Manufacturing Glass-fiber Reinforcement for Grinding Wheels

by

Nicolas Joseph Avril

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Abstract

By analyzing the manufacturing process for organic grinding wheels, some characteristics of the reinforcing glass fiber disc added during the fabrication of these wheels are determined. The toughening mechanisms at work in a fiber glass reinforced grinding wheel are analyzed. The stresses inside a grinding wheel in use are determined. Different designs for a reinforcing glass fiber disc are then presented and discussed. One design is chosen and the plans for a prototype machine that will manufacture a reinforcement disc with the chosen design are presented. The different tasks and the issues associated with the manufacturing process are discussed. Finally, an economic and material feasibility analysis is made to determine the possibility of eliminating the current reinforcement supplier.

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Acknowledgments

As I am finishing writing this thesis, I believe this is the final point of my life as a student. This is the end of a journey that started in Bordeaux, France where my family is still living. In a safe and lovely atmosphere, I discovered my attraction for science and technology.

I studied within the French educational system, first in Lyon then in Paris where I entered the *Ecole Superieure de Physique et de Chimie Industrielles de la Ville de Paris*. Some teachers in this school and the director, Pierre Gilles de Genes, gave me their enthusiasm for science.

I then came to MIT to complete my education with a program sponsored by Norton Company. The friendship of the employees of the organic R&D at Norton made my decision to come here easy. I also gained from them the belief that engineering work can be done in a relaxed atmosphere and that too much stress is not a requirement even in competitive industries.

During my whole life as a student, I made friends who believed in the same value as me, namely love, optimism and work, balanced in a life leaving room for sports and arts.

So in a formal way here, I would like to thank all these persons (they know who they are) for having made my life so easy and enjoyable; for their advice and their love.

Thank you all.

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Chapter 1

Introduction

In order to face their competitors more efficiently in a free market society, companies need to continuously decrease the cost of their products. But in an environmentally concerned society, saving energy (in order to slow down the rate at which we burn fossil fuel) by reducing the waste of manufactured materials has become a requirement. Our project with Norton Company for the Material Processing and Manufacturing Institute at M.I.T. targeted these two purposes as we wanted to reduce the waste of glass associated with the making of reinforcement discs and at the same time reduce the cost of making these discs.

1.1 The Reinforcement Problem

Our research was done with the R&D department of the organic branch. The goal of the reinforcement project was to reduce by the costs associated with making the woven glass-fiber disc reinforcing the wheels. The origins of the disc cost are given in table 1.1. The reasons for setting such a target are multiple. The new reinforcement system must equal the performance of the current system in terms of grinding characteristics, as well as product safety. This system must fit easily into an automatic or semi-automatic molding operation.

In the classical manufacturing process, these discs are die-cut from a woven glass-cloth coated with a polymer. It is obvious that cutting discs from a part which has

operation/material	% of disc price
fiberglass roving	14%
paper, drying, packing	62%
resin	12%
weaving	6%
material wastage	6%

Table 1.1: Origins of the cost of a reinforcement disc.

a square shape immediately generate about 22% waste. There must be some way to reduce this waste by either changing the shape of the reinforcement or by changing the way these disks are manufactured.

In addition, in 1994, a new reinforcement disc that looks like a spirograph was introduced to the market. There is no denying that such a design creates very little waste, which is also one of our purposes, but we need to keep in mind our other priorities, a reduction in cost for example, and it is not certain that such a reinforcement can meet this goal.

The other issues related to this project are the following:

- Since the cost reduction will have a variable impact at various Norton facilities, the implementation of an individually manufacturing disc device will have to be adoptable to the plants.

- The prototyping and development of a new machine must meet the company goals for capital investment.

- The new system should not affect the environment in a negative fashion more than the current system does today. As appropriate, solutions that can further reduce the environmental impact will be investigated.

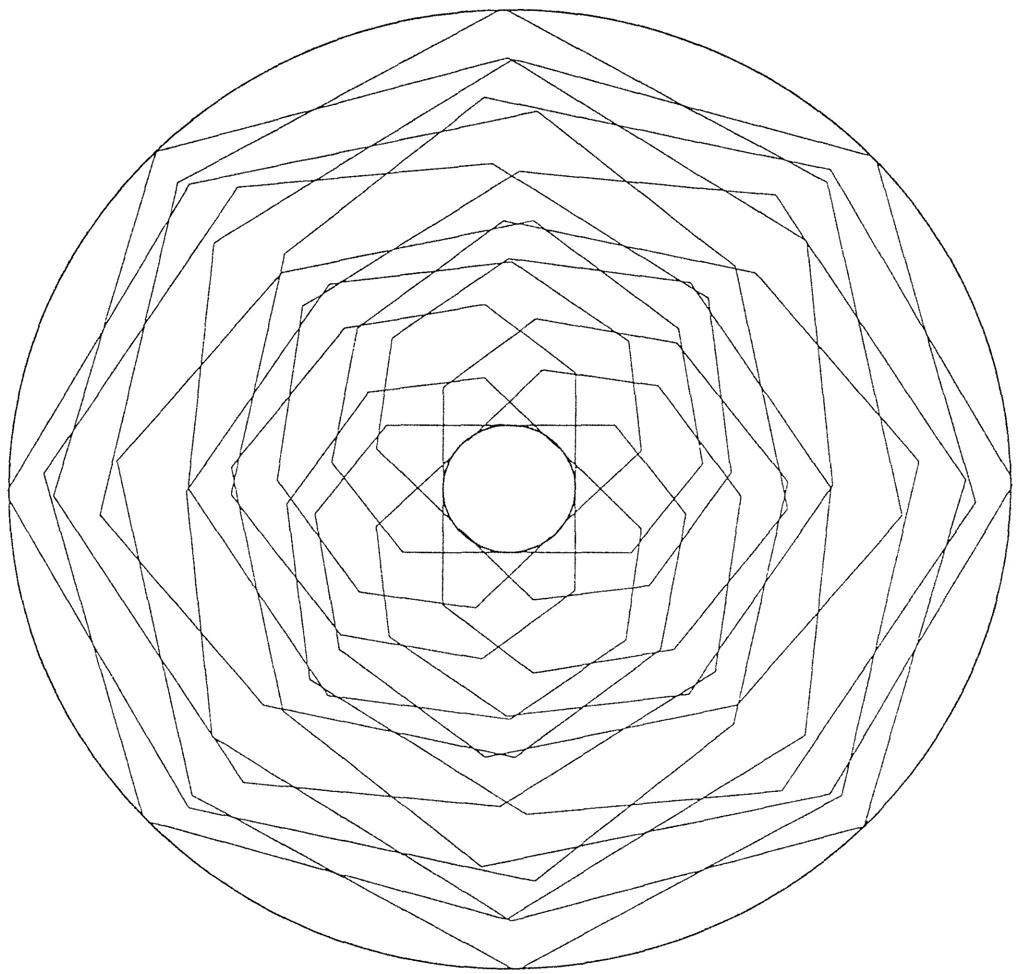

Figure 1-1: Reinforcement design of the Olbo Patent.

1.2 Thesis Outline

In Chapter two we give information about abrasives in general and deal with issues associated with reinforcing a grinding wheel with glass fibers. The process of manufacturing a grinding wheel is presented.

Chapter three analyzes grinding wheels as a glass matrix composite and presents the deformation and reinforcement mechanisms at play in a wheel in use.

Chapter four analyzes the stresses in a disc using analytical solutions and finite element analysis.

In chapter five we discuss different designs that can be used to make a reinforcement for a grinding wheel and their advantages and disadvantages.

Chapter six reviews the different tasks performed by the prototype machine and presents the different parts of the machine.

In Chapter seven, the feasibility of such a machine for a larger scale has been evaluated from an economic as well as from a material point of view.

Chapter 2

The Making of a Grinding Wheel

Everybody who has worked with wood, metal, plastic or ceramic materials knows what abrasive products are. However, very little is usually known about how these products are manufactured and what they are made of, as this is not fundamental for the end-user. To understand this research, we need a deeper knowledge of these characteristics. This chapter gives some information about abrasive grains in general and about the manufacture of grinding wheels. The reinforcement disc is in contact with the grain and goes through the same process as the mix, made of abrasive grains, fillers and polymeric bond, does, once they are in the mold. It is of interest to know the material and shape of the grain, as well as the characteristic parameters of the manufacturing steps, in order to decrease the detrimental effects of these actions and interactions.

2.1 Grains

The active grinding part in a grinding wheel is mainly the abrasive grain[1]. Of course as the product to be ground varies, the size, material and hardness of the grain also varies. The grain size or grit of a wheel is determined by the size or combination of sizes of abrasive grains used. The Grinding Wheel Institute has standardized sizes. The finer sizes, known as flours are designated with high numbers (500, 600, 900)

[1]Some fillers, called *active fillers*, incorporated in the mix also actively participate in grinding.

while smaller numbers refer to coarser grain size (8, 14, 46). The grit size number corresponds to the number of openings per linear inch of the smallest screen the abrasive grain can go through.

The abrasive grains are usually manufactured rather than found in nature because of the greater control over the chemical composition and crystal structure and the greater uniformity in size, hardness, and cutting qualities, as compared with natural abrasives. The most commonly used types of artificial abrasives are diamonds, crystalline alumina (Al_2O_3), silicon carbide (Carborundum^{TM}, Carbolon^{TM}, Crystolon^{TM}), boron carbide (B_4C), boron nitride (BN), crushed steel, rouge (Fe_2O_3) and crocus ($Fe_2O_3.H_2O$). The natural abrasives used in the past were usually diamond, corundum (Al_2O_3), emery (Al_2O_3), garnet (Silicate minerals), buhrstones (Siliceous rocks), millstones and pumice (67-75% SiO_2 and 10-20% Al_2O_3).

2.2 Bond

The bond holds the grains together. It is usually a mix of solid and liquid polymers. Phenol-formaldehyde resins are usually used in order to make organic grinding wheels. The grade is the hardness or relative strength of the bond of a grinding wheel. In a soft wheel, the grain particles are easily broken away, causing it to wear rapidly. A hard wheel is able to retain its particles longer.

Novolaks are formed when phenol reacts with formaldehyde at a molar ratio of one to less than one (about 1:0.4 - 1:0.9) in the presence of added mineral acids or strong organic acids used as catalysts. Novolaks are generally solid materials with a softening point of about 40^o - 110^oC and a molecular weight of 250-900.

Novolaks alone do not react at elevated temperatures. They are most frequently cured using hexamethylene tetramine ("hexa"), which forms methylene and dimethyleneamino links with the novolak.

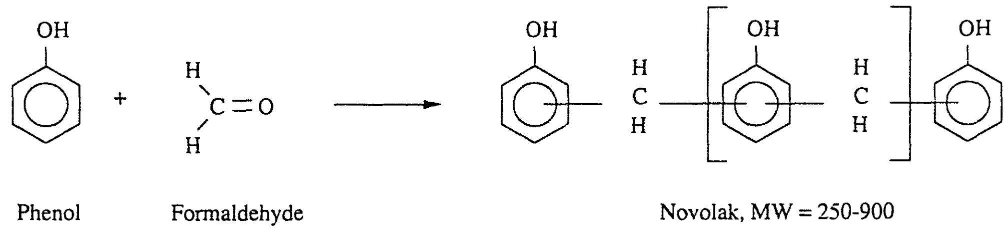

Figure 2-1: Chemical reaction of the formation of Novolak

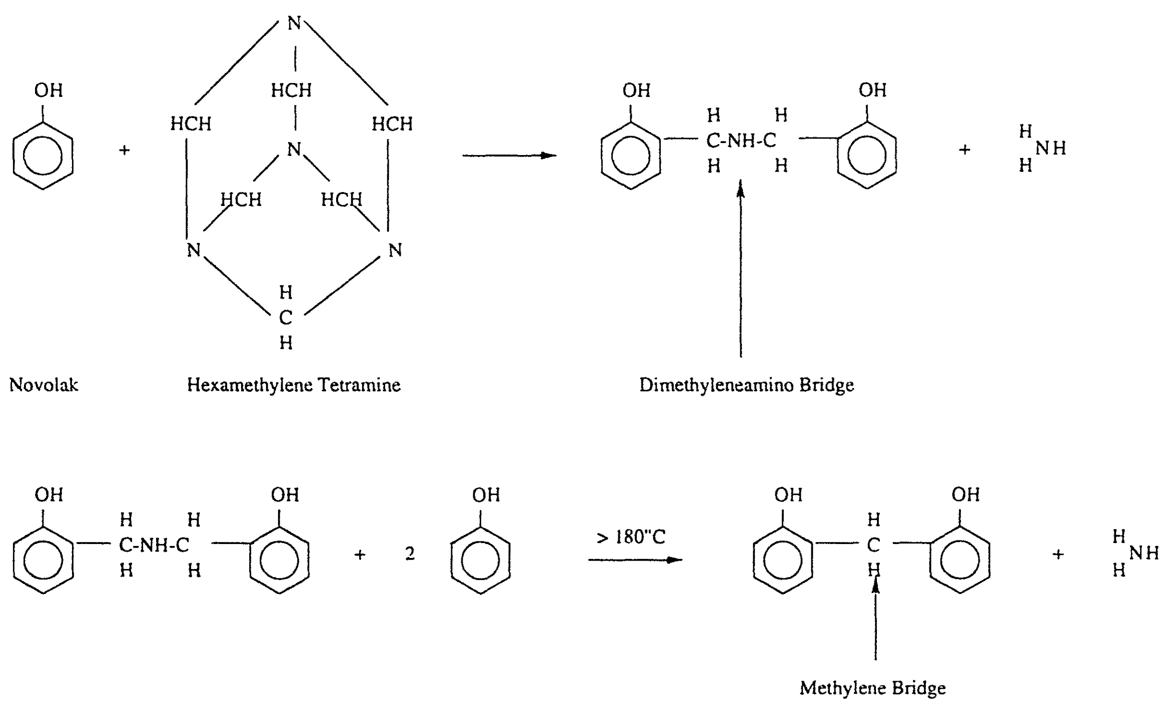

Figure 2-2: Creation of dimethyleneamino and methylene bridges

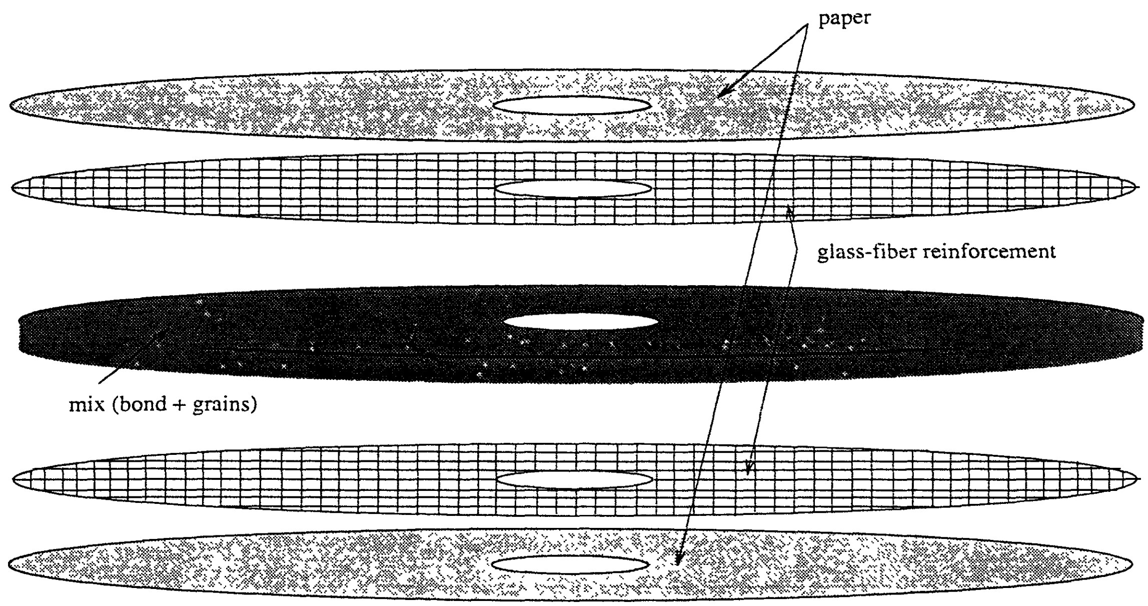

Figure 2-3: Exploded view of a grinding wheel

2.3 Fiber Reinforcement of Grinding Wheels

One of the most important and most expensive elements of some of today's high quality grinding wheels is a glass fiber reinforcement which is mostly hidden from view and is detrimental to the grinding performance. The main reason to reinforce abrasive cut-off wheels with woven fiberglass is to hold the different parts of the wheels together after the matrix has cracked. Other reasons are to increase overall strength, to allow wheels to be run at higher speeds and to allow the wheel to resist side pressures without breaking. This is because before being allowed to put a grinding wheel on the market, the manufacturer has to make sure that his products will pass a series of tests. These are supposed to recreate the conditions the wheel can face while in use and hence make sure that the product is safe. There are three basic tests used by the grinding wheel industry as we will see in Chapter 3.

The fiber reinforcements are usually one of the two following types:

1. Glass fibers: Strong, easy to weave and of low cost they usually reduce wheel performance.

2. Aramid fibers (e.g. Kevlar™): are strong and of higher shear resistance than glass but difficult to weave. The wheel performance is better than with glass

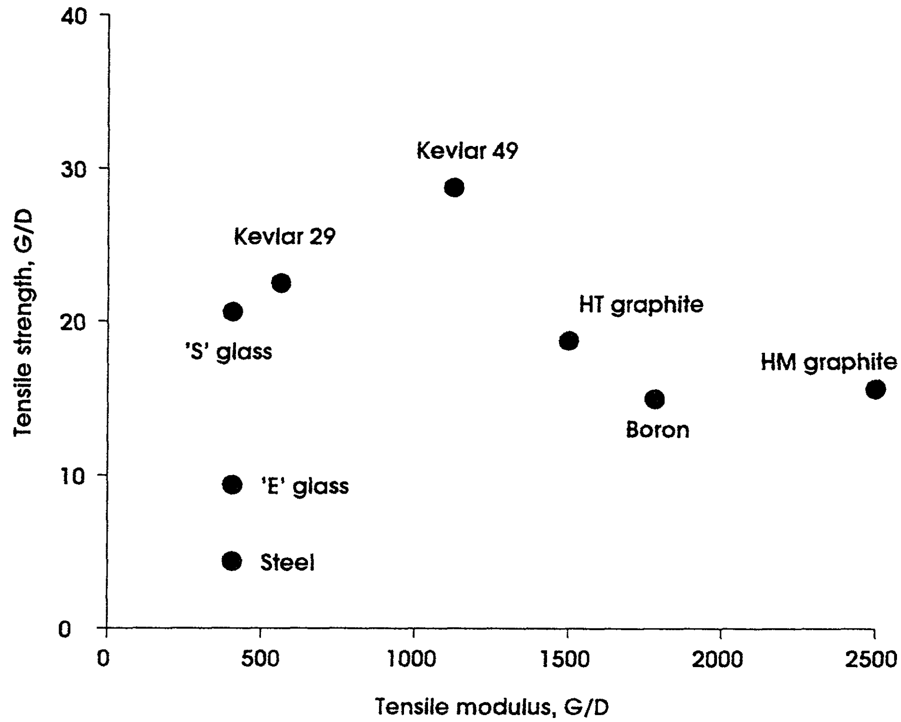

Figure 2-4: Strength and modulus of reinforcing fibers

but the cost is also higher.

Other types of reinforcing fibers are sometimes used also but usually in addition to one of the two previous types. Figure 2-4 gives the strength and modulus of the most common ones. The current reinforcement is made of glass

Glass as a material is perhaps as old as civilisation itself, but the use of glass as a reinforcing material is a relatively modern idea. Glass is an inorganic fiber which is neither oriented nor crystalline. Glass used as a high-performance fiber is made from similar ingredients to any other glass material. The ingredients normally used in making glass fibers are: silicon dioxide (SiO_2), calcium oxide (CaO), aluminium oxide (Al_2O_3), boron oxide (B_2O_3) plus a few other metal oxides. Structurally, glass has an isotropic three-dimensional network based on a tetrahedron of four oxygen atoms around a silicon atom, but made irregular and amorphous by metal ions.

Even if, over the last two decades, glass fiber has lost its market share to aramid and carbon fibers in the area of advanced fiber reinforced composites, it is still the most important reinforcing fiber in terms of volume. Besides, the grinding wheels we are working with have material cost constraints and there is very little chance that the glass fibers will be replaced by aramid or carbon fibers.

In general, composition and the thermal history of the glass fiber govern its physical properties. In the manufacturing process of grinding wheels, the reinforcing glass fibers go through the curing program determined to cure the polymer matrix of the wheels. Therefore their initial properties may be altered. Glass fibers are strong, nonflammable and heat-resistant. They can also be highly resistant to chemicals and moisture when properly sized. The strength of glass fibers at room temperature and at 65% relative humidity is a function of the glass composition, the diameter of the fiber, and the temperature of the glass from which the fiber was drawn.

E-glass is normally accepted as a standard high-performance glass fiber [2]. The reinforcing glass fiber disc used in the grinding wheel industry is made of E-glass. In current high-performance applications, in particular those requiring high mechanical performance, S-glass is becoming much more fashionable than E-glass, although the latter is still more economical with its balanced set of properties. But we need to keep in mind that the product being reinforced does not need a high-performance reinforcement. Therefore, we do not need to use a special glass, unless the gain in strength allows us to reduce the amount of material and decrease the disc cost.

The strength of glass fibers however, can be easily lost by surface damage. In most cases, their high performance characteristics are maintained by embedding or coating the fibers in a protective resin. In grinding wheels, the reinforcing glass cloth is imbedded inside a mix made of bond and grains which is highly abrasive. Therefore the reinforcing glass cloth is coated with a resin to prevent damage on the surface of the glass [2].

There are also two types of strands of fibers.

- Yarns are bundles of twisted fibers. The twist is on the order of one turn per inch of length. Glass fibers for yarns are treated with starch to lubricate the

[2]The coating also helps increasing the strength of the bond between the fibers and the mix and thereby prevents delamination and fiber pull-out.

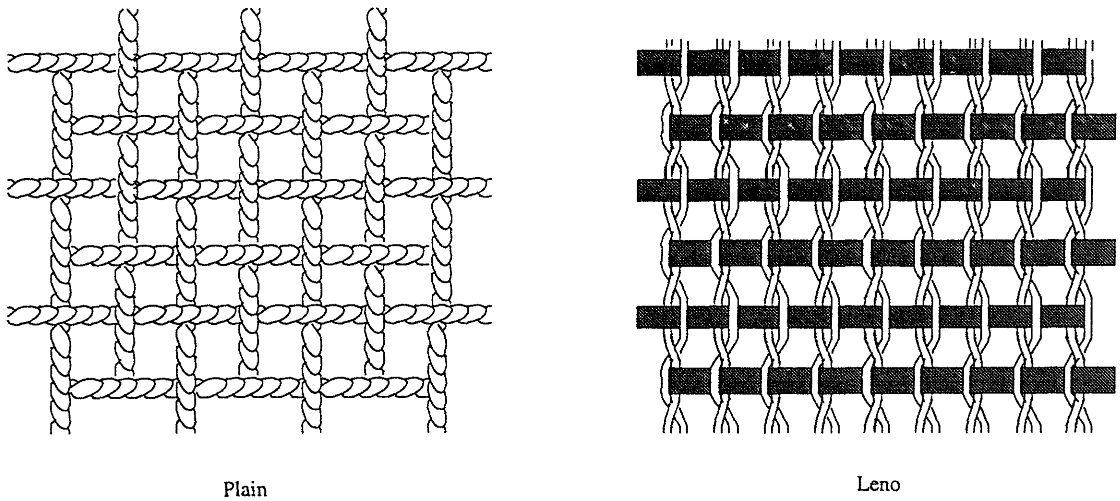

Figure 2-5: Two very common types of weaves.

surface of the fibers. This is necessary to reduce friction between fibers when processing the twisted yarn.

