfaces. As a result higher clamping forces were required to resist the slippage or rotation of the workpiece.

The change in drill size has no effect on the relationship obtained. It is still valid except that reduction in the drill size also reduces the metal removal rate. As a result the thrust force, torque and clamping force are also linearly reduced, keeping the relationship the same. This suggests that the relationship is independent of the drill size.

The material of the workpiece did not affect the relationship in any way either. The mechanical and chemical properties of each material is different but a harder material will require higher machining forces whereas, a softer material will require smaller forces. But the same linear relationship will be followed and results will not deviate from the derived relationship.
5.3.2 Verification of the Model

Center drilling is applicable to the model because a center drill is designed in a similar manner as the twist drill. The center drill used was smaller in size. The same principle applies when the model was tested for different drill sizes i.e., the forces will decrease linearly following the same relationship.

The other machining operation that was tested for verification of the model was punch milling. Even though the forces acting on the workpiece are similar to the drilling operation, the model cannot be applied to punch milling because the milling cutter is designed differently from a twist drill as shown in Figure 5.6 and Fig. 5.7. According to Bhattacharya and Sen [33] the total thrust force during drilling is a summation of 3 components:

1. Thrust force due to cutting at both the lips excluding the chisel edge zone.
2. Thrust force due to flank friction at both the lips excluding the chisel edge.
3. Thrust force at the chisel edge due to indentation action.
Figure 5.4: An Example of a Typical Twist Drill

Figure 5.7: An Example of a Punch Mill
This clearly states that the thrust force is dependent on the shape and dimension of the drill. In a punch mill the tool is shaped very differently and it has a flat bottom with no chisel edge. Therefore, the resultant thrust force in milling will be different from that in drilling. Because of the dependency of the tool geometry on thrust force, it can be concluded that the proposed model is valid for drilling operations only.

The developed model in this research can determine the "safe and unsafe" clamping domain and predict the minimum clamping force required of a workpiece during a drilling operation without allowing any slippage or loss of rigidity. The model describes the clamping force to be a function of thrust force, torque and frictional forces. The friction was kept constant by maintaining the surface finish of the contact areas as similar as possible and developing a relationship as a function of the other two variables; thrust force and torque. The thrust force and torque are dependent on each other, therefore, a linear increase in one variable leads to a linear increase in the other.

The proposed model is satisfactory in a drilling operation only. This is because in drilling the thrust force and torque are dependent on the shape of the tool e.g. the chisel edge, lips and flanks of the twist drill. Other machining operations such as milling, boring have very different tool geometry, resulting in different relationships for clamping forces. The same concept that was used in this research can be applied to other machining
operations to develop a model for minimum required clamping force in untended machining operations.

5.4 DISCUSSION OF THE MODEL

An area overlooked by the researchers in development of flexible fixtures or expert systems is quantifying the clamping force during the machining operation. This study is important because, a very small a clamping force can lead to slippage of the workpiece, chattering, poor geometrical tolerances and can be hazardous. On the other hand, overclamping can lead to other problems such as part distortion and deflection resulting in inaccurate machining. Results mentioned in the beginning of this chapter clearly show that in industry, machinists have a tendency to overclamp the workpiece. The model developed in this study can reduce the clamping force by at least 50%, if not more. Rahman [34] has studied the effect of overclamping a cylindrical bar in a 3 jaw chuck during a turning operation. Figure 5.8 shows deviation of the workpiece during clamping. The variation in stiffness (directional orientation) was studied and factors like clamping force and contact between the workpiece and jaws were found to be responsible for the variation in shape of the workpiece. The study done in this research has attempted to overcome the clamping problem and propose a model for safer and more accurate machining, but by no means has it been fully developed, it is just the first step in the right direction.
The minimum clamping force can be determined for a cylindrical workpiece of any length, diameter or material during a drilling operation regardless of the drill size provided that the friction is the same as it was in the instrumented fixture. The model would be more useful and applicable if the frictional coefficients could be quantified but physically this was difficult to achieve. One way to quantify the friction at the sides of the vise would be to reduce the bottom support friction to almost zero. This can be done by placing a pyramid shaped HSS pin as the base and support the workpiece at the tip of the pin during the drilling operation. In this case the frictional forces at the sides only will resist the slippage of the workpiece. With this model other machining setups like a 4 jaw chuck can be used during the drilling operation, as long as the friction on the sides of the jaws do not vary.
from the friction at the sides of the vise on the fixture. Drilling operation in a 4 jaw chuck does not have a bottom support therefore, similar concept will apply if the frictional force is reduced to zero on the instrumented fixture. According to Rahman [34] the greater the contact area between the jaws and workpiece the less is the deterioration and deformation of the material. But by increasing the contact area the friction coefficient will change and the model will not be applicable any more. Anytime the friction changes for example change in surface finish, change in materials, amount of contact of workpiece with the fixture, the model will change. Therefore it is very important to determine how friction is related to clamping forces under different frictional conditions and incorporate it into the model to make it more general and useful so any machining operation can be performed.
CHAPTER VI
CONCLUDING REMARKS

6.1 CONCLUSIONS
Automated flexible fixturing systems are efficient and productive, but these fixtures cannot determine the clamping force required for a part during a machining operation. A technique to determine the minimum clamping force in a safe domain has been developed, without slippage or deformation of the part. This can lead to a safer and more reliable untended machining practice.