- Rovings are essentially groups of parallel untwisted fibers. There is only a very slight twist of about one turn per yard of length. Glass fibers for rovings do not need lubrication. The fibers are silane [3] treated instead, which improves bonded adhesion between glass fibers and phenolic resins.

The present reinforcement is a woven cloth and there are also different kinds of weaves. Plain weave has identical warp and fill yarn (rovings). Fabrics are prevented from shifting by tying them with a rayon mono-filament introduced in the fill direction. Basket weave is basically the same as plain weave except with two half yarns (rovings) in both warp and fill directions. It provides a greater surface area but reduces window openings in the fabric. Last is leno weave, where the warp consists of a single yarn (roving). The fill consists of two half yarns (rovings) which lock the warp yarn in a helix (see Figure 2-5). This eliminates the necessity of a rayon tie line used to lock the mesh as in plain weave.

[3] Silane (silicon tetrahydride SiH_4) is also used in other industries as a doping agent for solid-state devices and production of amorphous silicon.

2.4 Critical Factors

The purpose of a grinding wheel is to remove material from an object by contact, the rate of removal being generally in direct proportion to the peripheral speed. The material being ground ranges from wood and plastics to concrete and metal. Apart from the variations in characteristics (diameter, thickness, size of the grain, etc.) due to differences in end-use applications, the environment often varies too, as some wheels may be used in very corrosive atmospheres while others are used in very well-monitored environments with controlled water pressure or temperature. Also the organic bonded wheels we are dealing with are different from vitrified wheels.

Organic adhesives are used for high speed wheels, and are equally well adapted to the manufacture of very thin wheels because of their flexibility compared with vitrified bond. There are three distinct organic processes used in bonding grinding wheels: the "shellac process", the "rubber process" and the "resinoid process". With the resinoid process, the only one discussed here, the wheel is formed by compacting the mix made of abrasive grains, fillers and synthetic resins at room temperature ("cold press" process). After heating, the resultant bond is an insoluble, infusible product of notable strength and resiliency. The resinoid bond is used for the majority of high speed wheels in foundries and welding shops, and also for cutoff wheels.

Critical factors in manufacturing grinding wheels include:

- Efficiency of abrasion: The wheel should remove the maximum amount of material without an excessive decrease in its diameter. The efficiency is determined by measuring the decrease in the diameter after having cut a certain number of steel-rods. Having a reinforcement disc in the wheel always decreases its efficiency. However, as some designs decrease it more than others, we seek a disc design that will give at least the same grinding efficiency to the final product as the current design.

- Balance: The wheels are often used at high speed, so they must be very well balanced. The grain and the resin must be uniformly distributed. In general, every single wheel is tested for balance before being sold. The new disc must therefore also be balanced so as not to introduce imbalance in the wheels.

- Low cost: In order to face its competitor efficiently, the company has to make the wheels at the lowest possible cost with at least the same quality. Usually the simplest and fastest processes are also the cheapest. The new process to create reinforcement discs aims to decrease by 30% the costs of the reinforcement.

- Heat dissipation: It is a well known fact that polymers degrade when exposed to too high a temperature for too long a time. As a consequence, if we want the grinding wheel to remain efficient, the heat generated has to be evacuated efficiently. We also have to make sure that the resin coating the glass fiber disc does not melt or degrade before the polymer matrix. Otherwise, some debonding may occur.

- Safety: In order to prevent the wheel from suddenly breaking into many parts, the manufacturers have to reinforce them. Often this is done by incorporating a woven glass cloth on each side and sometimes (for thick wheels) in the middle of the wheel. Because the reinforcement discs are dropped inside the mold during the manufacturing process, they should resist careless handling.

2.5 Manufacturing a Wheel

Some aspects of the process of making a grinding wheel have been used for more than 100 years. However, some steps are performed without a deep understanding of the mechanisms of the improvement but merely because the resulting quality will be improved. This traditional manufacturing process can be separated into six different steps (see Figure 2-6).

1. *Mixing:* The mixing operation may be separated into two steps. First, the abrasive grains and the liquid resin are mixed together; next the solid polymers are incorporated into the previous mix. These two steps are performed in a batch mixer. That allows, during the cycle, variations of the operating conditions,

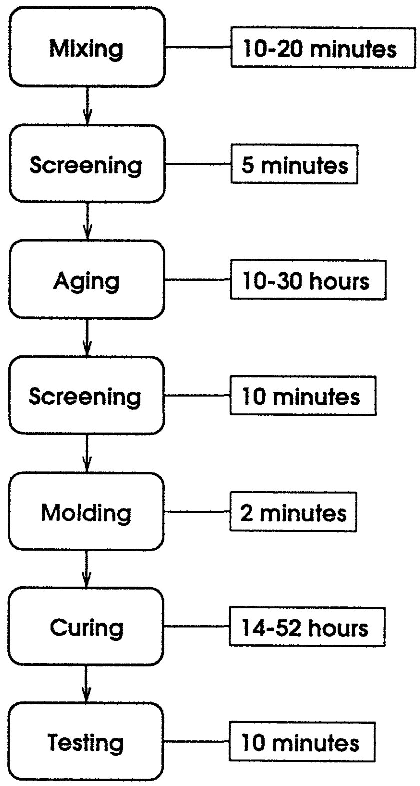

Figure 2-6: Steps for manufacturing a grinding wheel.

additions of additives at an optimal time sequence and a good temperature control.

2. *Screening and handling:* Once the mix has become homogeneous, it is screened and transferred into boxes.

3. *Aging:* It has been observed that the properties of the grinding wheels will be improved if the mix is allowed to age for a period of time ranging from ten to thirty hours. After that time, the mix has to be broken into small parts and screened again, but it would not be mixed again.The reasons for the improvements in quality resulting from this additional step, aging, are not very well understood.

4. *Molding:* The molding operation is often not automated. The woven glass web has to be placed manually in the mold; then a precise amount of mix is dropped on the top while the mold rotates to obtain a uniform dispersion of the mix. These operations may be repeated when thick wheels are being produced.

Otherwise, a second woven glass web only is positioned on the top, together with a light black paper, and everything is compacted. A pressure of about 900 tons is applied for approximately 5 seconds before the wheel is removed. The mold is then cleaned and prepared for the making of another wheel. The reinforcement disc that will replace the woven glass web will therefore have to resist the same pressure and keep its own characteristics as the mix is dropped and moved on its surface.

5. *Curing:* During the curing step, the wheels are stacked. The stack, composed of approximately fifty wheels, is then placed in a hot-air oven at a temperature of between 160 and 200°C and is cured for 14 to 52 hours. During this step, the resin that coats the discs also cures. Therefore the polymers composing this resin have to cure fast completely at these temperatures but not degrade.

6. *Testing:* Every wheel is tested at high speed to check its balance. Other tests are also performed on some wheels randomly chosen. For instance, to quantify the bending of discs during operations, a static flexural test is used. The disc is clamped centrally and is subjected to transverse load along a chordal line. We must emphasize here that if side-loaded stress is a very important consideration in the use of grinding wheels, it is of paramount significance in the case of abrasive cutoff discs.

2.6 Cost Analysis

R&D expenses are not considered in this thesis; neither is the indirect cost such as management expenses, warehouse managing, shipping, sale costs, etc.

The different origins of the cost of a wheel showed in Table 2.1 are based on the following assumption:

item	cost
raw material	42%
labor	37%
power consumption	13%
equipment	8%

Table 2.1: Origins of the cost of a wheel

- total maintenance cost is 10% of equipment price

- a line produces 80,000 wheels per year

- six operators are working on a line

- a line is composed of one batch-mixer, one pressurizing pump, one oven and four motors (one for screening, one for rotating the mold and two for testing the wheels).

According to Table 2.1, the most expensive item is raw material (42%). Next is labor cost (37%) since the line was not automated at all at the time of this analysis. Power consumption is next with 13% of the total cost. Equipment cost is the lowest (8%) because the equipment was mainly homemade and old.

The company however is reducing its labor cost by progressively automating one sub-operation after the other, and the numbers presented here may not be valid in a few years.

As far as the cost of the reinforcement disc is concerned, the origins of its cost are given in Table 1.1.

Chapter 3

Strengthening Mechanisms in Glass Reinforced Grinding Wheels

The reinforcement disc used in organic grinding wheels is made of a glass fiber cloth coated with polymers. We want to change this reinforcement disc in order to reduce its cost by 30%. Understanding the toughening mechanisms in a glass fiber reinforced product and knowing the properties of the material we are using will enable us to design a better reinforcement. There is no doubt that we can reduce the amount of material in a disc through the use of a stronger material and bond or by placing the fibers in the most efficient direction for reinforcement and thereby reduce the cost of a disc.

This chapter reviews the properties of glass reinforced products and the reinforcing mechanisms of fiber reinforced materials. It then uses this information to define the characteristics of a new design for reinforcement discs.

3.1 Properties of Glass-reinforced Products

The main problem of grinding wheels manufactured without a reinforcing disc is their inherent brittleness. This characteristic is common to all monolithic ceramics, up to relatively high temperatures. However, the stress for matrix cracking is not degraded by the existence of large flaws, in contrast to the response of monolithic materials [8].

The toughening approach attempts to create a microstructure that imparts sufficient fracture resistance so that strength become insensitive to the size of the flaw. It has the obvious advantage that appreciable processing and postprocessing damage can be tolerated without compromising structural reliability. This microstructure is created by adding a glass fiber cloth on each side of the wheel.

Of course, when a second material is combined into a matrix, there is usually a mismatch between it and the first matrix in terms of structural and/or mechanical properties. However, the differences in thermal expansions and the elastic moduli, leading to residual stresses, are pertinent to the toughening and strengthening of ceramics and are discussed in the next section. These stresses influence matrix fracture in two ways. Stresses parallel to the fibers superimpose directly to the applied stress whereas stresses normal to the fiber axis affect the frictional forces between the fibers and the matrix.

In the following analysis of the reinforcement mechanisms, we only consider the glass-cloth and the matrix. Other particulate fillers are also present in the mix. However, even if they can improve mechanical, thermal or electrical properties, we will neglect their effects and concentrate only on glass reinforcement .

3.2 Deformation and Reinforcement Mechanisms

Since the main motivation for adding high strength glass fibers to the brittle abrasive mix is to create a "tough" material, an understanding of the mechanisms by which they fail is important, both for material evaluation and as a basis for the reinforcement design.

A ceramic component will fracture from the defects where stresses will combine with the flaw severity to cause the defect to grow.

The four effects which influence toughness in reinforced ceramics that fracture by the growth of a single dominant flow are [8]:

- debonding (generation of new surfaces)

- frictional dissipation upon pull-out

- residual stresses present in the material
- dissipation through acoustic waves of the elastic energy stored in the fibers

Usually a ratio of the Young modulus of the fibers to that of the matrix greater than two is required to achieve a significant increase in strength [1]. However, both high fiber strength and low sliding resistance combine to maximize frictional dissipation by inducing sliding over the largest possible fiber surface area.

Continuously reinforced composites such as the woven cloth used to reinforce grinding wheels incorporate many of the principles well-known for discontinuously-reinforced composites. However, usually more than one mechanism operates simultaneously and it is of course advantageous to combine multiple toughening mechanisms for maximum effect. These mechanisms of reinforcement are presented below.

3.2.1 *Microcracking*

The thermal expansion anisotropy gives rise to local stresses in the microstructure when the material is cooled from the processing temperature [19]. Sometimes the stress can produce spontaneous microcracks which increase toughness by decreasing the stress intensity at the crack tip (Figure 3-1). The energy dissipated in generating microcracks is used primarily to create new surfaces. Maximum toughening is achieved by a narrow distribution of particle sizes close to the critical size. Besides, the microcracks can induce crack branching which entail additional toughening. Microcracking often appears to produce toughening in conjunction with other mechanisms such as phase transformations to be discussed in section 3.3.6.

For grinding wheels, we may think about increasing the discrepancy between the thermal expansion coefficient of the matrix and the one of the glass to reduce the amount of glass necessary to achieve reinforcement. This will be done if the reduction in the cost of the discs cannot attain 30% by changing the design and the

[1] Rubbery particles are sometimes used to increase toughness by greatly enhancing the extent of plastic-shear deformation in the epoxy polymer at the crack tip, due to interactions between the stress field ahead of the crack and the rubbery particles. However, our concern is to decrease the cost of the glass reinforcement disc and we do not aim at changing the reinforcing material. Therefore, in this thesis, we only consider reinforcements using glass fibers.

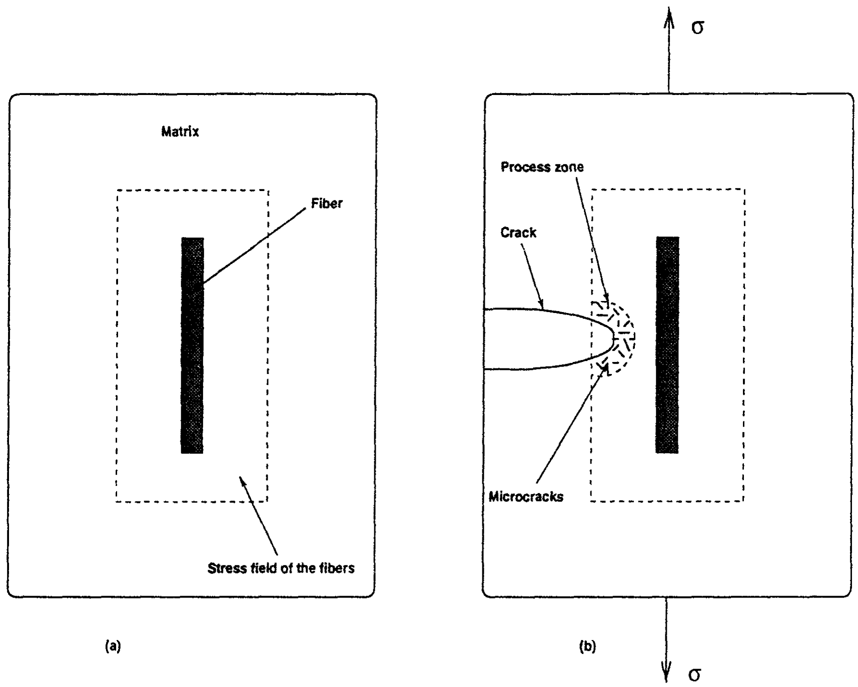

Figure 3-1: Microcracking toughening mechanism: (a) residual stress field alone and (b) combination of the residual stresses and the applied stresses causing microcracking in a process zone in front of a macrocrack.

manufacturing process.

3.2.2 *Crack Deflection and Branching*

If the crack meets an obstacle such as a second phase particle or fiber, then the direction of the extension of the crack may change (Figure 3-2). This is often due to the misorientation of the easy fracture from one point to another along the crack front. This deviation in direction means that the crack travels a longer path and the stress intensity at the crack tip is reduced since the plane of the crack is no longer perpendicular to the tensile stress. In general, a crack propagates perpendicular to the tensile axis and parallel to the compressive stress. It is usually thought that a rod-shaped reinforcement is the most effective in enhancing toughness. The toughness is also increased by increasing the volume fraction of the second phase but is usually thought to be independent of the size of the second phase. In the case of a grinding wheel, we want the glass volume fraction to be as small as possible since the glass reinforcement decreases grinding efficiency. Also some experiments proved that using the same amount of glass as the standard discs but with strands twice thicker than the standard strands did not reinforce as well as the regular disc. Therefore in the case of grinding wheels, not only the glass volume but also the size of the reinforcement play a role. We need to keep that in mind when we will design the new discs.

In this toughening mechanism, the maximum reinforcement is obtained when the fibers are neither perpendicular not parallel to the stress direction. Therefore, if crack deflection and branching are the main toughening mechanism acting in grinding wheels, we can determine which direction we should avoid for the fibers in the reinforcement disc once we have established a map of the stresses inside a grinding wheel in use.

3.2.3 *Fiber Pull-Out*

When a tensile load is applied to a composite, a shear stress is established at the interface between the fiber and the matrix and this shear stress leads to a tensile stress along the axis of the fiber. If the fibers are shorter than a critical value, the fiber is pulled out before fracture while a longer fiber is broken without pull-out. Fiber pull-out requires additional work and thus toughening effects are achieved in the process. The bond between the matrix and the fiber may result from a chemical reaction or mechanical friction. In the case of a grinding wheel, the mechanical part of the friction is insignificant and can often be neglected compared to friction resulting from chemical reactions. With the coating resin currently used, the fibers must be longer than two inches to avoid delamination (or pull-out). However, by creating a new resin we may increase the strength of the bond.

It is important to note that this mechanism of reinforcement requires the fibers to be aligned with the direction of the stress. If this is the main mechanism of reinforcement of glass reinforced grinding wheels, we will be able to design a universal reinforcement once we know the direction of the stresses in a wheel in use.

3.2.4 *Crack-Bridging*

In this mechanism, the front of the crack passes beyond the reinforcing fibers but the fibers remain intact and bridge the fracture surfaces in the wake of the crack. The open displacement of the crack is then limited and this makes further propagation of the crack difficult (Figure 3-3). Experience and analysis confirm that crack-bridging is usually the most potent mechanism of reinforcement when the brittle phase is continuous which is the case for grinding wheels. As in the previous reinforcement mechanism, the fibers need to be parallel to the direction of the stress to reinforce efficiently.

3.2.5 *Crack-Pinning*

Crack propagation may also be stopped and the crack pinned at the fibers or particles. This assumes that cracks can be impeded by impenetrable, well bonded particles. When a crack meets an array of such obstacles, it becomes pinned and tends to bow out between the particles, forming secondary cracks. Thus new fracture surface is formed and the length of the crack front is increased due to its change of shape between the pinning positions. Energy is then not only required to create the new fracture surface but, by analogy with the theory of dislocations, energy must also be supplied to the newly formed non-linear crack front, which is assumed to possess a line energy. This latter factor particularly leads to the enhanced crack resistance often observed when impenetrable particles are well-bonded into a brittle matrix. In grinding wheels, the grains play this role more than the glass fiber.

3.2.6 *Phase Transformation*

This new mechanism of toughening is limited to materials containing a phase that undergoes a transformation during the fracture process. It certainly does not happen in the present grinding wheels as the polymer matrix is amorphous. However, this attractive mechanism may play a role if we change the mix. It is only presented here for background information.

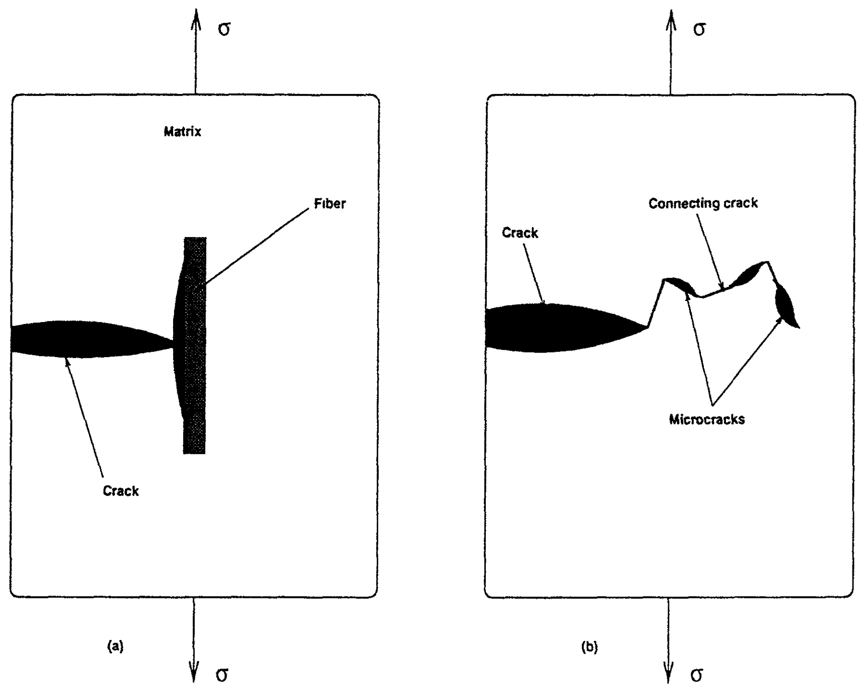

Figure 3-2: Toughening by crack branching or deflection:(a) a crack deflected along the interface and (b) a crack deflected by connecting microcracks.

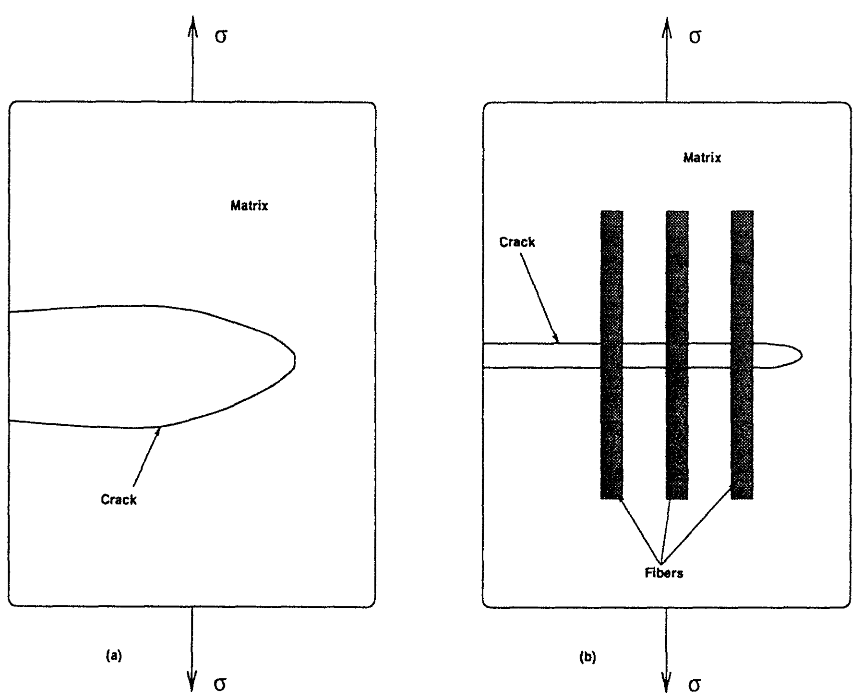

Figure 3-3: Toughening by crack bridging: (a) a crack in a matrix with no fibers and (b) a crack bridged by fibers.

This transformation usually involves a change in the volume and/or shape of the second phase particles. During processing of the composite material, the strain energy associated with the shape change during transformation may prevent the process from occurring when the phase particles are contained in a stable matrix. Toughening takes place when the stress field at the crack tip is relieved by the transformation of the second phase particles near the crack. The transformation is diffusionless and athermal. For this transformation to take place, an appropriate stress field is necessary to provide energy. As a result, the stress field is reduced.

3.3 Results for Grinding Wheels

Recording the load while the crack is propagating during a push-out test confirmed that the crack bridging process is involved in reinforcing the grinding wheels.

First we observed a linear relation between the load applied and the deformation. Then we heard a crack and the relationship became non-linear. Usually, the stress at which the first matrix crack occurs is not altered by the presence of indentation flaws [8]. The slope of the curve before the crack is independent of the reinforcement design and depends only on the quality of the mix. Before the matrix crack, the material is elastic and would return to its original shape if the stress were removed.

Second we witnessed a regime called unstable-brittle propagation where the crack propagated in a stick and slip manner. The applied load dropped when crack growth started but crack propagation was immediately arrested and the load increase was resumed. The extension of a crack proceeded in an irregular manner by repeated initiation and arrest, thereby achieving a toughening effect. The load displacement curve presented a sawtooth shape. A typical example of the response of a reinforced grinding wheel to an increasing load is given in Figure 3-4.

It is the non-catastrophic decrease in load that gives these materials the appearance of being very "tough". This is the property we are looking for as we want the wheel to remain in one piece for at least a short while after the first matrix crack. The user, hearing this crack, will then have time to change the wheel before it disin-

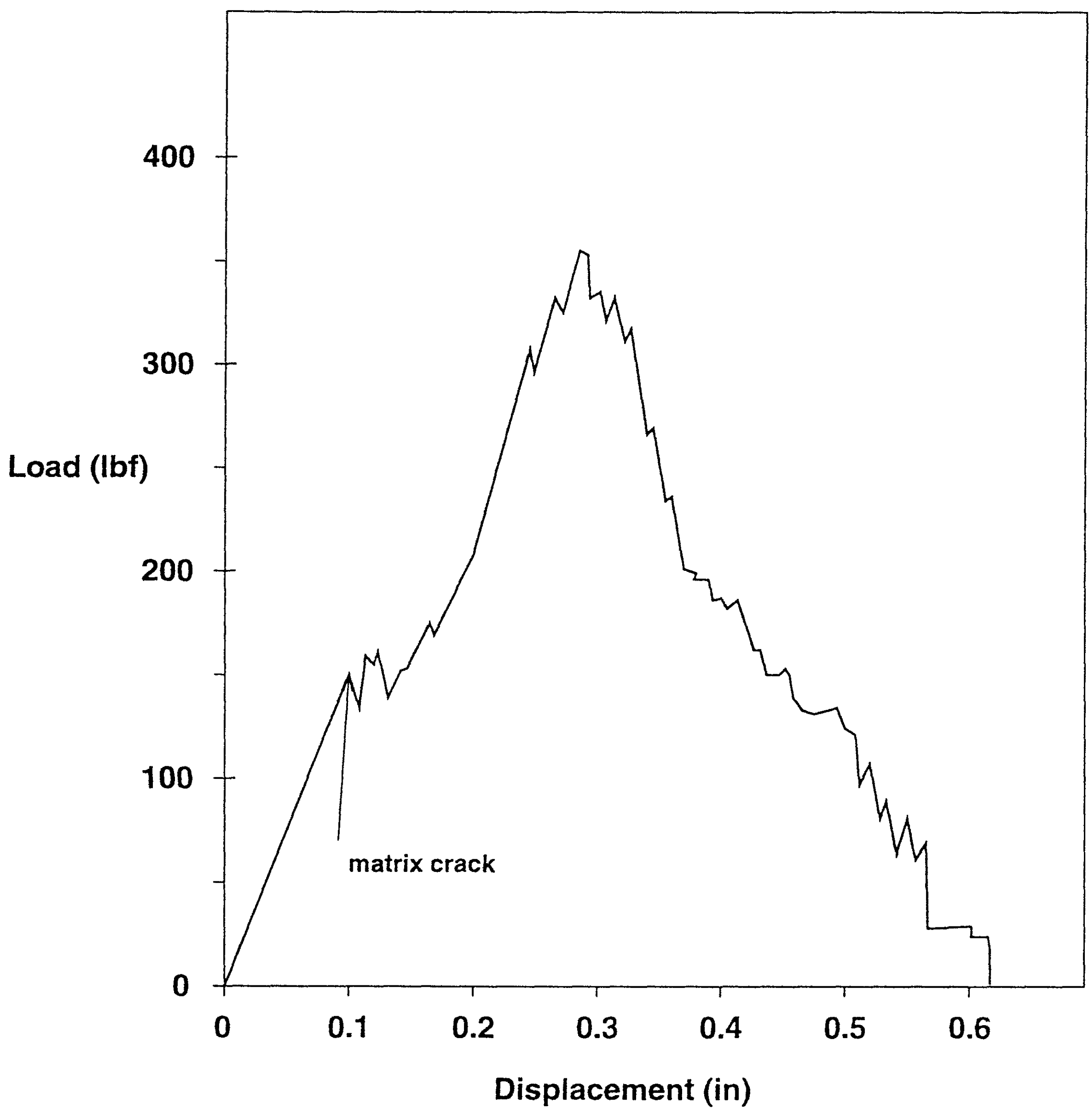

Figure 3-4: Typical load vs displacement response for a reinforced grinding-wheel during a push-out test.

tegrates.

The influence of material modifications can be determined after the test by observing the fracture surface. We discovered that the flaw propagates mainly intergranularly in the case of a grinding wheel and not transgranularly. We were also able to determine when delamination occurred between the fibers and the matrix.

Also, as we witnessed that crack deflection occurred, we became aware that the best orientation for the fibers with respect to the stress direction cannot be determined unambiguously. Some mechanisms need the fibers parallel to the stress direction and others need them at an angle to it.

Other experiments have been conducted by Tom Service in order to determine whether a direction for the fibers was preferable to achieve reinforcement. Tensile stresses have been applied to samples reinforced with a glass fiber cloth oriented at angles varying from zero to forty-five degrees with respect to the stress direction. However, all the results were satisfactory and no direction could be said to be better than the others.

Therefore, even if we can determine accurately the direction of the highest stresses in a grinding wheel in use, it is not certain that we can design a universal reinforcement pattern. However, the analysis of the stresses inside a grinding wheel made in the next chapter is helpful to determine, if not the direction, at least the location of the highest stresses.

Chapter 4

Stresses Experienced during Grinding

The reinforcement disc is added for safety and, at the manufacturing level, this translates into a pass/fail result for the tests presented in the following section. Therefore, to design an efficient reinforcement, we need to know where the highest stresses are created. This is determined in the second part of this chapter, using analytical solutions as well as finite elements analysis. This stress analysis is, however, more useful as background information than as a guideline to place the fibers, as it is not certain we can manufacture a reinforcement that would work in only one direction. As we were doing these calculations, some experiments proved that the orientation of the fibers does not make a big difference in the tensile strength of a sample. Different mechanisms contribute to reinforcing the wheel, some acting parallel to the fibers, other acting perpendicular to them. Therefore if it is important to know where the stresses are the highest, the nature of the stresses is not so important.

4.1 The Tests

The tests that type 1 cutoff wheels need to pass are known as the ANSI B7.1 design tests. These tests, developed by the Grinding Wheel Institute (GWI), set minimum safety standards for cutoff wheel designs.

The German DSA certification tests for cutoff wheels, although different from the tests presented here, test the same wheel characteristics. In all these tests, wheels are subjected to the same types of abuse that can be expected in service. Limits for the minimum amount of abuse each design can withstand are given to the manufacturer by the GWI.

1. *Speed Test*

   The first testing requirement is a spin burst test. The wheels are spun until they break, which typically occurs around 14,000 rpm for an eight-inch wheel. The wheel must withstand a speed of about 150 $m.s^{-1}$ to pass the test. The reinforcement glass fiber disc increases the maximum speed by up to 20% depending on the style of the reinforcement glass but the most important role is to hold the different pieces together. Only dust remains after the test if no reinforcement is added. With a reinforcement, big pieces of grinding wheel are found which proves the importance of the reinforcement.

2. *Push-out Test*

   In this test, the wheel is supported by a ring on its external diameter and a smaller ring is clamped around its internal diameter. A load is then applied to the small ring and the load vs deformation curve is recorded. A typical load vs deformation response of a grinding wheel is given in Figure 3-4.

   The matrix cracks early but the glass reinforcement must enable the wheel to withstand a load of about 500 lbf for an eight inch wheel, 0.130 inches thick. A representation of the setup for this test is given in Figure 4-1.

3. *Grinding Test*

   This is a simple test where the wheels are used to grind a metal rod and the wear is measured (decrease in diameter or volume variation). No side load is applied. This test determines the efficiency of the wheel and of the mix. It is the first characteristic the user is interested in. The presence of a glass disc decreases the performance of a disc during this test and our new design should

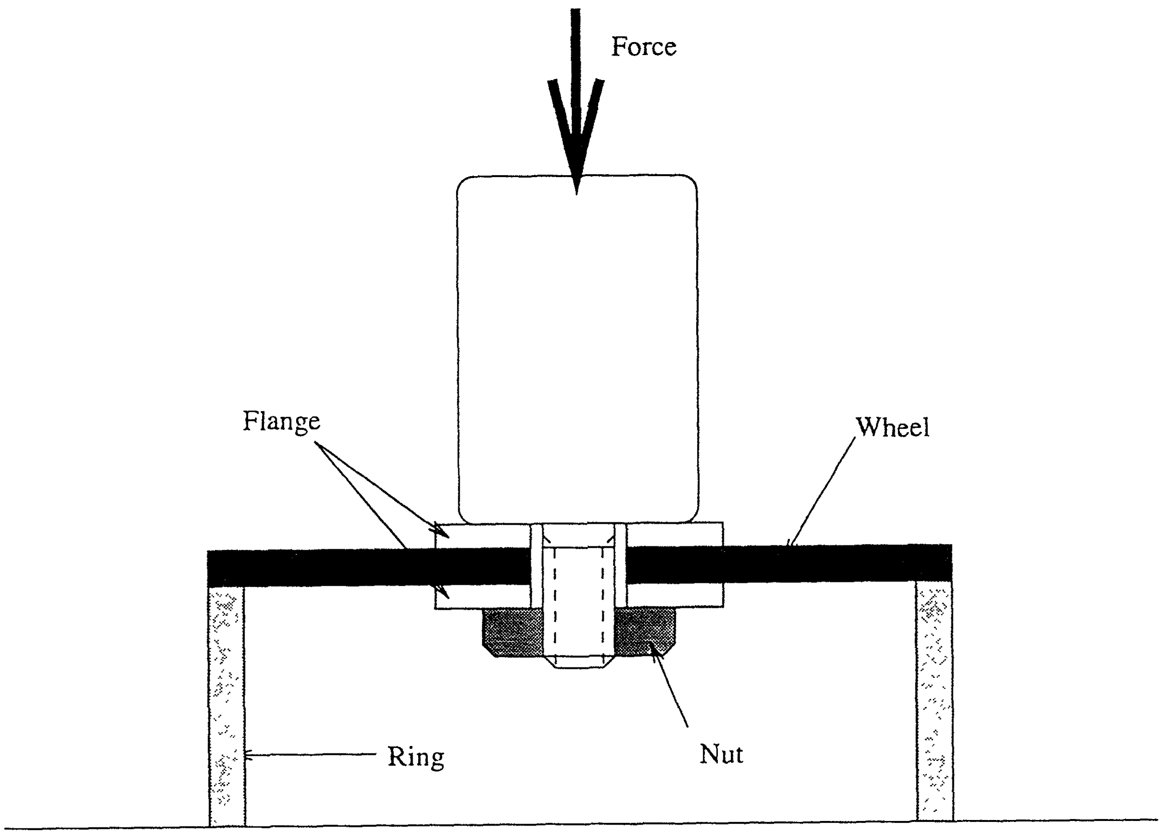

Figure 4-1: Setup for Reinforced cut-off Push out test

minimize these effects. The efficiency of a wheel is measured by recording the power used to cut and the G ratio which is the metal removal rate divided by the wheel wear rate.

Sometimes other experiments are performed in order to test the same characteristics. However these are not used by the American grinding wheels manufacturers in general, and therefore we will not analyze the stresses they create.

One test sometimes performed is a rotating side load test. A wheel is spun at its maximum operating speed while a side load is applied to the periphery, causing the wheel to flex. The side load is applied at a constant rate causing the wheel to deflect out of plane and eventually fail. In order to pass the test, the wheel must be able to withstand a minimum side load before failure.

Another test is a rotating three-point side load test. In this test, a side load is applied, as in the previous test, while the wheel is supported from behind at two locations. This has the effect of pinching the cutoff wheel and simulates the case where a wheel is twisted during a cutoff operation. Again, a minimum side load must be attained before failure in order to pass the test.

Finally a rotating impact test, where a spinning cutoff wheel is subjected to a side impact, is sometimes performed. Impact energies are increased until failure occurs. The standard gives minimum energies that each wheel design must pass.

4.2 The Tools

Like most of the problems in solid mechanics, our problem can be represented in mathematical terms by one or more partial differential equations. While some partial differential equations are amenable to classical analytical solutions, most are not. In the next section we give the analytical solutions that exist in the simplest cases. Then we describe the finite element method as a technique to obtain numerical solutions to the most difficult problems.

4.2.1 Analytical Solutions

The simple geometry of the wheels (axial symmetry) and the use of simple loads allow us to simplify the compatibility and equilibrium equations and then find an analytical solution. By avoiding the discretization step, we can find an exact solution and not an approximate one as is the case using a finite element method. Such solutions were found in the case of a rotating disc where the loading is only due to centrifugal forces. Considering a wheel rotating around its z-axis, if r_o is the outside radius and r_i the inside radius, then the stresses and displacements at a radius r are given by

$$\sigma_\theta(r) = \frac{1}{8}\frac{3-2\nu}{1-\nu}\rho\omega^2(r_o^2 + r_i^2 + \frac{r_o^2 r_i^2}{r^2} - \frac{1+2\nu}{3-2\nu}r^2) \tag{4.1}$$

$$\sigma_r(r) = \frac{1}{8}\frac{3-2\nu}{1-\nu}\rho\omega^2(r_o^2 + r_i^2 - \frac{r_o^2 r_i^2}{r^2} - r^2) \tag{4.2}$$

$$\sigma_{zz}(r) = \nu(\sigma_\theta(r) + \sigma_r(r)) \tag{4.3}$$

$$v = \frac{r}{E}(\sigma_\theta - \nu(\sigma_r + \sigma_{zz})) \tag{4.4}$$

Where ρ is the density, E is Young's modulus, ν is Poisson's ratio and v is the displacement in the radial direction. Figures 4-2 to 4-5 represent the curves obtained using these equations for an eight inch wheel with a one inch diameter hole in the center, 0.2 inch thick. In the case of a cutoff wheel, because the disc is thin relative to its radial dimensions, we can assume that the disk is in a state of plane stress, with the axial stress $\sigma_{zz} = 0$.

The case of a plate of diameter a and thickness h, supported by a thin cylinder on the edge, with a uniform pressure p applied above, can give us an idea of some of the stresses that can act on a rotating wheel with a uniform side load. The analytical solutions for an isotropic, homogenous disc are given below as a function of the radius r. The axis are the same as for the second finite element analysis and are defined in Figure 4-11.

$$\sigma_{xx}(r) = \frac{6M_x}{h^2} = \frac{6p}{16h^2}(a^2(3+\nu) - r^2(1+3\nu)) \tag{4.5}$$

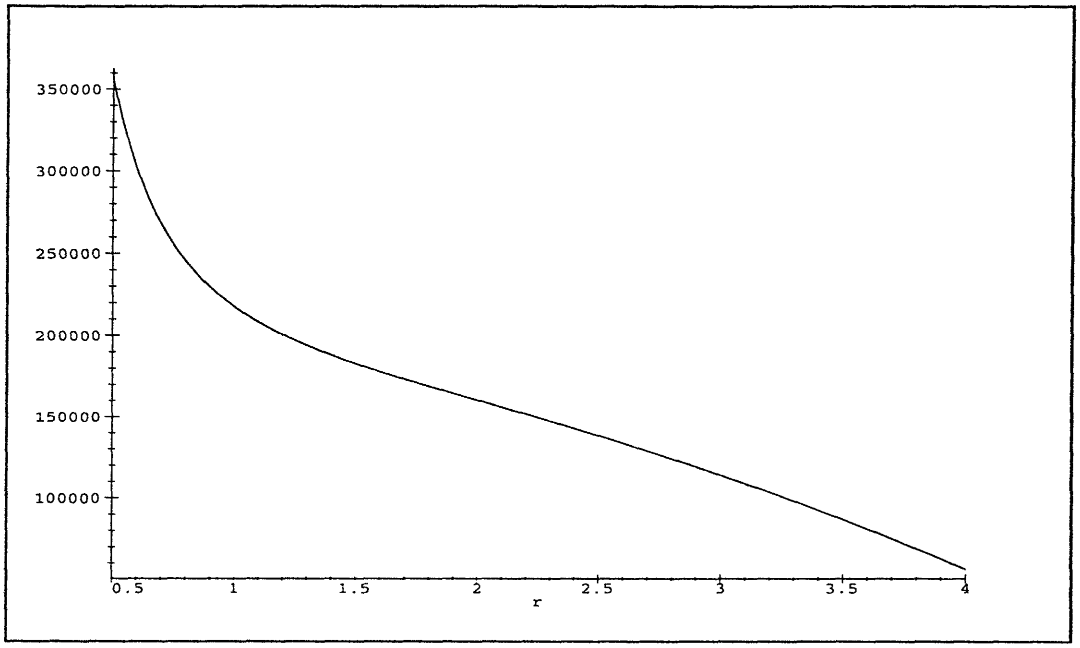

Figure 4-2: Stress σ_θ as a function of the radius r for an eight inch wheel in rotation.

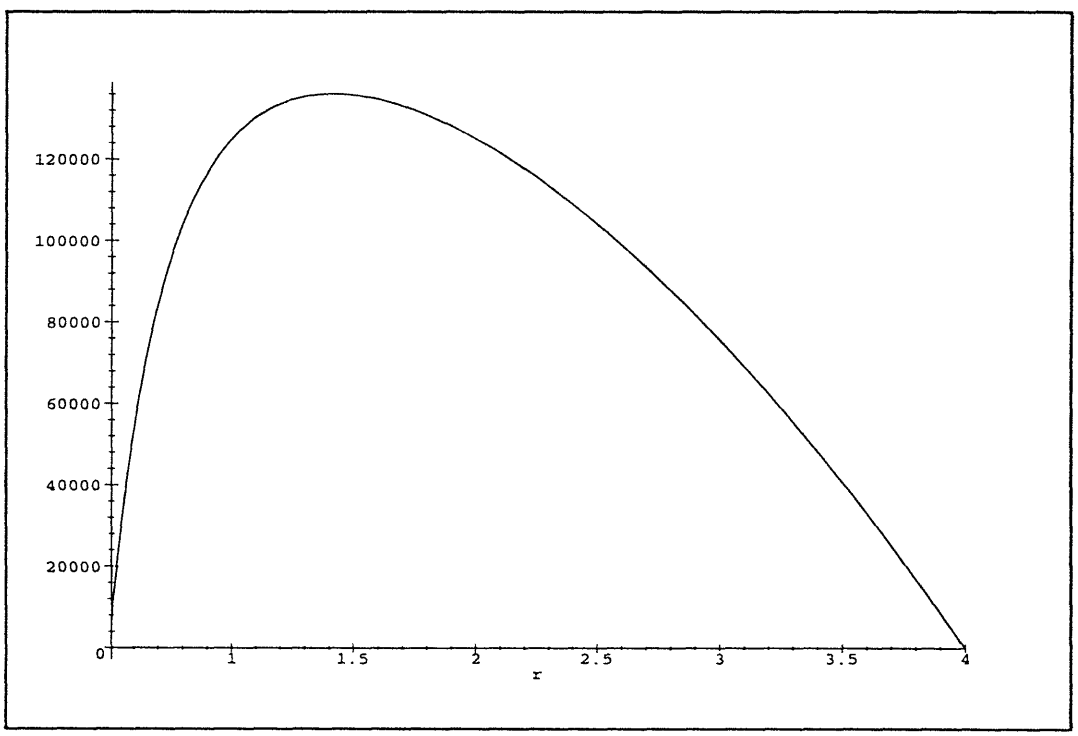

Figure 4-3: Stress σ_r as a function of the radius r for an eight inch wheel in rotation.

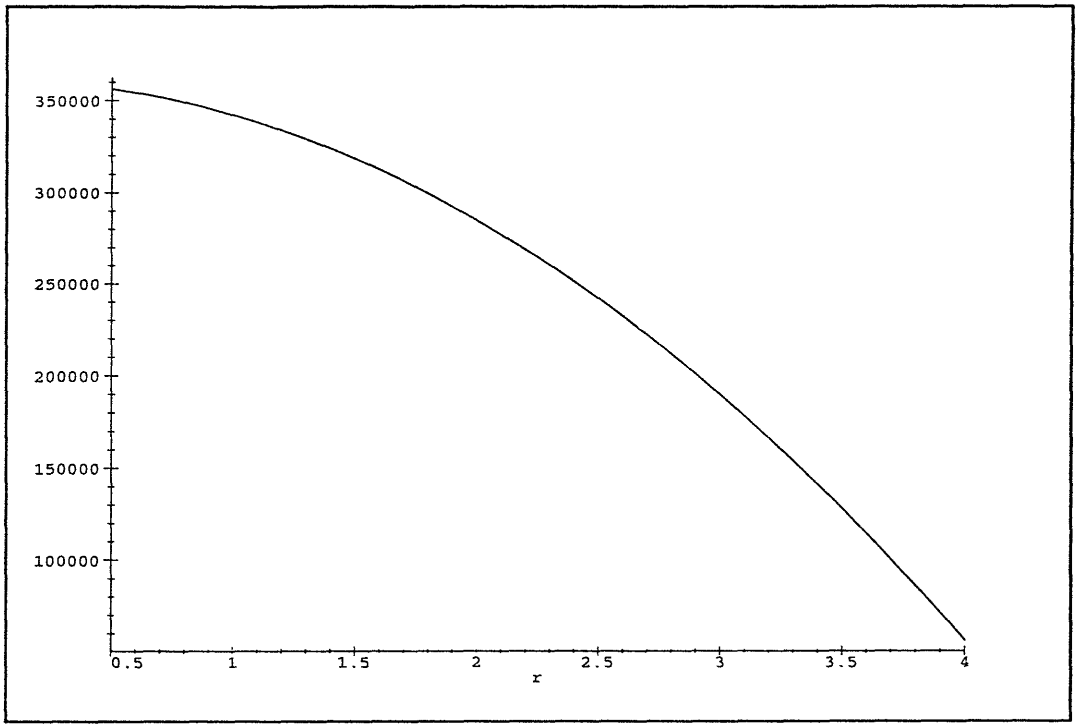

Figure 4-4: Stress σ_{zz} as a function of the radius r for an eight inch wheel in rotation.

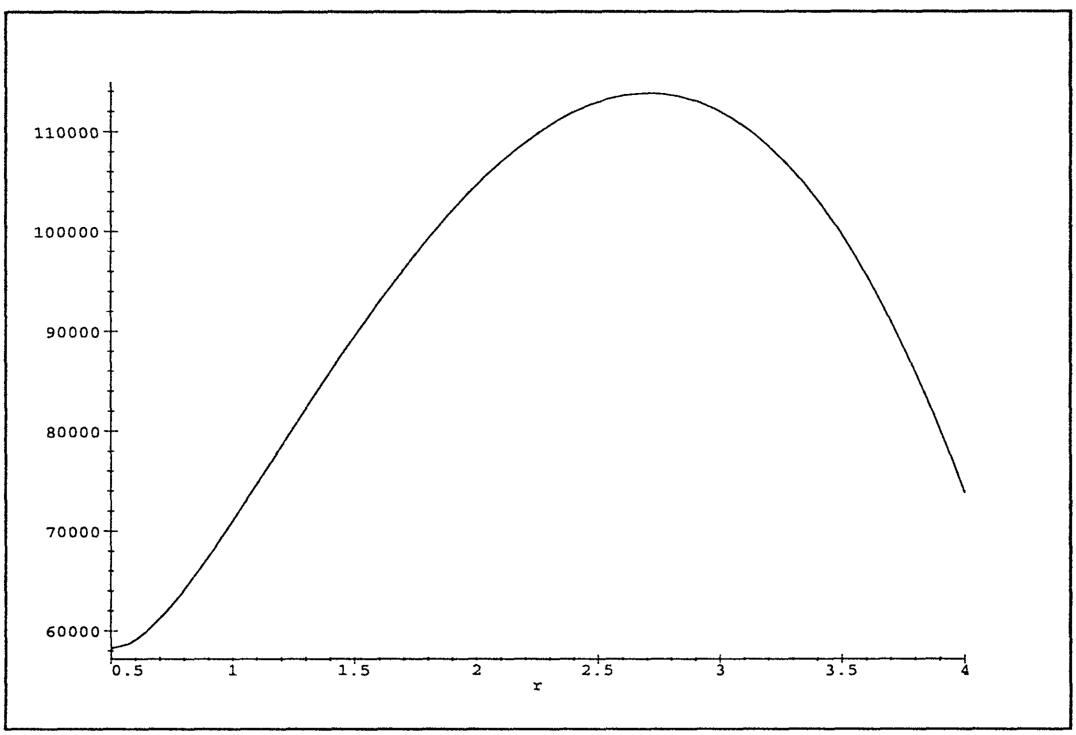

Figure 4-5: Displacement v as a function of the radius r for an eight inch wheel in rotation.