The slip sensor designed to detect the slip of the workpiece is believed to be the first of its kind to be used in conjunction with a fixturing system. The design is simple, easy to implement and can detect the minutest (1° of slip) rotation during drilling. The slip sensor would have future potential if the sensor data could be used to modify the clamping force and machining parameters in an untended manufacturing environment.

In this research an instrumented fixture and the slip sensor were used to develop a model to determine the minimum clamping force in a safe clamping domain. The model resulted in a linear relationship of clamping force as a function of thrust force and torque. Summary of the models developed are listed in Table 6.1. Other machining parameters, such as length of the specimen, drill size, workpiece material and frictional forces were changed to study their effect on the clamping force. Change in length of the specimen, drill size and material of specimen had no effect on the developed relationship, whereas, a change in friction affected the clamping force.
Results show that the model obtained for the "fail-safe" region holds for drilling operations at constant frictional forces used during the experiment. To make the fixture more versatile the frictional forces need to be incorporated into the model. The concept is believed to be general enough that it can be applied to other processes, especially for untended machining.

Table 6.1: Summary of the Developed Models

<table>
<thead>
<tr>
<th>Parameters Included</th>
<th>Model</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust Force</td>
<td>$18.1 + 0.394$ (Thrust Force)</td>
<td>98%</td>
</tr>
<tr>
<td>Torque</td>
<td>$57.6 + 1.52$ (Torque)</td>
<td>95.8%</td>
</tr>
<tr>
<td>Thrust Force &amp; Torque</td>
<td>$20 + 0.372$ (Thrust Force) + 0.0886 (Torque)</td>
<td>98%</td>
</tr>
</tbody>
</table>

6.2 FUTURE RESEARCH

6.2.1 Short Term Objectives

This research is the first step in the direction of automating clamping within a safe region without under or over clamping the workpiece. In order to use the model for machining operations the frictional forces need to be incorporated into the model.

A relationship of clamping force as a function of thrust force, torque and frictional force (at the contact areas) should be developed. Frictional forces are generally difficult to obtain because the surface finish and contact
area between the workpiece and fixture are constantly changing and there are no simple way to quantify this force.

Recently Lee and Haynes [35] have developed a program using finite element analysis which applies Coulomb's law of friction at the interface of contact between two bodies. It can only determine the frictional forces between limited number of interfaces. With the help of this program, it might be possible to carry out experiments with known frictional forces.

It is obvious that the relationship between clamping force and machining force and torque will change for different machining operation. In this research the model was developed for cylindrical workpieces and for drilling only. Further research should be carried out to determine clamping forces for other machining operations, such as turning, milling, boring etc. The model should also be able to accommodate different part shapes, sizes, finishes and weights for greater flexibility and versatility.

6.2.2 Long Term Development

The ultimate goal is to develop an automated clamping system which can determine and apply the safe minimum clamping forces for a workpieces of any shape, size or weight during any machining operation. The two main areas that need to be studied are: incorporating the coefficient of friction, and developing a generic model for all machining operations. In the first area of study the problem is that the fundamental calculations for friction are difficult to correlate with the material that is being machined [36]. The added practical constraints of change in material, surface finish, contact
area, lubricants etc. make the problem of determining friction far from ideal. A fruitful area of research would be to develop heuristics and a chart for frictional forces for work materials that are commonly machined. In the second area of study, studies should be done to develop a common model for safe clamping should be developed for all machining operations.

It is envisioned that the factory of the future would utilize a Computer Integrated Manufacturing (CIM) system where a modular fixturing system would be used in conjunction with a component geometry based on Computer Aided Process Planning (CAPP) and NC part program generation. CAPP would use as input the description of both the desired finished workpiece geometry and the original workpiece geometry. CAPP, utilizing the workpiece specification, could then determine the proper sequence of machine tool operations to produce the part and have the capability of evaluating the appropriateness of the machine tool operation and tooling combination. In the design and specification phase, a data base can be established that the fixturing system could access to determine acceptability of a given fixture design. This data base would determine the clamping combination of a workpiece and clamp without slippage or part distortion for a given cutting tool specification.