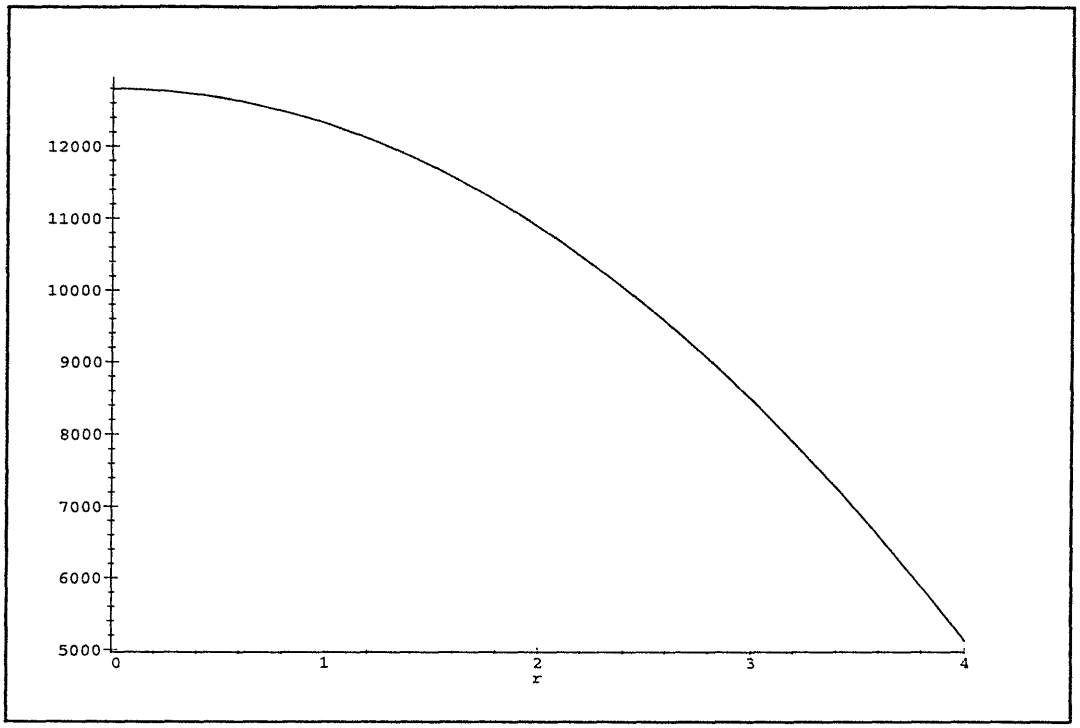

Figure 4-6: Stress σ_{xx} as a function of the radius r for an eight inch wheel under uniform pressure.

$$\sigma_{yy}(r) = \frac{6M_y}{h^2} = \frac{6p}{16h^2}(3+\nu)(a^2 - r^2) \tag{4.6}$$

$$\omega_{max} = \frac{(5+\nu)pa^4}{64(1+\nu)D} \tag{4.7}$$

$$D = \frac{Eh^3}{12(1-\nu^2)} \tag{4.8}$$

Where ω_{max} is the center deflection in meters, ν is Poisson's ratio, E is Young's modulus and the stresses are in N.m^{-2}. Figures 4-6 and 4-7 give the curves obtained using these equations.

As we can see in Figure 4-2, the tangential stress (or hoop stress) σ_θ is maximum near the center of the wheel when only rotation creates stresses. The radial stress σ_r however increases sharply as the radius increases and is maximum at about one third of the radius of the wheel from the center (Figure 4-3). As expected, the radial stress is zero on the external edge and in the center. It is also to be noted that even if it increases, the radial stress σ_r is always lower than the tangential stress σ_θ and its maximum is less than half the maximum of the tangential stress.

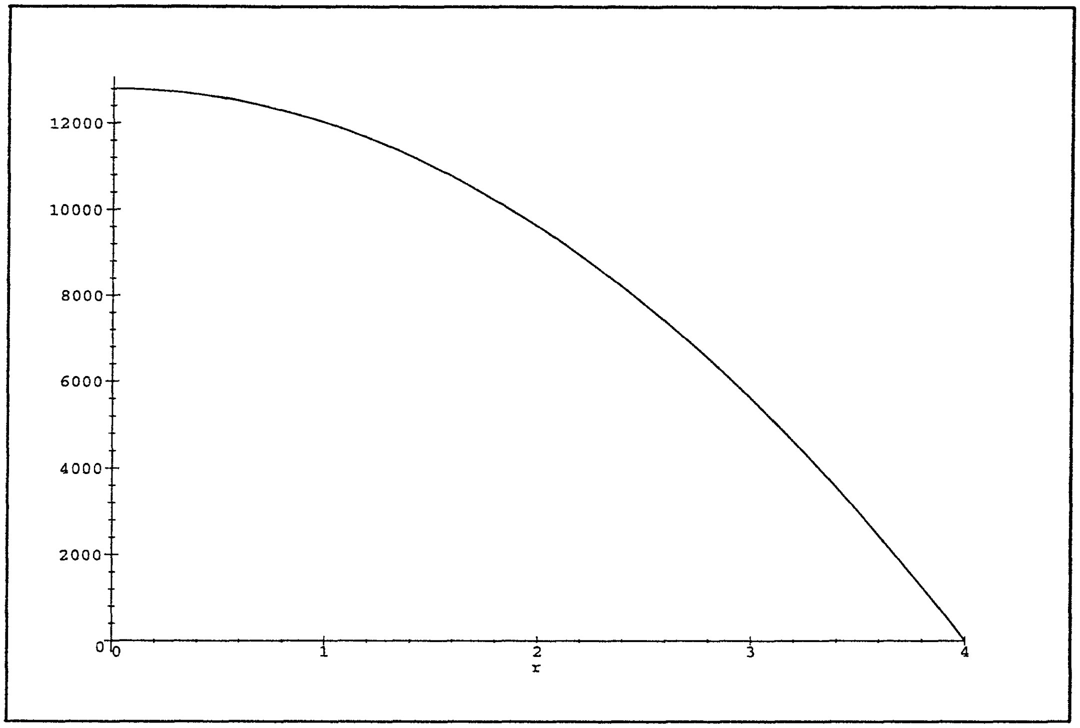

Figure 4-7: Stress σ_{yy} as a function of the radius r for an eight inch wheel under uniform pressure.

A reinforcement adapted to such a combination of stresses would be very strong in the tangential direction near the center and then could decrease in strength in the tangential direction to become stronger in the radial direction. It could then decrease in strength as both stresses drop when we get closer to the edge of the wheel. The next chapter will present different designs adapted to different situations.

In the case of a wheel under uniform pressure supported by a ring on the external edge, the stresses in the radial and tangential directions have the same shape and are higher in the center as is shown in Figures 4-6 and 4-7.

4.2.2 Finite Element Analysis

The finite element method is a numerical tool to obtain approximate solutions to complex problems. To determine the strains (displacement gradients) and stresses within a rotating wheel, the relevant equations are the equations of static equilibrium from the theory of elasticity together with the kinetic and constitutive equations. The equilibrium equations result in a set of partial differential equations which must be satisfied at all points within the region of interest. The finite element method can be thought of as replacing this complex system of equations with a simpler system of algebraic equations, obtained by dividing the structure into a number of elements which are interconnected at discrete points or nodes.

A number of finite element analysis have been performed to simulate different situations encountered by a rotating wheel and to determine the stresses created. The effect of rotating a wheel at high speed have been considered and the stresses inside a simply supported disc under a pressure loading have been calculated. The different causes of stresses have been separated as it is easier to deal with separate causes and effects than to have one single analysis giving the stresses resulting from all these causes acting simultaneously. An analysis simulating a load perpendicular to the wheel-axis in the plane of the wheel could have helped in determining other stresses a wheel must resist but we decided to focus on designing a reinforcement that would made the wheel pass the different tests and not on understanding all the types of stresses a wheel can go through while in use. This decision was made partly because we had only one month to analyse the stresses and design a reinforcement but also because the stress analysis was considered more as background information than as a way to determine how to place the fibers in the disc.

The analysis used the program ADINA and a listing of the datasets used is given in appendix B. An eight-node axisymmetric element has been used in all these programs.

Analysis of a Rotating Disc

In the first analysis, a thin disc rotating with an angular velocity of $10,000 rad.s^{-1}$ is considered (Figure 4-8). The disc is assumed to be guided so that no axial displacement can occur.

Due to the end boundary conditions and the applied loading, the zz-component of strain is zero along the axis of rotation. This does not mean that the stresses in this direction are zero but it enables us to discretize only a unit radius of the disc.

A representation of the eight eight-node axisymmetric elements used to model the disc in the radial direction is presented in Figure 4-9. The results of such an analysis

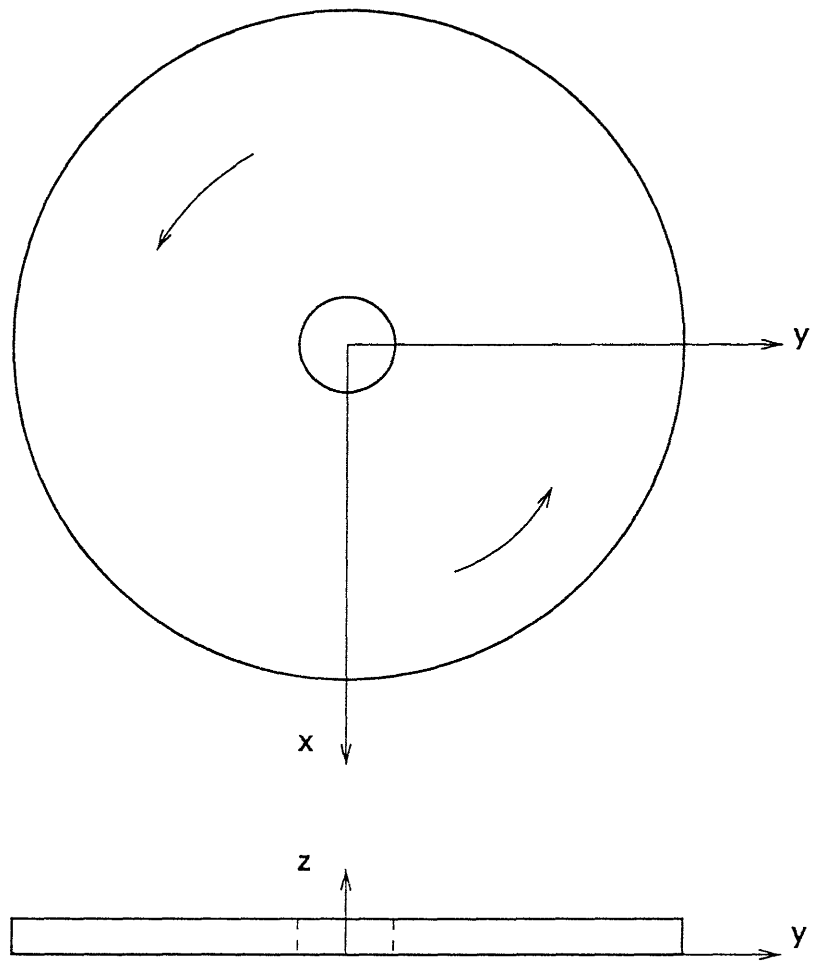

Figure 4-8: Definition of the axis for the finite element analysis of a wheel.

are not reproduced here but are obviously very close to the analytical solution.

The second analysis examines the consequences of a pressure loading on a disc supported by a ring on its external edge. Figure 4-10 shows the model to be analyzed and Figure 4-11 shows the finite element model, using an eight-node axisymmetric element. No hole in the center was made as the wheels are clamped in the center during the tests and while in use. Therefore, a disc with a hole in the center would not be a better model than without hole.

As expected, the wheel deforms more at the center. The deflection is maximum where the hoop and radial stresses are maximum, in the center of the wheel. The results are given in Figures 4-12 and 4-13.

If we were to reinforce a wheel submitted only to these stresses, we would decrease

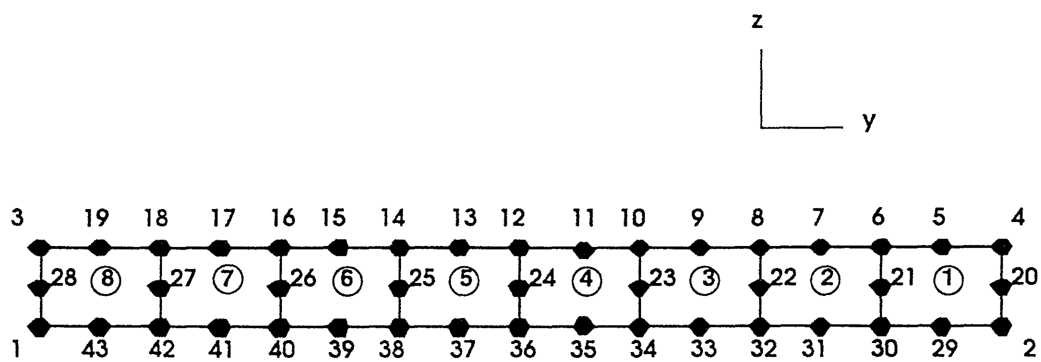

Figure 4-9: Model for the analysis of a rotating disc.

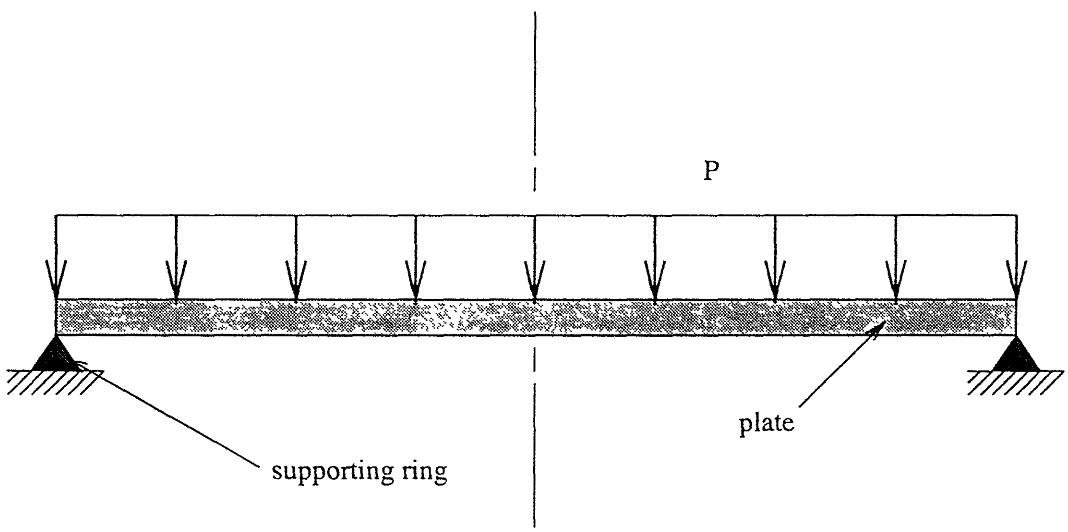

Figure 4-10: Model for the finite element analysis of a disc under a pressure loading, supported by a ring below its external diameter.

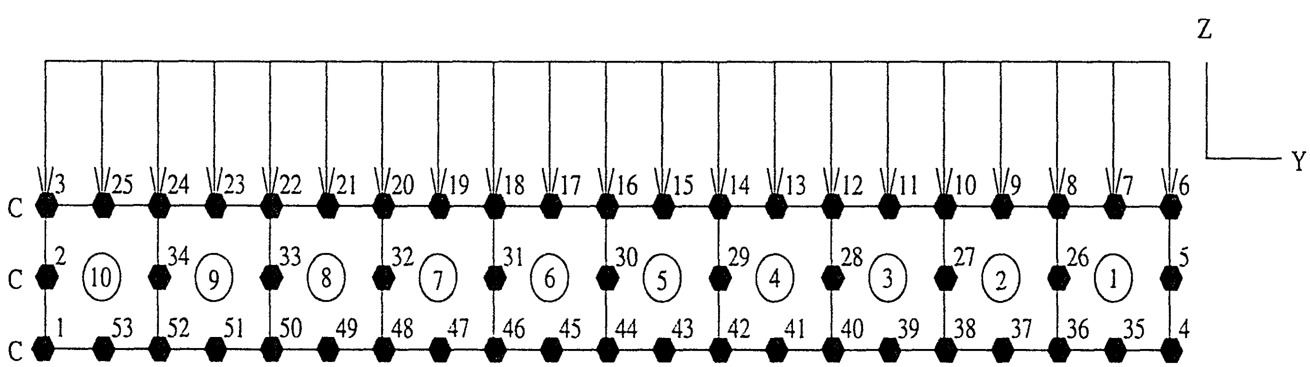

Figure 4-11: Finite element model.

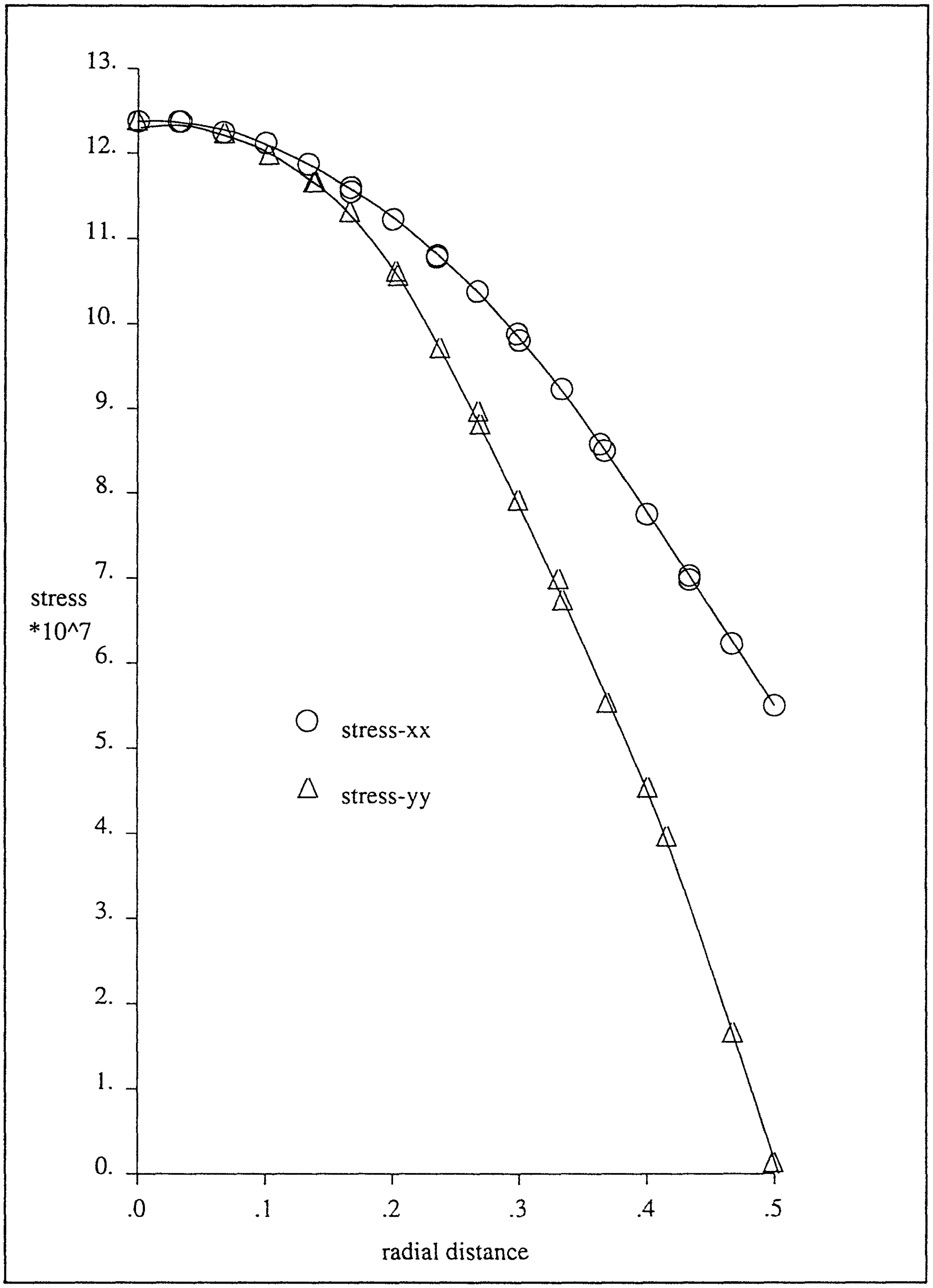

Figure 4-12: Stresses calculated using a finite element model for a disc under pressure supported on its edges.

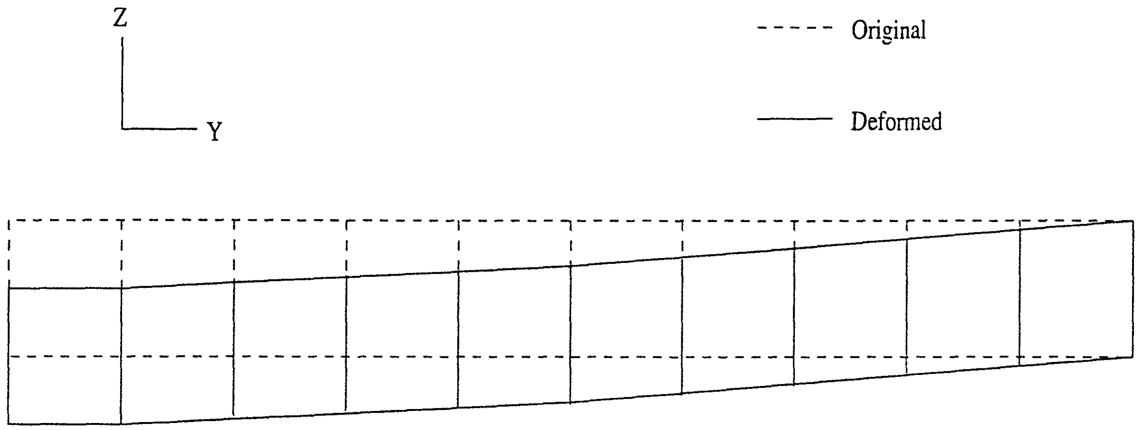

Figure 4-13: Aspect of the model before and after loading.

the amount of glass as the radius increases . In the center, there would be the same amount of reinforcement in the radial and tangential directions but as we get closer to the edge, the percentage of tangential reinforcement would increase to reach 100% on the edge.

However we need to remind our readers that we do not know how to place the fibers to make a reinforcement acting in only one direction, so we can only vary the strength of the reinforcement by varying the density of fibers. More than one mechanism existing to reinforce the wheels with glass fibers together with the wish to have the smallest amount of fibers in the disc prevent us from designing a universal reinforcement disc. Keeping this in mind, we can design many different reinforcement discs and the next chapter presents and analyzes the most interesting ones.

Chapter 5

Reinforcement Designs

In the previous chapter we determined the major stresses in a grinding wheel in use. In chapter three we reviewed the different reinforcement mechanisms of a glass reinforced composite. We now have all the tools to create new designs for our product. The main issues we want to keep in mind are the following:

1. Reduce by 30% the current cost of manufacturing the discs.

2. Do not decrease the grinding performances more than the current design.

3. Use the same amount of glass and resin as in the current discs or less if we can achieve the same performance.

4. Design discs that can be manufactured rapidly (less than 10 seconds per disc).

5. Reinforce more where the stresses are the highest.

6. Have the reinforced wheels pass the tests required for safety.

7. Reflect the circular geometry of the grinding wheel in the design of the reinforcing disc.

8. Balance the discs as the wheels are spun at high speed.

5.1 Purely Tangential

One design that immediately comes to mind by focusing mainly on the geometry issue is that of a purely tangential disc where the fibers would be displayed in a spiral pattern (Figure 5-1(a)). The main advantage would be the relatively short time needed to manufacture such a disc. Changes in the density of glass-fiber can be achieved without losing balance. However, some concerns are that the glass is parallel to the edges, which could decrease the grinding performances, and that the customer may feel it will not reinforce as well as the current design (and therefore customers and standard organizations will have to be educated which should be avoided). More importantly, however, is that a wheel using this reinforcement cannot resist a side load as the push-out tests proved. The wheels reinforced this way did very poorly on this test and we would not be allowed to put wheels reinforced this way on the market. This design had to be abandoned.

5.2 Purely Radial

Another design that rapidly comes to mind is a disc with glass fibers oriented radially around the wheel (Figure 5-1(b)). This definitely respects the geometry and will certainly not decrease the grinding performance of the wheels more than the actual design does. There are, however, some major drawbacks with such a design. One is that precise manufacturing of the design will be challenging. Yet the major inconvenience is that there is a very high concentration of fibers in the center. There is a lot of overlapping in the center where the density of fiber is high but the glass density drops as we get closer to the edges. Finally some experiments proved that wheels reinforced this way could not pass the speed test required. This last problem, together with the lack of uniformity, makes this design inappropriate.

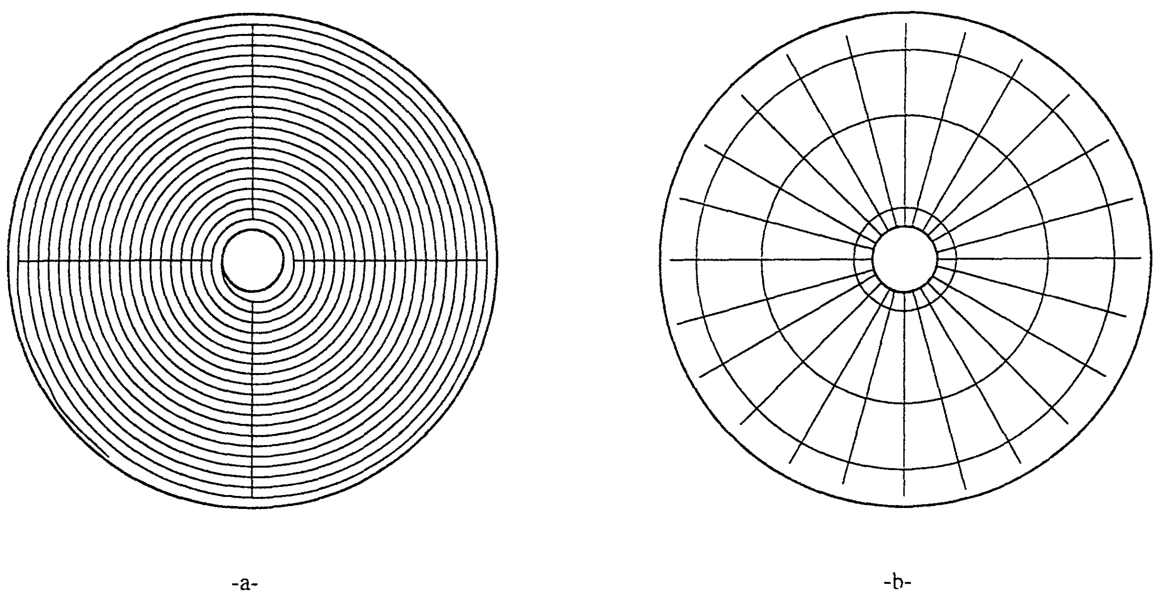

Figure 5-1: Examples of reinforcement: (a) purely tangential and (b) purely radial.

5.3 Zig-Zag

If we focus more on reducing waste and consider that the current design works well, even if it doesn't respect the geometry, then we will certainly want to try a reinforcement made of a double zig-zag (Figure 5-2(b)). The big advantages of this design are that it is really close to the current design and eliminates the waste and the weaving step. The disadvantages are mainly the presence of sharp curves on the edges of the wheel and the challenges associated with making such a disc by hand initially, controlling the tension in the fiber as the disc is made and keeping the fibers in place in order to make preliminary experiments. As a consequence, this design could not be tested and has not been pursued.

5.4 Flower-Design or Spirograph

Focusing more on the location of the stresses and assuming that the main reinforcement mechanism is by fiber pull-out, we could design a perfect reinforcement. The fibers would be placed tangentially close to the center and then become more radial. One problem is that the fibers must come back to the center if we want to use more

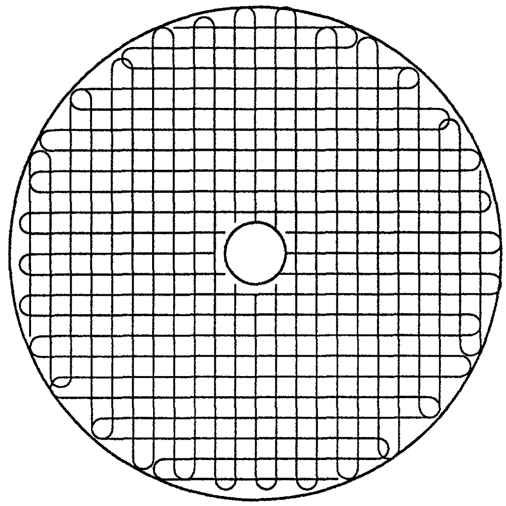

Figure 5-2: Example of reinforcement: Zig-Zag.

than one spool, which means they would be parallel to the edges. This is not good for the grinding efficiency. A possibility to avoid that would be to have the fibers make a sharp turn, but we know that this is detrimental to their integrity. If we think about something in between, then we fall into the design now realized by the German manufacturer Olbo(Figure 1-1). As this reinforcement would be difficult to manufacture at a lower price than what we now pay, we put this design aside.

2.6 Hexagon

If we want to reduce the waste but don't want to change the material used, we could design a hexagonal reinforcement, using the same woven cloth that we use presently (Figure 2-2(b)). The advantages would be a net reduction in waste and only a change in the shape of the die. The reasons why we abandoned this idea are numerous. One is that a wheel using such a reinforcement wouldn't fit in the category of *fully reinforced wheel* which is the market we are targeting. But the second reason is that, although this would induce a decrease in waste and hence in price, it is very unlikely that a major decrease in cost could be achieved, as the weaving step would still be present, as well as the other steps.

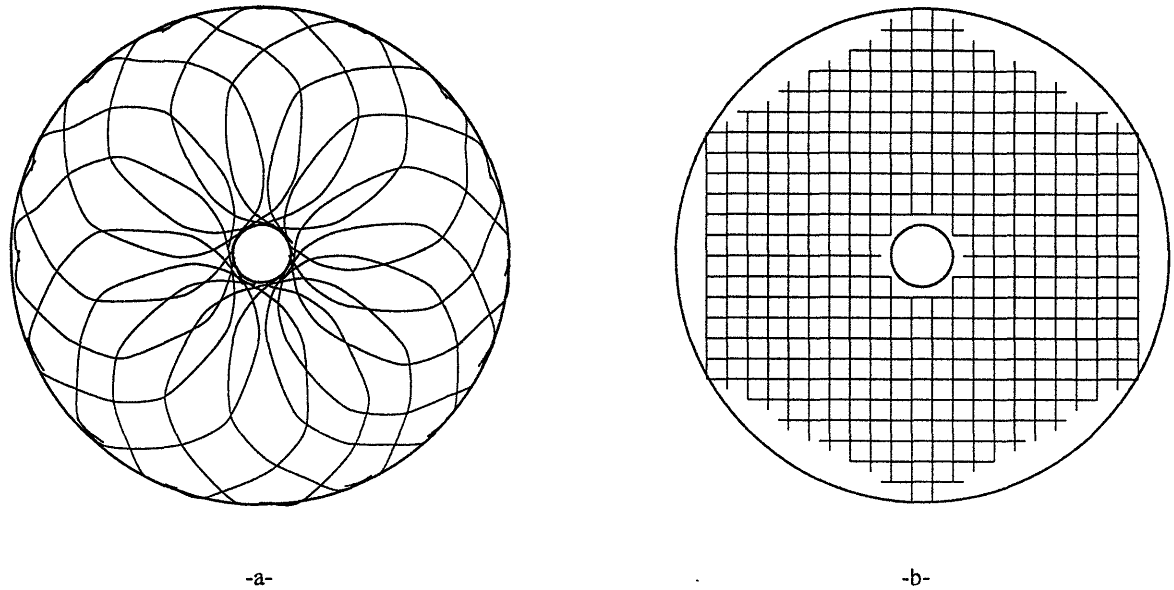

Figure 5-3: Examples of reinforcements: (a) flower and (b) hexagon design.

5.6 Cross-Hatch Design

A big advantage of a woven cloth is that it can be handled without being degraded. However, the curves created by the weaving pattern are detrimental to the reinforcement strength. If we could manufacture the reinforcement disc *in situ* or with very little handling, we could use the same design as the one presently used but with the fibers making a simple cross-hatch instead of a woven pattern. By making each disc individually, we would save on the waste and by eliminating the weaving operation we would save on manufacturing costs. To manufacture a few wheels with this design by hand for testing is not too hard, as we don't need to control the tension as in the zig-zag design, and it is only time consuming. The prototype machine we are going to build will aim at manufacturing this kind of reinforcement as it seems the most promising even though it does not differ fundamentally from the current design.

5.7 Woven Design

The potential advantage of a non-woven glass cloth is that unlike woven yarns (or rovings) which are woven over and under each other, the yarns are drawn into the fabric without warp or waviness. Therefore, for a given weight of glass cloth, the non-woven should be able to support a greater stress than its woven counterpart. However, the current reinforcement disc being woven, we can also consider a woven design, as the target is to reduce the costs and not to increase the strength of the reinforced wheels. We considered the weaving techniques used in the basket weaving industry, as well as some special patterns, used by Native Americans in New Mexico. One characteristic is that we can realize a disc without any waste. Nevertheless, the time to manufacture one of them would be very long and certainly not economically feasible, which is why we abandoned these designs.

5.8 Time-Related Issues for Manufacturing a Disc

To use the current manufacturing line, we want to incorporate the making of the reinforcement disc as an additional station on the line's carrousel and we need to manufacture it within a minimum amount of time. If a reinforcement cannot be made in less than 10 seconds, we will need twice as many machines as we would if the reinforcement could be made in 5 seconds, which is tantamount to saying that the ten-second machine should cost half as much as the five-second one. All these reasons stress the importance of estimating the time needed to make a disc beforehand.

It seems intuitively obvious that a parallel approach, drawing fibers from many spools at the same time (in parallel) would be faster than a serial approach, using one spool after the other, placing one strand after the other. In the following, a rough calculation is made to confirm this intuition. The times given, however, are not the total manufacturing times as the laying down of the fibers may not be the limiting step. Hot-pressing or cutting the fibers may be more time consuming.

The time necessary to lay down the fibers is calculated using hydraulic devices which are slower than air cylinders but will give us an upper limit.

The calculations have been made using a cylinder of diameter $d = 1/2''$. The stroke necessary is about $L = 9''$ (the web to be manufactured being about 8" in diameter) and the volume of fluid [1] that should arrive in the cylinder is given by

$$V = \pi \frac{d^2}{4} L = 157\,\text{in}^3 \tag{5.1}$$

Using a servovalve of the series 30 from Moog, we can determine the time necessary to go back and forth once, knowing that the fluid flow is of the order of 10 cis and that the switching time is of the order of 5 ms.

$$time = \frac{volume}{fluid\,flow} + 2 * switching\,time = (\frac{157}{10} + 0.005) * 2 = 0.32\,\text{s} \tag{5.2}$$

Of course some servovalves have a higher fluid flow and in the following we will consider that the time to go back and forth once is about $0.2s$. As a consequence, the time to lay the fibers with the parallel approach would be about 4 times this amount of time as we need to lay them down in two directions but also to move the mechanism out of the way of the hot press and knife. With the serial approach we need to go back and forth twenty times to lay the fibers in one direction. As a consequence the time required to lay the fibers down with the two approaches is

$$Time(parallel) = 4 * 0.2 = 0.8\,\text{s} \tag{5.3}$$

$$Time(serial) = 40 * 0.2 = 8\,\text{s} \tag{5.4}$$

It seems relevant to notice here that these times will vary differently with the size

[1] One could argue that the cylinder for the parallel approach should be larger in diameter than for the serial approach and therefore the amount of fluid would be bigger as the force needed would also be higher. This would make the difference in manufacturing time less obvious as only the switching time would differentiate the two approaches. However, using hydraulic cylinders, force is not an issue as we will have more power than necessary even using the smallest cylinder as we did.

of the web to manufacture. If for instance we double the diameter, we may double the time necessary with the parallel approach (this time varies as the first power of the diameter) but it will multiply by four the time necessary to create one web using the serial approach (this time varying as the second power of the diameter because the strokes would be two times longer and the number of strokes is also double).

The other step that will increase the manufacturing time is the hot pressing of the newly laid fibers in order to obtain a web that can be handled. During this stage, we also plan to cut the web using a knife that would go down at the same time as the press. The cutting operation is therefore as fast as the cylinder can go. It seems reasonable to use the same servovalve and cylinder. We will consider that we need about 0.5 s to move the press and the knife down, cut the fibers and then move everything up.

However the time to hot press the disc would be the limiting step. Especially if we want to use a radiation heater like heat bulbs, we would need at least 1 s to warm up the hot melt resin to a temperature such that it would be sticky, and this would require some very powerful bulbs. Pressing the fibers only with a thin ring on the external diameter is not certain to be sufficient to make a disc of constant thickness. An experiment will be conducted to determine whether a full hot pressing disc, which would be faster, does give a better result and whether we can get rid of the sticking problems.

We also need to determine whether hot-pressing is mandatory. Maybe a cold-press would be sufficient and would enable us to manufacture even faster.

Finally, as the coating of the fibers is realized in parallel with the laying down of the fibers, no additional delay is introduced. Therefore the manufacturing time would be of about 3 s for the parallel approach and of about 10 s for the serial approach.

Chapter 6

Prototype Reinforcement Fabrication Machine

Willing not only to find a new design for glass fiber reinforcement discs for grinding wheels but also to manufacture such a product, we had to bridge the gap between the purely theoretical aspect of our research and the practical aspect of the industrial world. Therefore, a prototype machine has been designed to manufacture what has been found to be the best solution for a net decrease in the cost of glass fiber reinforcement discs. In order to create one disc, the machine has to perform a series of tasks described in detail in the following section. The technical realization of these tasks is then presented.

6.1 The Tasks

The first step in building a computer controlled apparatus is to define the different tasks we want the piece of equipment to perform. The tasks that have to be completed by the machine are presented in Figure 6-1, then follows a detailed description or these tasks.

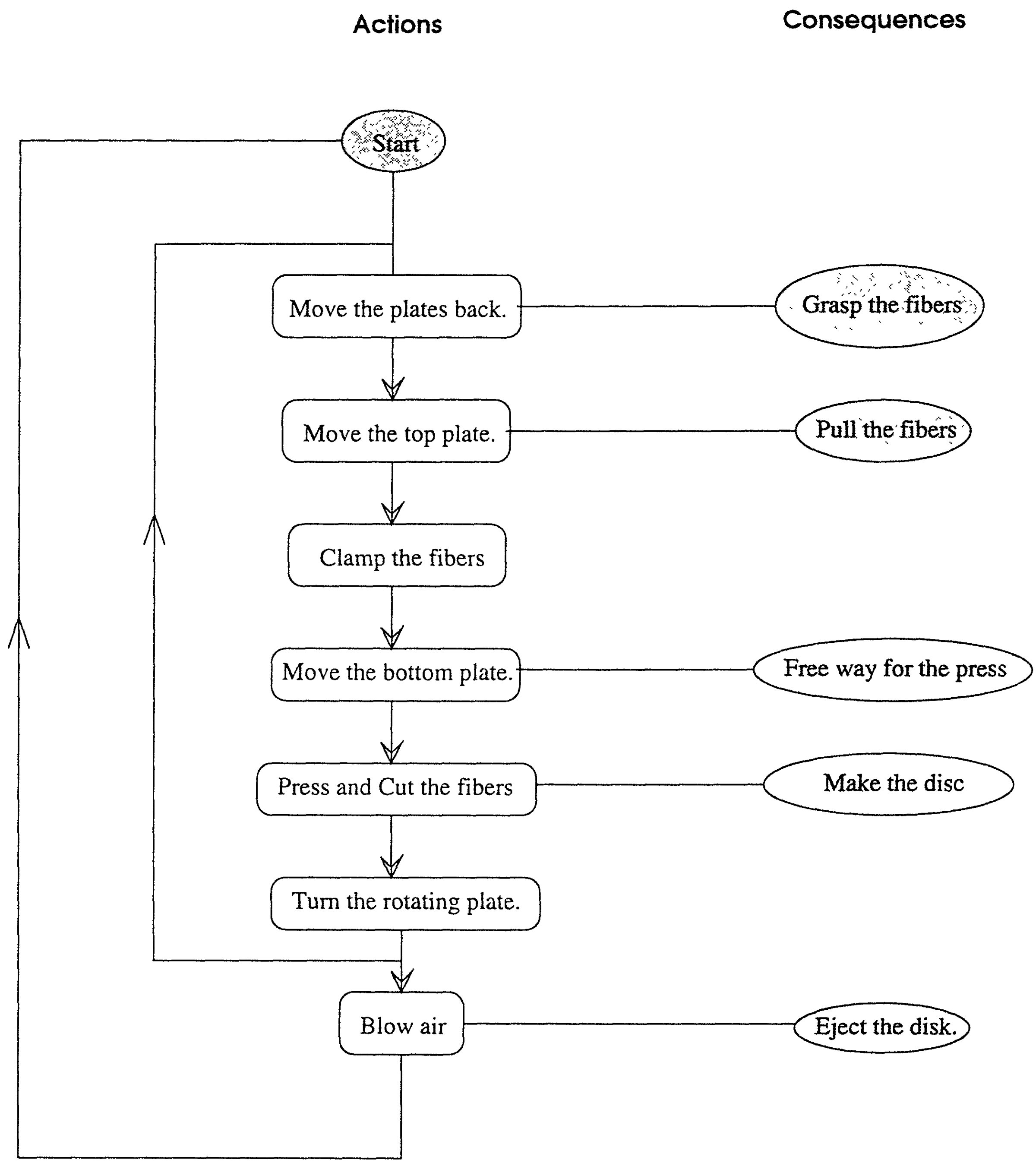

Figure 6-1: Sequence of tasks fulfilled by the machine.

6.1.1 *Coating:*

The machine uses uncoated rolls of glass fibers from Vetrotex-Certainteed. The glass fibers need to be coated with a polymer in order to protect their surface as they are coming into contact with the abrasive mix. To eliminate the need for drying, a hot melt resin that is solid at room temperature has been created.

The fibers go through a hot bath and then between two rolls to make sure the resin is homogeneously present inside the rovings. The shape of the coated fibers as well as the amount of resin are ensured by a die placed at the end of the bath. The bath is heated externally through a hot plate in order to avoid any leak and overheating of the polymer on the heater.

6.1.2 *Drawing:*

The coated fibers have to be drawn through a guide that ensures their position and allows them to dry by exposure to air for a couple of seconds. They are then grabbed individually by a gripper made of spring steel whose jaws are designed in order to ensure a good clamping without applying too much pressure on the fibers and to enable the fibers to be released easily. The drawing power is supplied by one air cylinder controlled by the computer.

This step is truly the critical step in the making of the reinforcement disc. This is the most time consuming task and it needs to be performed in less than three seconds. Obviously, a parallel approach has been chosen. The machine coats and draws forty strands [1] simultaneously from forty spools of uncoated glass fibers. Our solution to draw them creates no waste and originate from the idea of a "flexible-comb". The principle is presented in Figure 6-2. The idea is to grab the fibers with the grippers arranged in half a circle and to pull them across the rotating disc, deforming the "comb" into the miror image of its original shape. No waste is created when the fibers are pressed and cut because they have only been drawn by the length required

[1]There are five strands per inch in the cloth currently used and we aim to make an eight inch diameter reinforcement disc. Therefore we need forty parallel fibers in each direction.

for making the cross-hatch reinforcement design. Once the fibers have been cut, the rotating plate is turned by ninety degrees and another set or fibers is drawn across the plate, thereby making the reinforcement disc.

However, the protoype machine we built does not use a flexible device but a set of independent grippers, moving into parallel grooves machined in the part called "Bottom Moving Plate". The half circle shape is given by the top moving plate into which grooves of different lengths have been made. Dimensioned drawings of the different parts are given in Appendix A.

6.1.3 *Pressing:*

Once the design has been made on top of the rotating plate, the fibers lay above each other but do not make a reinforcement that can be handled in a factory and the thickness is not constant. The coated fibers have therefore to be pressed in order to make the reinforcement flat and also to make the fibers stick to one another so as to keep the design characteristics once the disc is removed from the machine and before it is put into a mold. The pressing operation is performed by a simple flat disc, coming into contact with the coated fibers.

6.1.4 *Cutting:*

Obviously the fibers have to be cut before turning the rotating plate. Different techniques can be used. Shear can be used. Pressure also can be used by having the fibers pressed between the rotating plate and a steel disc. We could also think about using a high power laser to cut them by melting the glass and burning the resin without contact. This would certainly be more expensive but would also be very clean as there would be no contact.

The prototype machine however uses shear to cut the coated fibers.