Finally, expert system can be developed to design and manufacture any part within a safe domain of minimum clamping force. Research in this thesis was the initial step of determining such a domain in an untended machining operation. It is a very effective and important stage but more research is required to fully manifest and launch the model into practice.
APPENDIX A
DYNAMOMETRY

In these experiments the clamping force was measured by a quartz 3-component \( (F_x, F_y, F_z) \) piezoelectric platform dynamometer manufactured by Kistler. The dynamometer has great rigidity and consequently a high natural frequency, while its high resolution enables the smallest dynamic changes in large forces to be measured. The dynamometer is shown in Fig. A.1 and its specifications are listed in Table A.1.

Table A.1: Specifications of the 3-Component Piezoelectric Platform Dynamometer[37]

<table>
<thead>
<tr>
<th>Type</th>
<th>9257 ASN 95368</th>
<th>( F_x )</th>
<th>( F_y )</th>
<th>( F_z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Messbereich</td>
<td></td>
<td>0...5 000</td>
<td>0...5 000</td>
<td>0...10 000</td>
</tr>
<tr>
<td>Gamme de mesure</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensibilität</td>
<td>[N]</td>
<td>-7.84</td>
<td>-7.91</td>
<td>-3.74</td>
</tr>
<tr>
<td>Linearität</td>
<td>[pC/N]</td>
<td>0.5</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Temperatur</td>
<td>0...70 °C</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Made in Switzerland by KISTLER

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Figure A.1: A 3-Component Kistler Piezoelectric Platform Dynamometer

[37]
The torque and thrust force were measured by a Kistler quartz 4-component (Fx, Fy, Fz, Mz) piezoelectric drilling dynamometer measuring the axial force, torque and deflective forces when drilling. This dynamometer also possesses high rigidity and therefore a high natural frequency, enabling the smallest dynamic changes to be measured in large basic forces. The dynamometer is shown in Fig. A.2 and the specifications are listed in Table A.2.

Table A.2: Specifications of the 4-Component Piezoelectric Drilling

<table>
<thead>
<tr>
<th>Type</th>
<th>SN</th>
<th>1 Fx / 2 Fy</th>
<th>Fz</th>
<th>Mz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Messbereich</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measuring range</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Empfindlichkeit</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitivity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linearität</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperatur</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9273</td>
<td>122981</td>
<td>0 ... 5000</td>
<td>0 ... 20 000</td>
<td>± 10 000</td>
</tr>
<tr>
<td>0 ... 5000</td>
<td>0 ... 5000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 3,71</td>
<td>- 1,95</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 3,70</td>
<td>1,97</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0,3</td>
<td>0,3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0,3</td>
<td>0,3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 ... 70 °C</td>
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</table>
Figure A.2: A 4-Component Kistler Piezoelectric Drilling Dynamometer

[37]
## WORKMATERIAL Properties

### Table B.1: The Mechanical and Chemical Properties of each Material used in the experiments [38]

<table>
<thead>
<tr>
<th>Material</th>
<th>Hardness</th>
<th>Mechanical Properties</th>
<th>Chemical Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR 1018 Plain Carbon Steel</td>
<td>BHN 163 R 885</td>
<td>82,000 70,000 65</td>
<td>C .15 - .20 Mn .60 - .70 P .04 S .05</td>
</tr>
<tr>
<td>12L14 Free Machining Steel</td>
<td>BHN 163 R 886</td>
<td>79,000 71,000 180</td>
<td>C Max .15 Mn .04 - .09 Pb .15 - .35 P .04 - .09 S .26 - .35</td>
</tr>
<tr>
<td>2024 T3-5 Aluminum</td>
<td>BHN 120</td>
<td>68,000 47,000 Very good</td>
<td>Si .50 Fe .50 Cu 3.8 - 4.9 Ti .15 Mg .30 - .90 Mn 1.2 - 1.8 Cr .10 Zn .25</td>
</tr>
</tbody>
</table>
APPENDIX C

NC PROGRAM FOR DRILLING EXPERIMENTS

In each experiment performed, the drilling operation on the Bridgeport Series II vertical milling machine was controlled by an NC program listed in Fig. C.1. The program was modified each time the feed rate of the drill was changed.

```
N10 G0 G90 X-2.000 Y-2.000 T1 M06
N20 G0 X0 Y0
N25 Z-3.750
N30 G81 Z0.50 F05
N35 X0 Y0
N40 G80
N45 G0 G90 X0 Y0 Z0
N50 M25 M02 M00
```

Figure C.1: NC Code for Drilling a 12.7mm Deep Hole
BIBLIOGRAPHY


37. Anonymous, Operation and Service Instructions, Kistler Corporation, Switzerland.
END OF THESIS