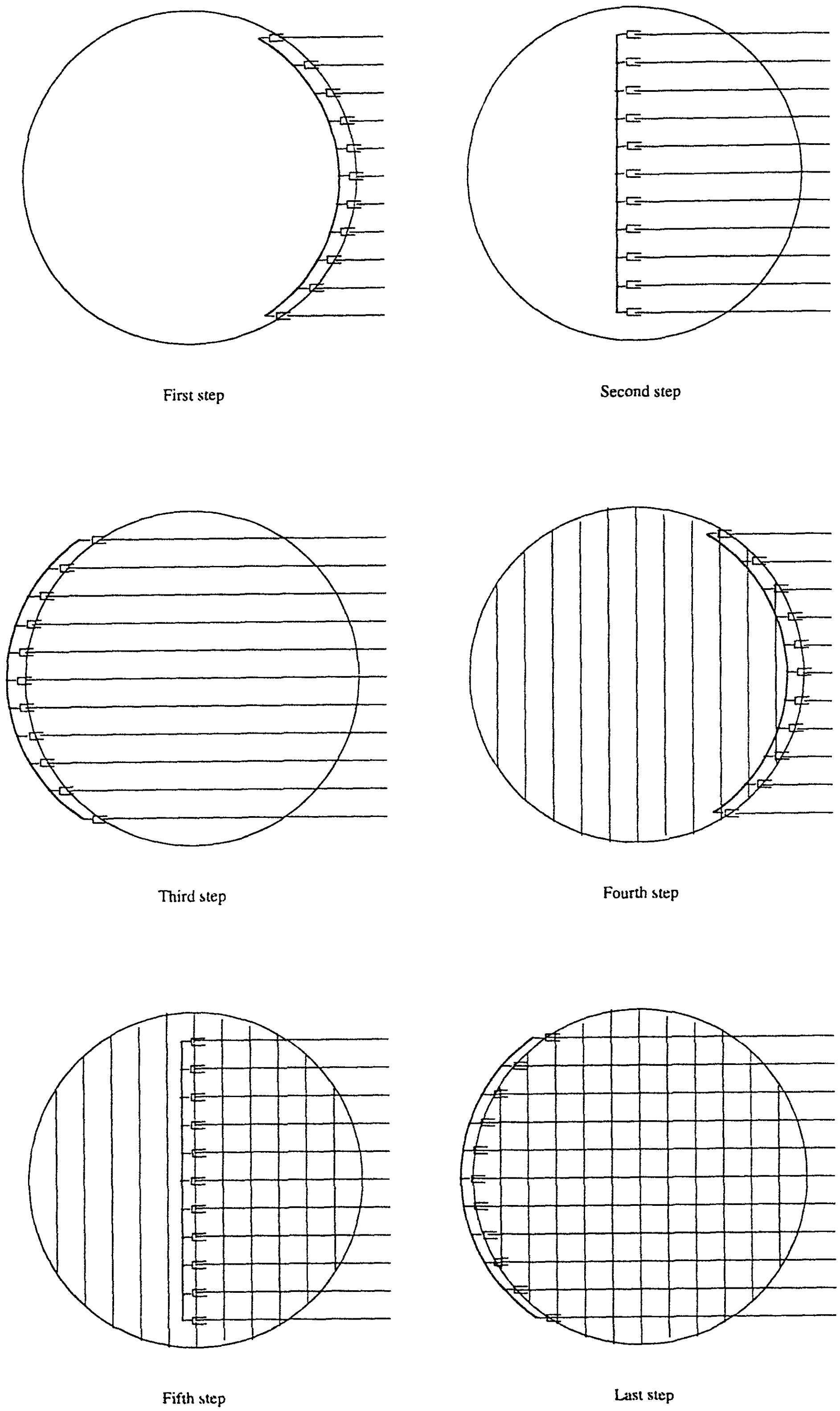

Figure 6-2: Schematic diagram presenting the principle of the flexible comb idea.

Name	Task
A	Move Top Plate
B	Move Bottom Plate
C	Move Press and Knife
D	Move Cam
E1 & E2	Move Clamp
F	Rotate Rotating plate

Table 6.1: Tasks performed by the different cylinders in the prototype machine.

6.1.5 *Ejecting:*

The reinforcement discs being made beforehand and not directly in the mold, they have to be removed from the top of the rotating plate and then placed into boxes before being used. A mechanical arm can be used even though some defects may be created on the disc. A better solution would be to use air under pressure and push the disc into a funnel leading to a box. This solution would need a lot of adjusting but could be fast, quiet and not detrimental to the newly made disc.

This last technique will be implemented into the prototype machine when mass production will be necessary for statistical testing of the quality of the new reinforcement discs.

The next step in making the machine is to determine how the previous tasks will be performed. We decided to use cylinders (these can be activated either by air or by hydraulic pressure). We named all the cylinders and designed the links between cylinders, valves and sensors. Table 6.1 gives the tasks performed by each cylinder and the name of the cylinder as it appears in the schematic figures that follow. A drawing presenting the links between the different parts of the power circuit is given in Figure 6-3. This schematic diagram, together with the sequence of events displayed in Figure 6-4 have then been given to a person specialized in designing computer controlled systems. Using this information, this person was able to give us the references of I/O cards that would fit our needs as well as the names of softwares to control these cards. Our task was then to write a program in the language of the software chosen. The computer then monitors the sequence of operations by activating servovalves through the card according to the inputs received by the card from different sensors and captors placed on the cylinders.

6.2 Issues Specific to the Industrial Machine

If the cost analysis for the full scale machine, determined with the data gathered while building the prototype machine, proves that these reinforcement discs can be manufactured with a 30% decrease in cost, then an industrial machine will be built to replace the present supplier of woven glass cloth. Very few differences will be noticeable in the mechanisms. The manufacturing times will also be the same. However, in order to meet the safety requirements, many features will have to be added. Among these we can cite

-an emergency stop button

-shields to protect the operator

-sensors to monitor the temperature more accurately

-more automatisms

-a table for the machine and the computer

-a shelf for the spools

-a mechanism to secure the spools in place

-an insulated box to keep the temperature cool and constant in the drying zone and around the box where the discs are stored.

6.3 Other Issues

As we were designing the different parts, some issues that could not be addressed beforehand needed to be kept in mind. A design had to be found that would allow us to modify the relevant parameters once the machine was built when the value of these parameters couldn't be determined by simulating the operation with experiments. We

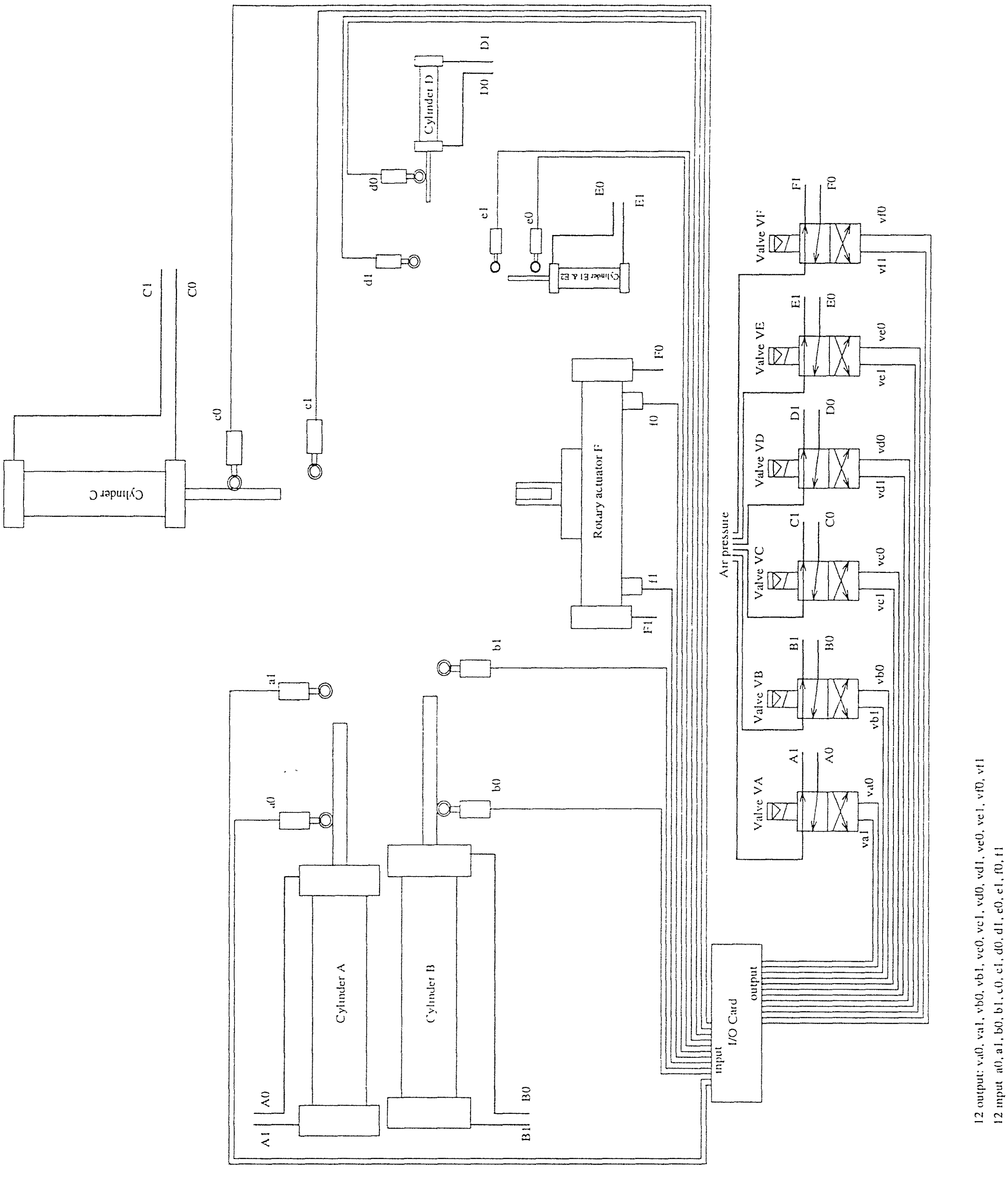

Figure 6-3: Schematic of the links and connections between the cylinders, the valves and the sensors in the prototype machine.

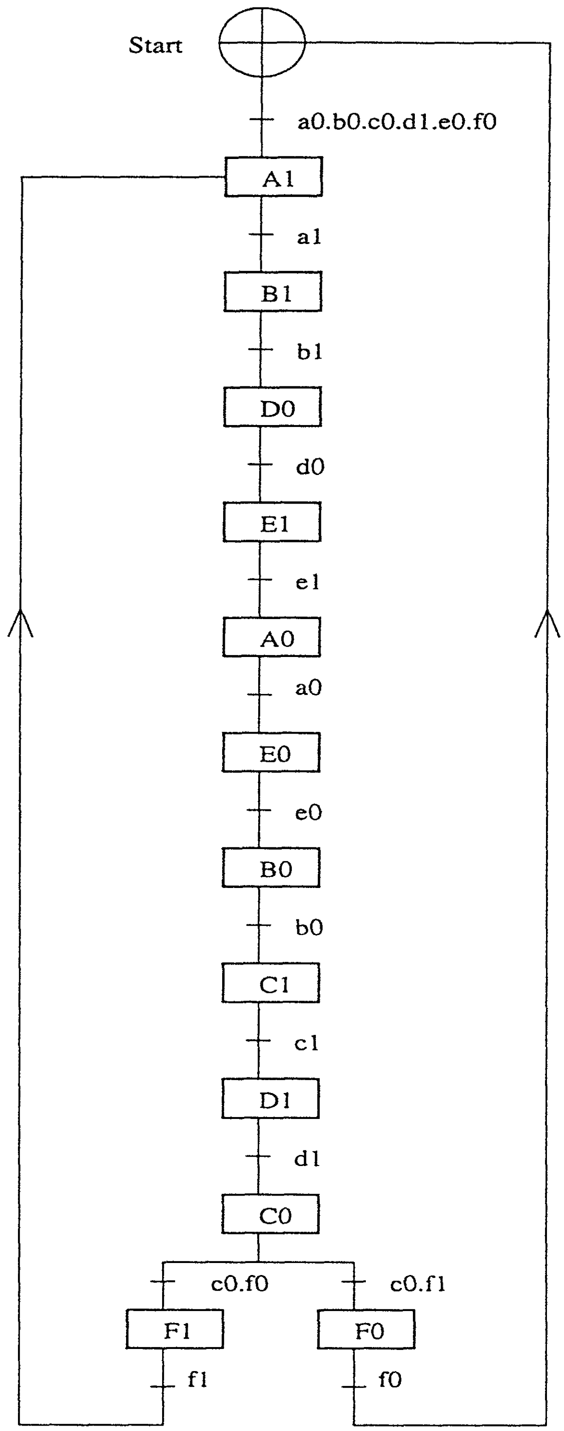

Figure 6-4: Sequence of tasks controlled by the I/O card.

tried to reduce the debugging process as much as possible because a lot of time is usually lost in factories for adjusting and tuning. The parameters have been made variable without having to take the machine apart. Some of the issues were:

1. *Tension in the fibers:* The exact value of the tension that would keep the fibers in the grooves as they are going into the resin bath has not been determined. This could have been done with experiments in the laboratory but instead a set of three eyes that can be oriented has been added where the fibers are coming out of the spools. This allows us to change the tension very efficiently in a large range rapidly and easily.

2. *Stiffness of the fibers:* In order to grab the fibers in the grippers, their position has to be known and held constant. This can only be realized if the fibers are stiff enough and if the amount of resin does not vary too much. This last operation is taken care of by the die at the end of the bath. Yet the geometry of the fibers being also determined by the shape they had as the resin dried, the tension in the drying zone (i.e in the guide) has to be held constant. This is done by changing the tension with the eyes before the bath and also by varying the pressure between the two rolls inside the bath. Finally, the temperature plays a very important role here. The hotter it is, the less brittle the resin is and therefore the less stiff the fibers are. An apparatus to change the temperature of the machine and of its environment and to hold it constant is therefore needed.

3. *Clamping the fibers:* We need enough pressure to prevent the fibers from going back to the resin bath or inside the guide. The pressure should also be high enough to enable the fibers to be released from the grippers once the design is realized. However we do not want to flatten the fibers too much and we definitely don't want to break the glass. The pressure in the cylinders cannot be changed easily but we can change the rod eye vertical position easily and this will modify the pressure on the fibers.

4. *Grabbing the fibers:* Here the design of the jaws is important as the pressure exerted on the fibers is only applied because the jaws are made of spring steel.

We will be able to change this pressure a little by bending the jaws and changing the area of contact. We can also think of changing one of them for one made of thinner spring steel but this would involve machining new parts and would be debugging only at the prototype level. It wouldn't involve any adjustment in the factory. The theoretical determination of such a force is very difficult too, as the surfaces are not really well defined where there is contact between the jaws and the resin and between the resin and the glass fibers. The surface of the jaws will change as the machine is used and will certainly be coated with polymer after a while so the rheological characteristics will change. Tuning by trial and error seemed the best solution for this problem.

5. *Releasing the fibers:* The design of the gripper jaws has to enable the coated fibers to be released once the tension inside becomes too high. The tackiness of the coating resin must also be determined at the operating temperature. This characteristic can be modified at a given temperature by changing the composition of the resin too. Ideally the fibers will be sticky enough to be handled without too much pressure and not too sticky to be released without problems. Also the position of the fibers as they are releaased from the grippers has to be held constant on top of the rotating plate. An additional guide may be needed and/or grooves on the circular plate may have to be machined in order to ensure this positioning.

6. *Cutting the fibers:* Whether we use shear or pressure, the pressure on the fibers or the movement of the knife will have to be adjusted. The variations in properties of the resin with temperature and the incertainty about the exact operating temperature prevented us from determining this value beforehand. The press that moves the knife can be positioned vertically in order to facilitate these adjustments.

7. *Splicing techniques:* The machine will run in a continuous way and the production will not be stopped to change a spool of fiber. Also, in a parallel approach, as the spools may not run out of fiber at the same time, stopping the production

every time one spool needs to be changed would slow the process a lot. Such a machine would be stopped very often and would not be economically feasible. A solution had to be found in order to link the end of one spool to the beginning of another. One approach used a cyanoacrylate glue that works very well with glass. One problem was that the ends need to overlap for the glue to work and therefore the diameter increased at the junction. The link was also very stiff and it is not certain that it could pass the curves inside the resin bath without breaking. Also these types of glue cannot resist high temperatures for a long time. A last concern was what might happen if the knife were to cut such a link. What would the force needed in that case be?

Another solution is to use a tape to splice the two ends. This of course requires some training of the operator and also induces an increase in diameter but not as big as in the case of glue. Some tapes have been found that resist the temperature of the resin bath. The joint was less stiff but longer than with cyanoacrylate and we must be concerned about introducing a new material in the reinforcement. What the adherence between the tape and the resin would be in this case still remains to be evaluated.

8. *Maximum pressure:* The maximum pressure applicable on a newly formed disc will have to be determined during the debugging process. We do not want to flatten the fibers too much and we also do not want to have half the disc stuck on the top of the press while the bottom remains on the rotating plate. A non-sticking coating will have to be found for these plates. However we want the fibers to stick to one another and form a disc that can be handled. The pressure will mainly be determined by the weight of the press plate. Some springs may be added and the position of the cylinder moving the plate can also be adjusted.

It may be interesting to use the prototype machine to determine some other characteristics. Among them we can think about the maximum speed at which the fibers can be drawns and coated, the maximum temperature for the bath fibers and the maximum angular speed for the rotating plate that keeps the fibers in place.

item	percentage
machined parts	60.6%
cylinders, sensors	18%
slides, rails	12%
press guides	3%
screws, nuts...	1.9%
bearings	0.7%
computer I/O card	1.3%
hoses, fittings...	2.5%
Total	100%

Table 2.2: Costs of the prototype machine.

6.4 Costs

Before building the machine, a cost analysis told us how much money we could spend on the prototype machine in order to ensure the economic feasibility of the project. The projected cost being in the range of this estimate, we started ordering parts to build the machine in the Norton R&D department in Worcester. Table 6.2 gives an account of how the budget has been spent.

The most expensive items are without surprise the custom parts even though we tried to use as many parts sold in catalogs as possible. Machining amounts to 60% of the total cost and this was with the lowest quote we got out of three.

We also need to remind our readers that these are the costs for a prototype machine and that even though the mechanisms and the pistons would be the same for an industrial machine, the safety items and all the other items mentioned in section 6.2 would add to the costs and we can foresee that the machine for the factory would cost between 500% and 700% more.

Chapter 7

Conclusions

As we are finishing this project, the debugging of the machine is not completed. Conclusions can however be drawn regarding the economic and material aspects of the manufacturing of coated glass fiber discs with a cross-hatch design for reinforcing grinding wheels.

7.1 Economic Feasibility

It is not possible to determine whether the machine would replace the current supplier by considering only one size of disc: Some discs are cheaper to manufacture than others. However, considering the total expenses for reinforcement discs and the price to run the machine and to supply the resin and the glass, it is possible to give an estimate of the maximum amount of money we can spend on the industrial machine.

A general answer to the economic feasibility can nevertheless not be given since we do not know if the company wants to make a short term investment or a long term investment. Also the money each site can invest in such a change varies.

The exact price for the industrial machine cannot be determined before contacting designers and asking for quotes from different companies. We saw during the building of the prototype machine, prices can double or even triple for the same work from one company to another. Extra care should therefore be spent doing cost analysis and inquiring in order to make the right choice for a given financial situation.

7.2 Practical Feasibility

The question is not whether we can make a new reinforcement disc using glass fibers with a new design, but rather whether we can make it in the 4 seconds targeted or not. Advances in science and technology allow us to manufacture in a way that would have been unthinkable a couple of decades ago. In the case of the prototype machine for instance, one of the longest steps could have been the warming up of the fibers to have them stick to each other and make a flat disc. Finding ways to heat up the glass rapidly is a possible approach. To create a resin that is sticky enough at room temperature in order to eliminate the heating step is another solution that would allows us to save a considerable amount of time once we found a way to prevent sticking to the other parts.

Also there is no denying that the parallel approach taken to manufacture the cross hatch reinforcement disc is mandatory. Drawing one fiber after the other or making the disc using a zig-zag pattern would be too time consuming. However there may be solutions for a parallel approach that may not require to have forty independent grippers. If we can afford a small amount of waste, we can design a gripper pulling two or five or even ten fibers at the same time and therefore using an active gripper instead of one made of spring steel. We could also use less spools and split them just before entering the bath. This is presently not doable because each fiber is drawn across the rotating plate over a distance that is different from its neighbor's. Whether we will explore these possibilities depends on the cost of manufacturing one disc with the prototype machine.

Therefore, to the question whether such a reinforcement can be manufactured, from a material point of view, we can answer "yes" without any hesitation but then announce that given the present technology and available materials, we can manufacture in an amount of time that may or may not meet with our objectives.

Appendix A

Dimensioned drawings.

This appendix presents the plans of the parts composing the prototype machine. Our intention in presenting these small scale drawings is to help the reader understand the issues associated with the building of such a machine as well as to present a solution to these problems.

Most of these dimensioned drawings were drawn to be used by a machinist for manufacturing the parts of the prototype machine. However, they are not presented here to serve this purpose but rather to present the type of machine that can be realized in ten months in order to create a link between a theoretical study and an R&D laboratory.

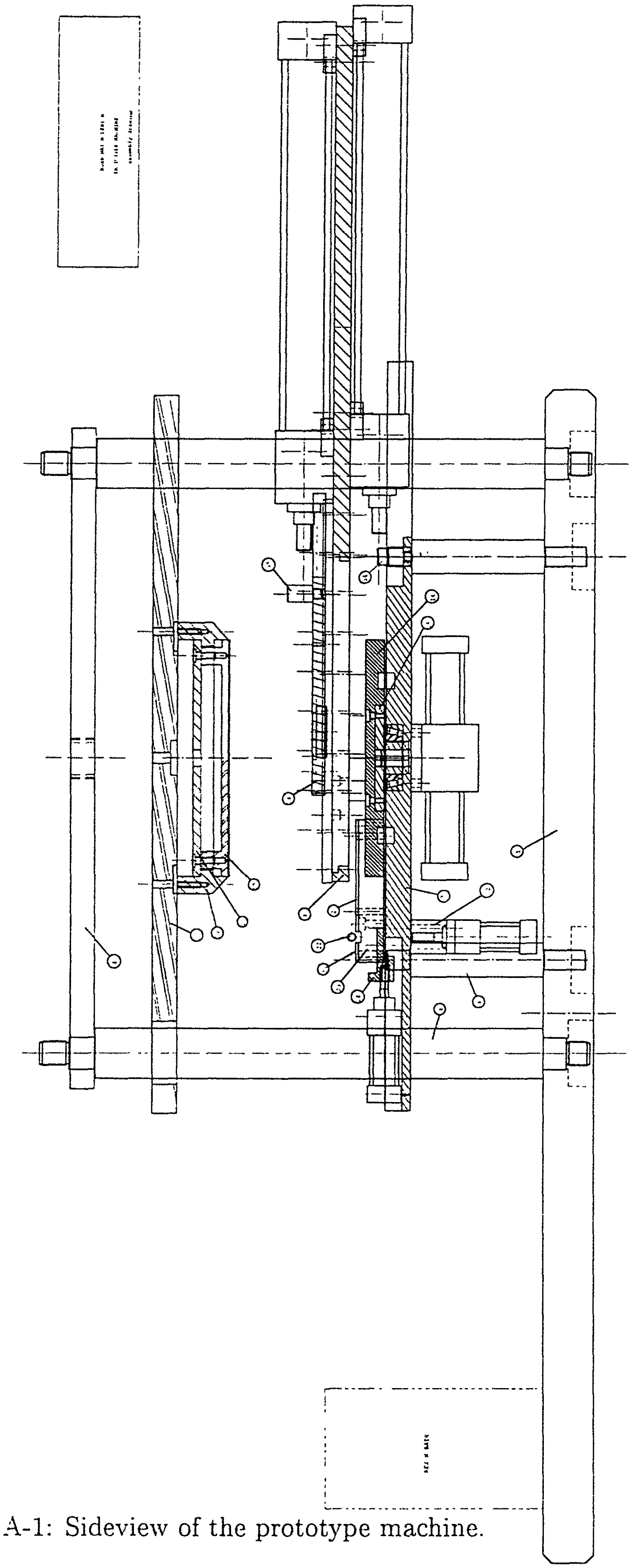

Figure A-1: Sideview of the prototype machine.

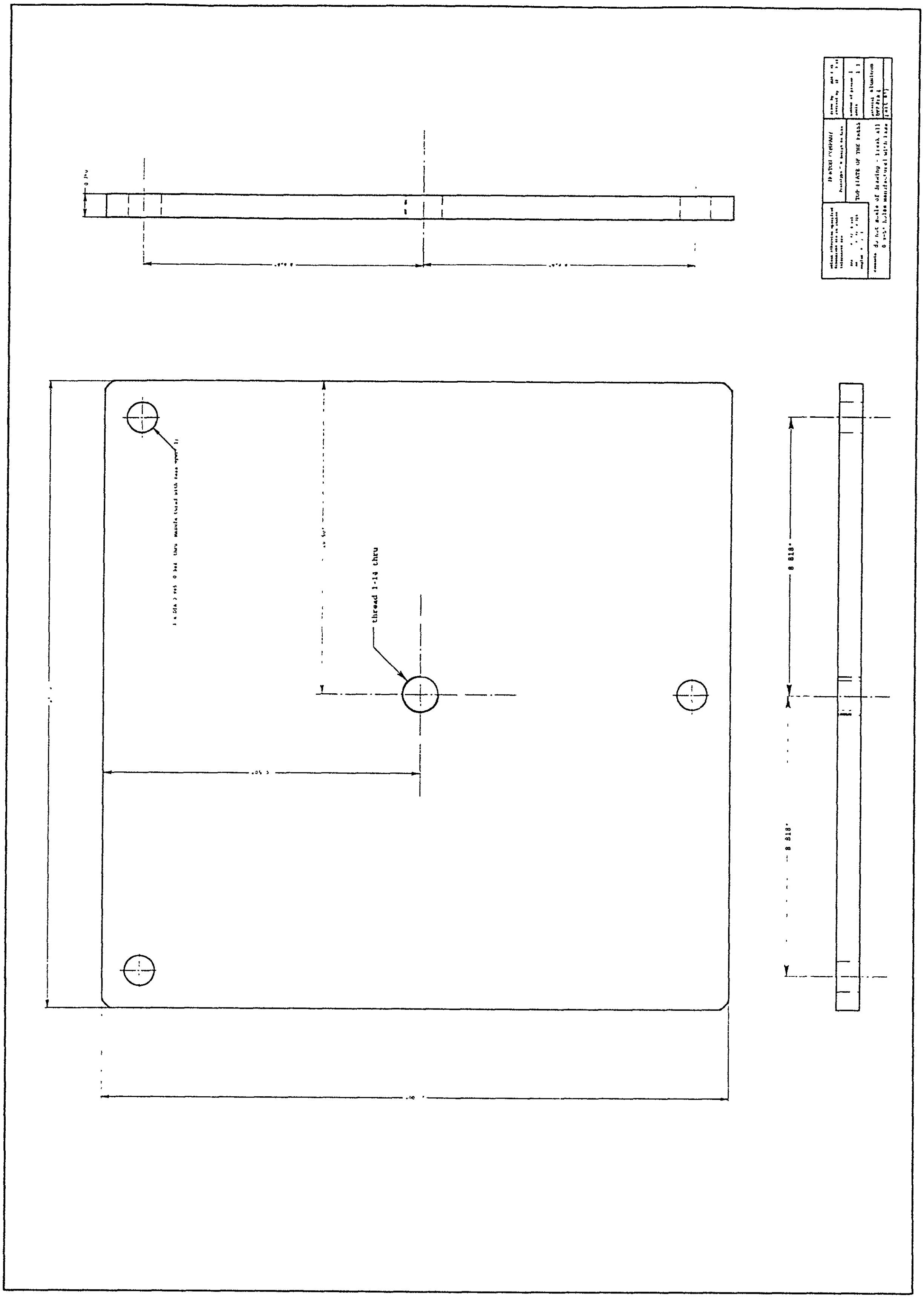

Figure A-2: Top fixed plate of the press.

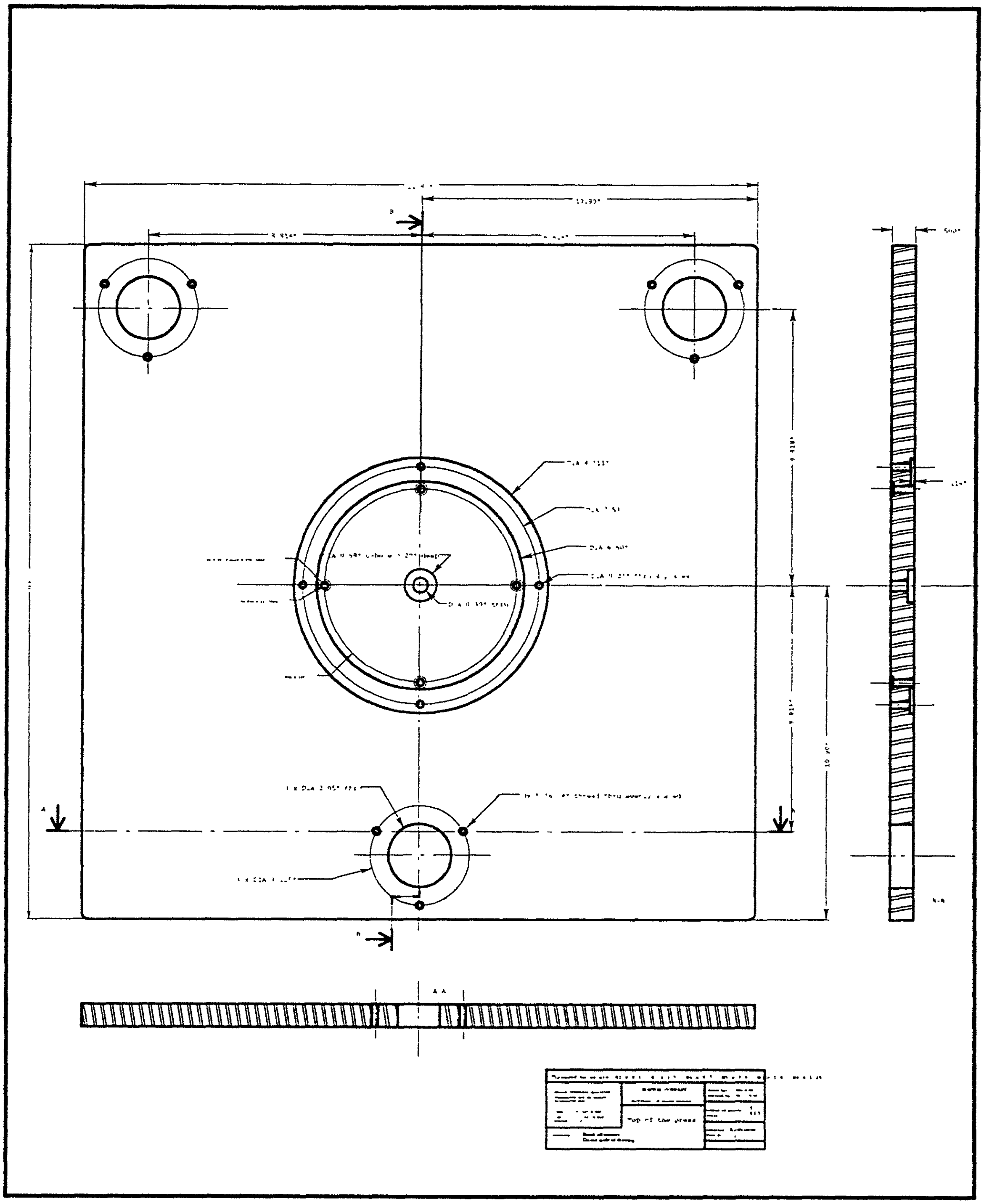

Figure A-3: Top moving plate of the press.

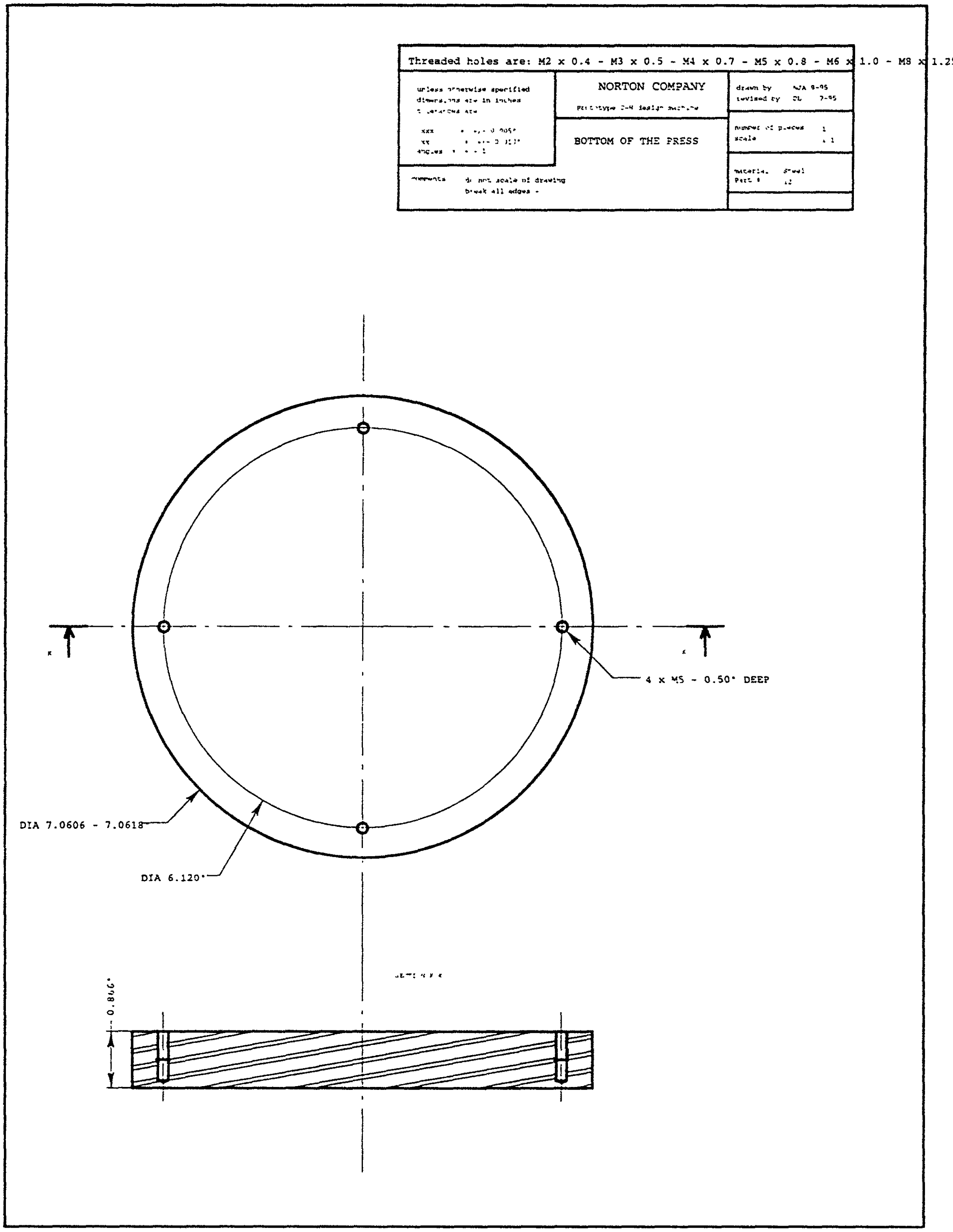

Figure A-4: Pressing disc.

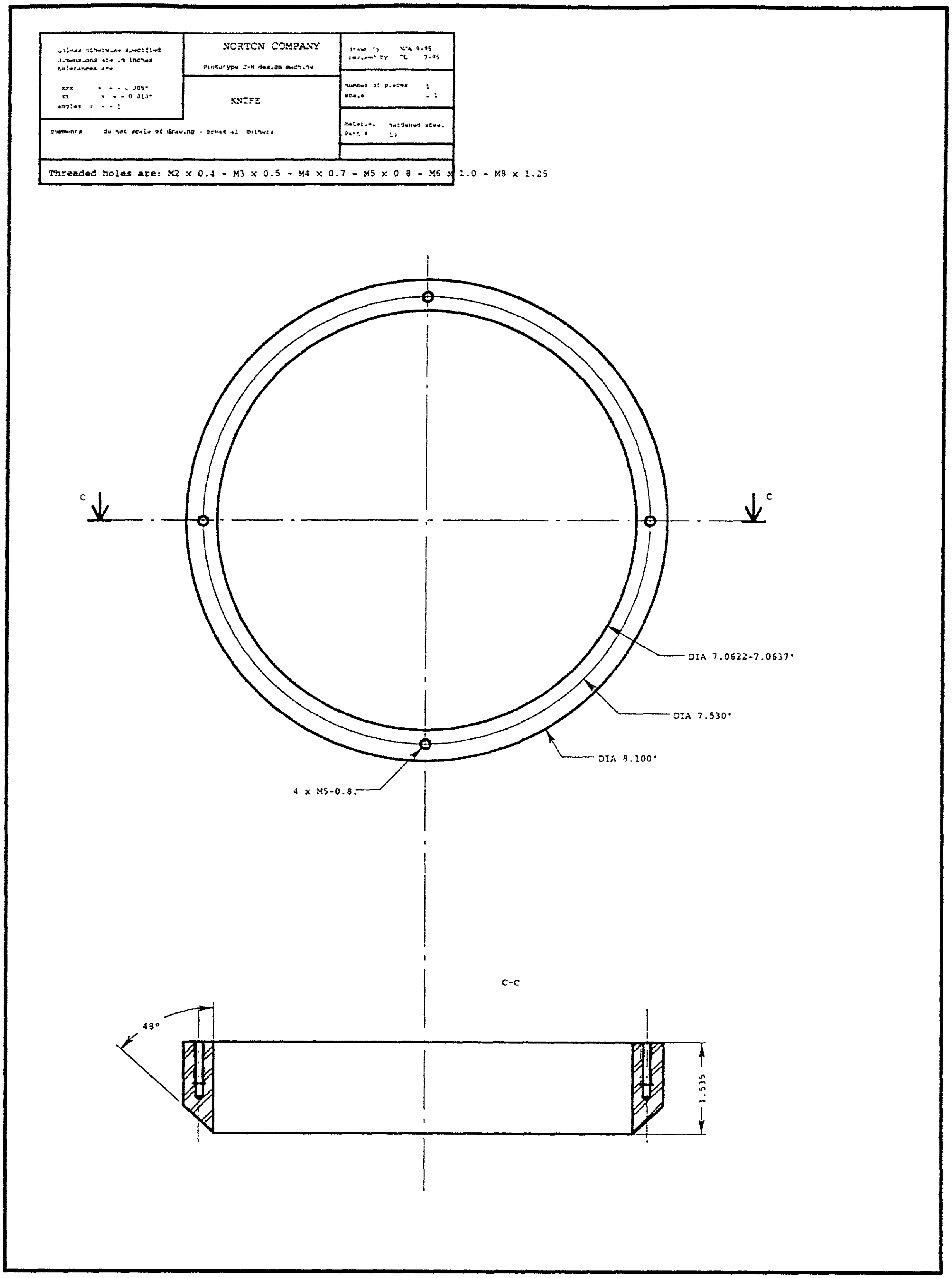

Figure A-5: Knife.

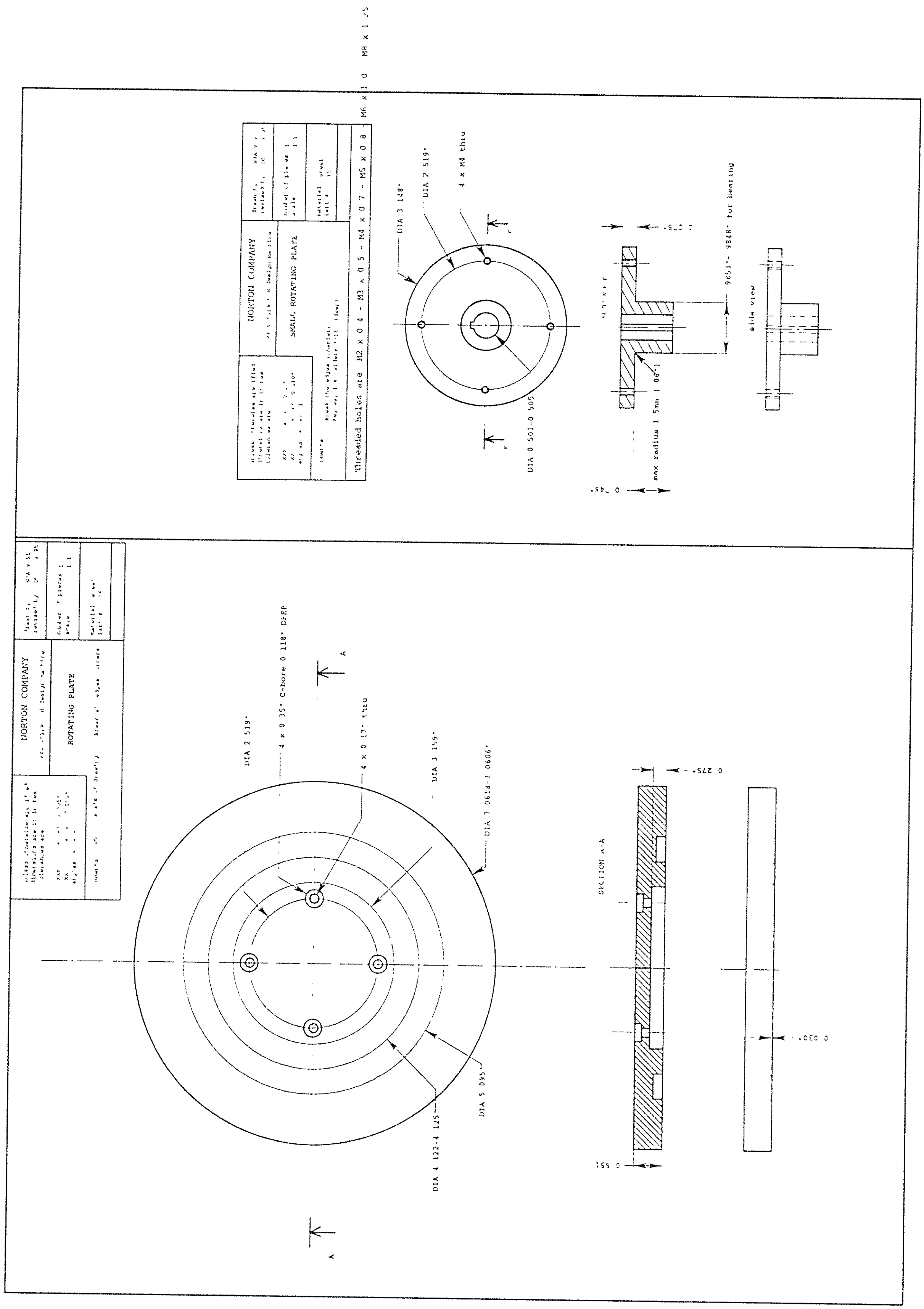

Figure A-6: Rotating plate.

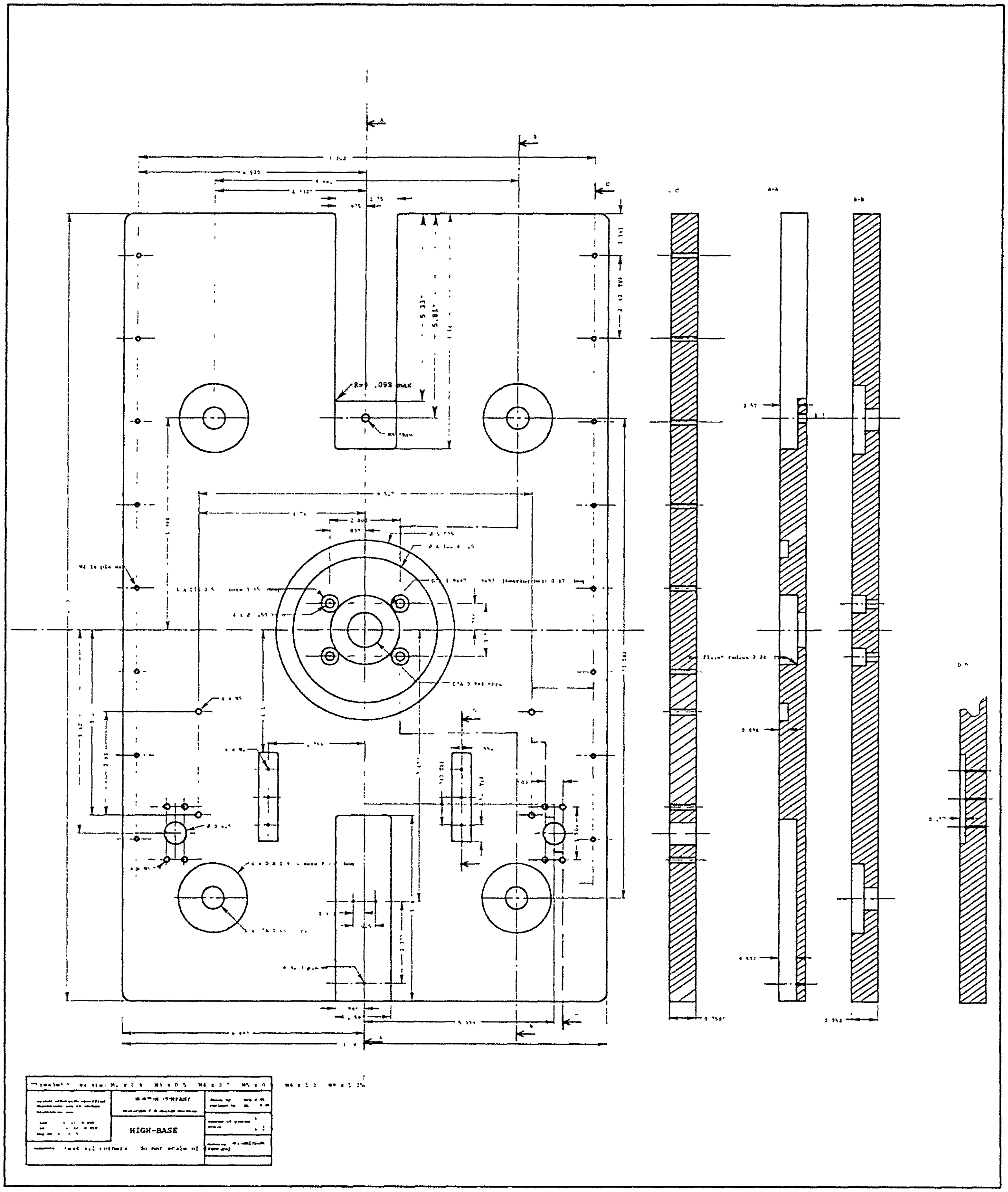

Figure A-7: Upper base.

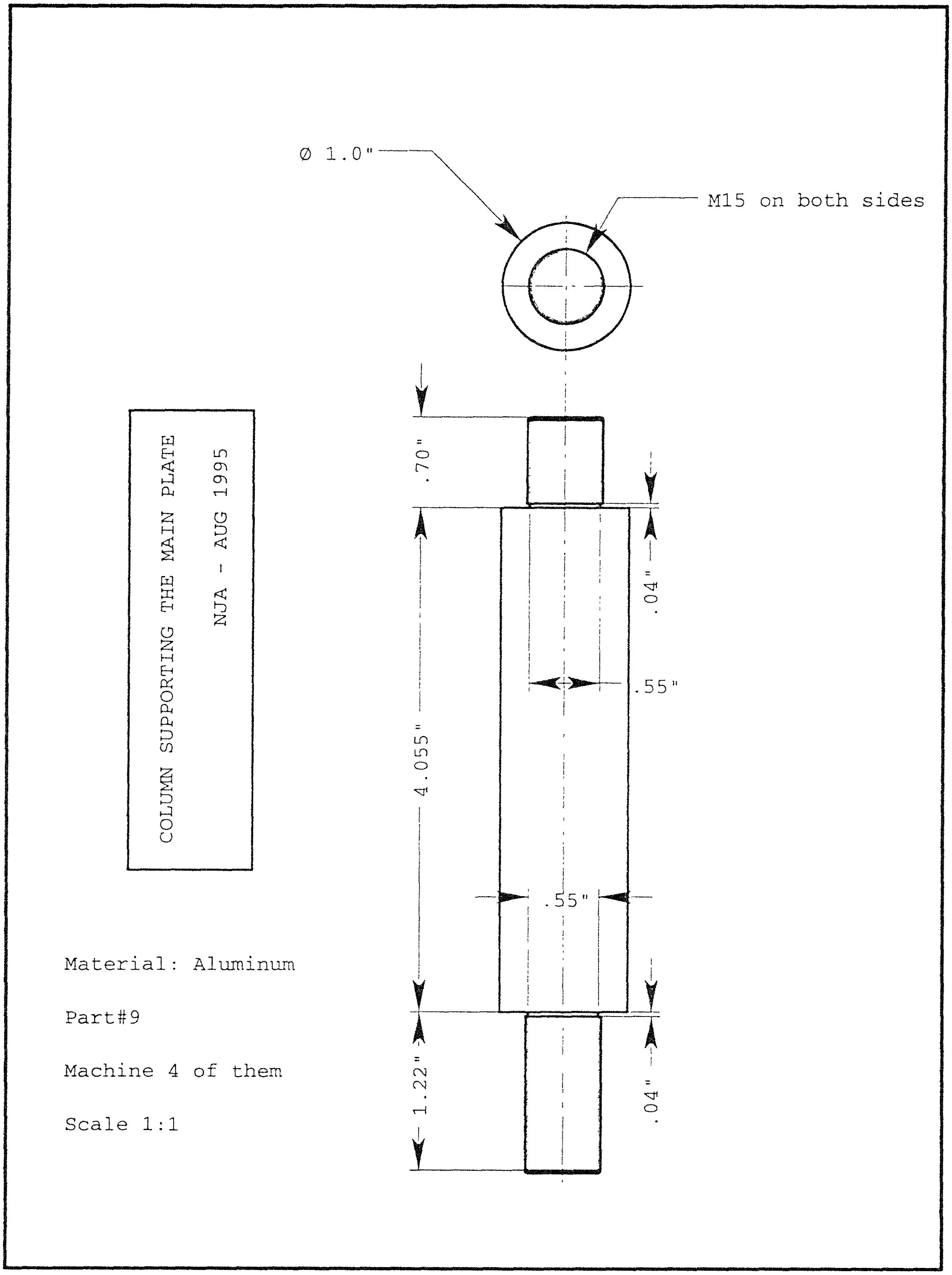

Figure A-8: Columns supporting the upper base.

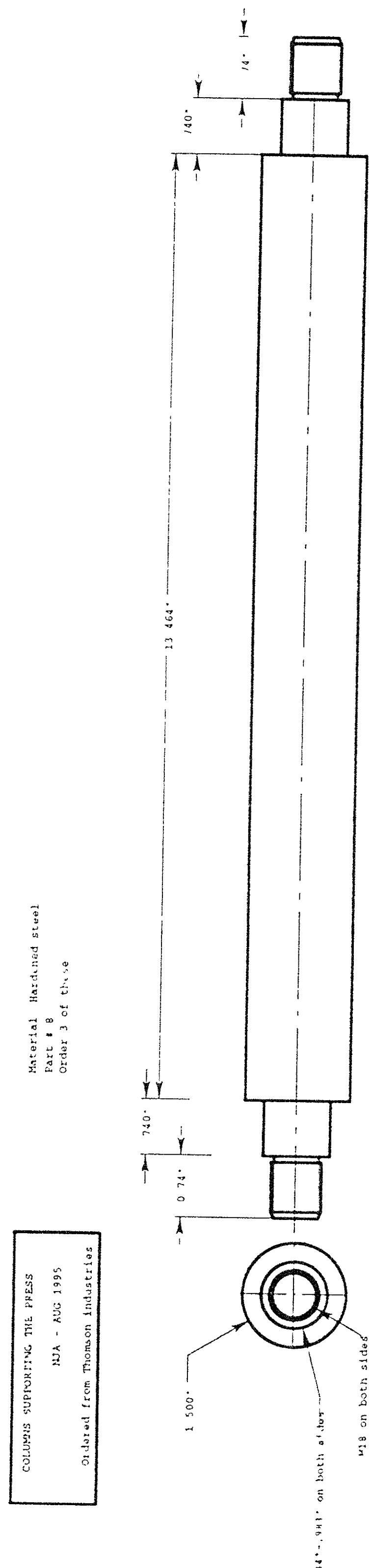

Figure A-9: Columns guiding the press.

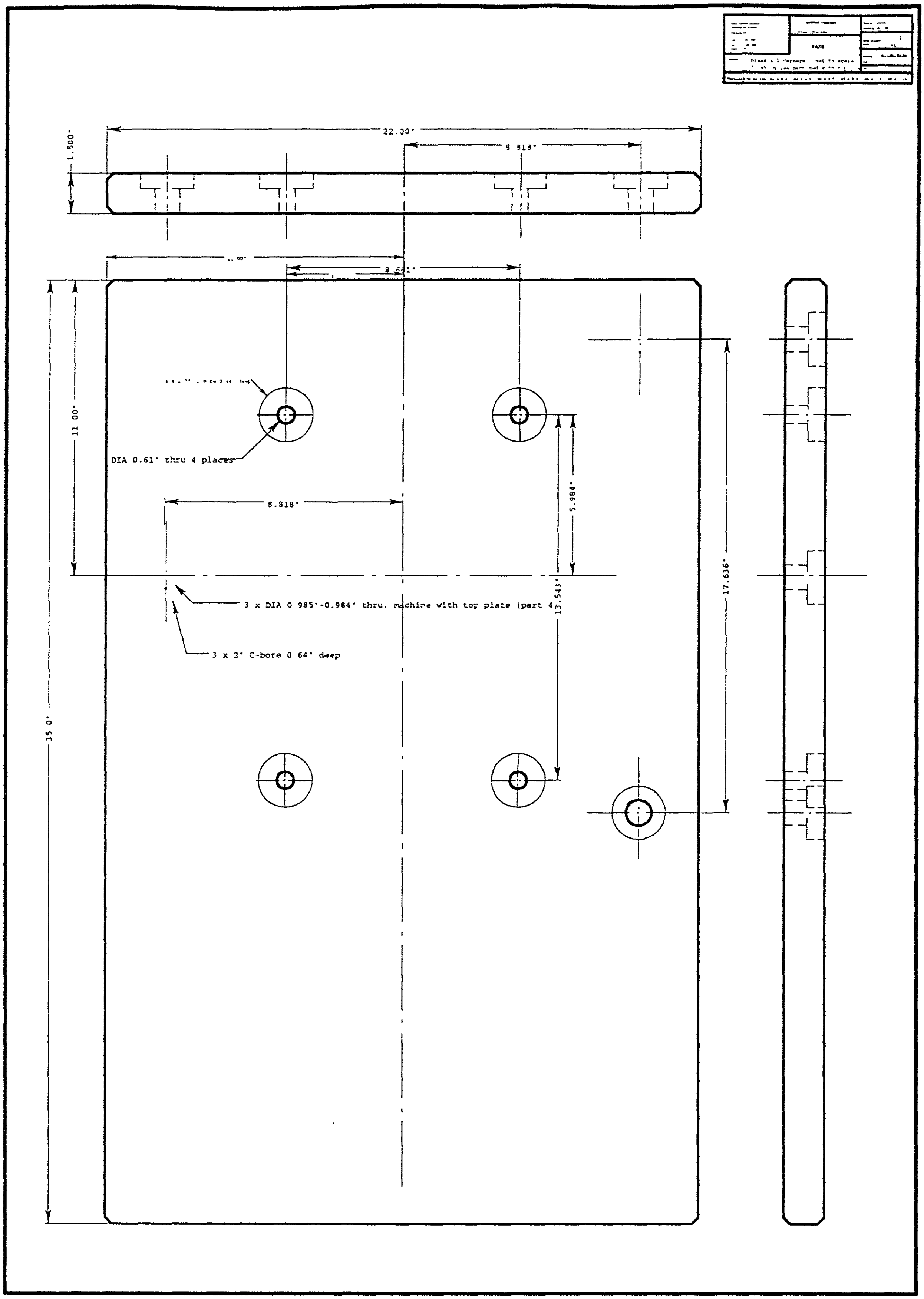

Figure A-10: Base of the prototype machine.

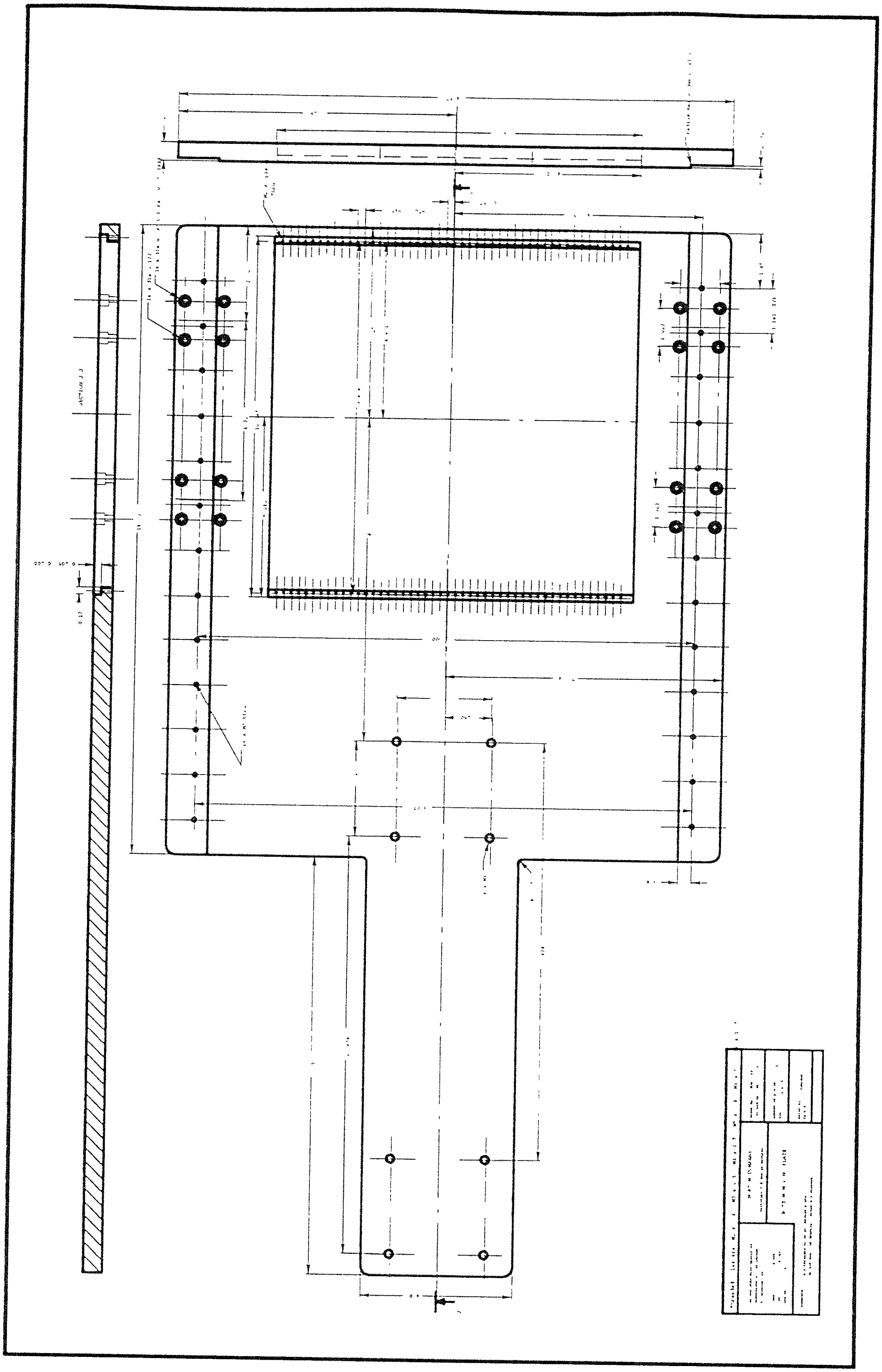

Figure A-11: Bottom moving plate.

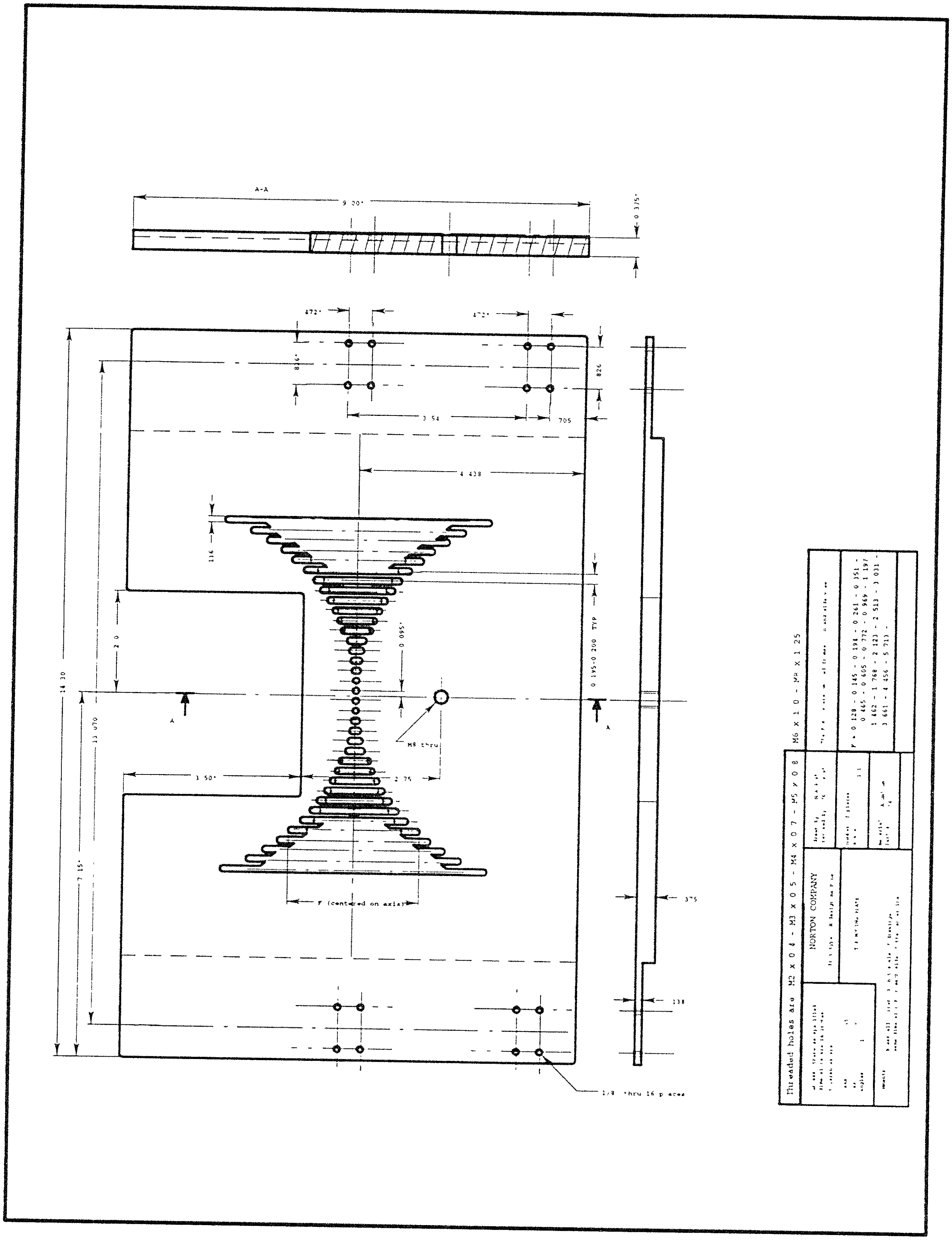

Figure A-12: Top moving plate.

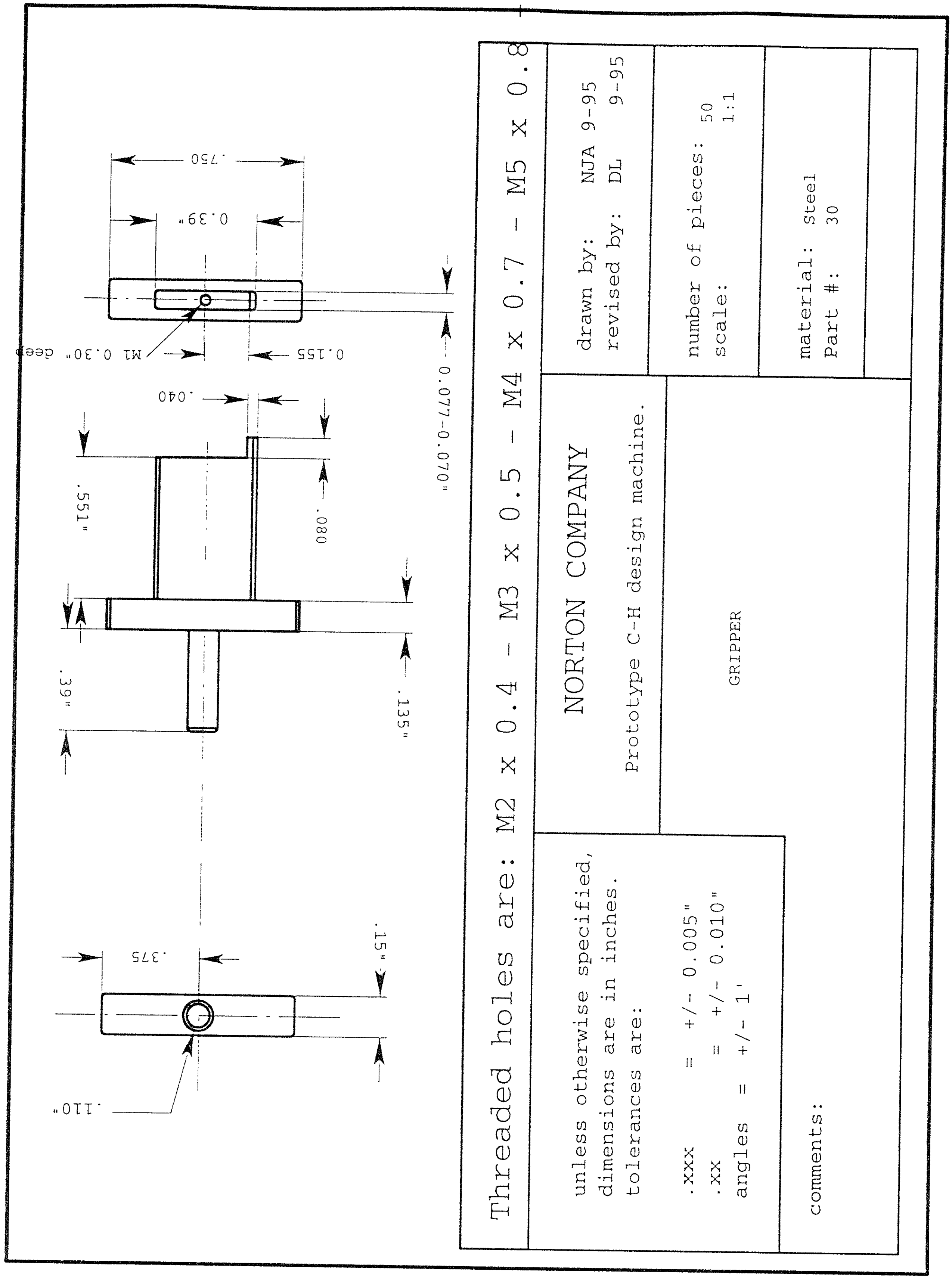

Figure A-13: Body of the forty grippers.

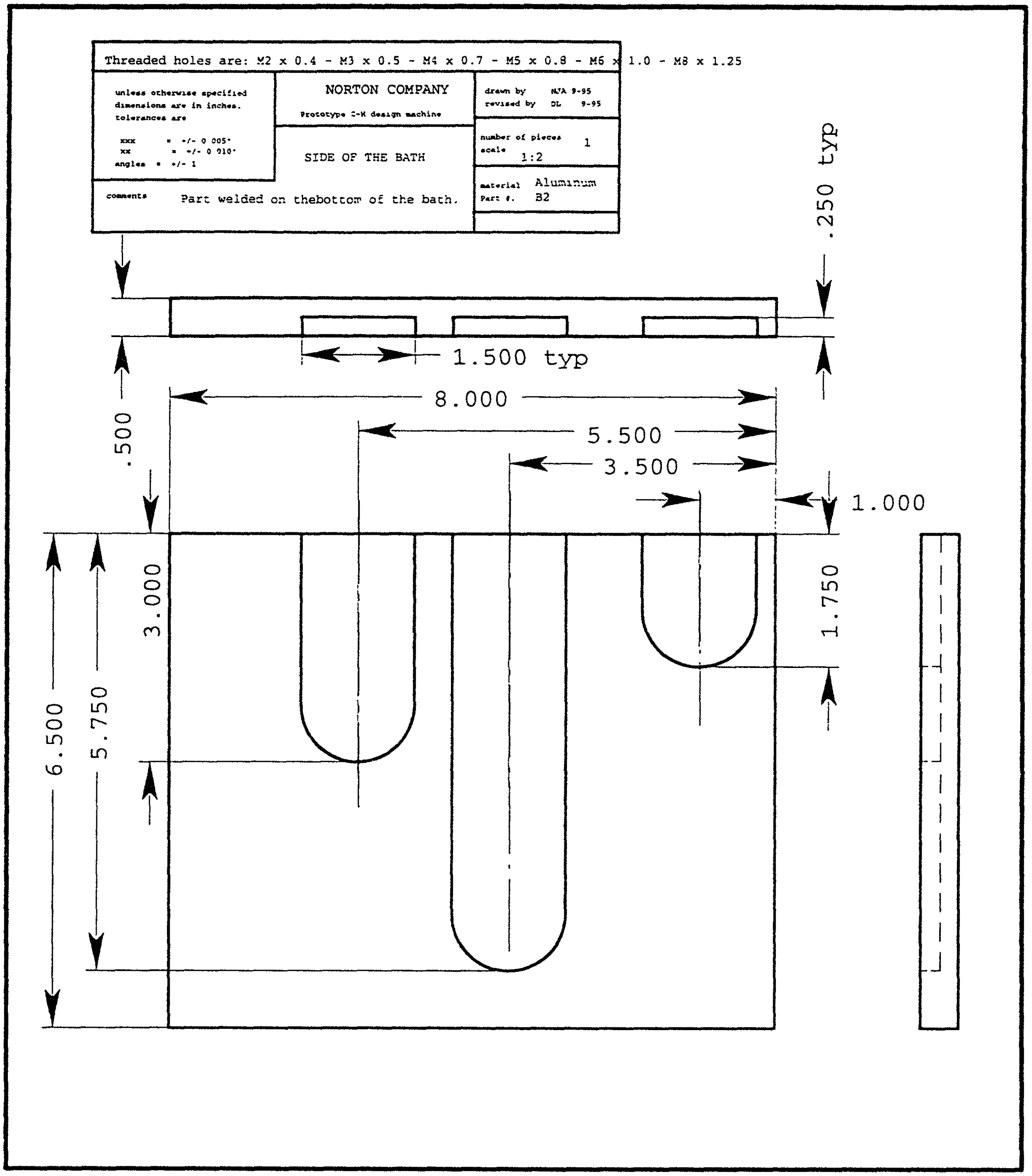

Figure A-14: Right side of the resin bath.

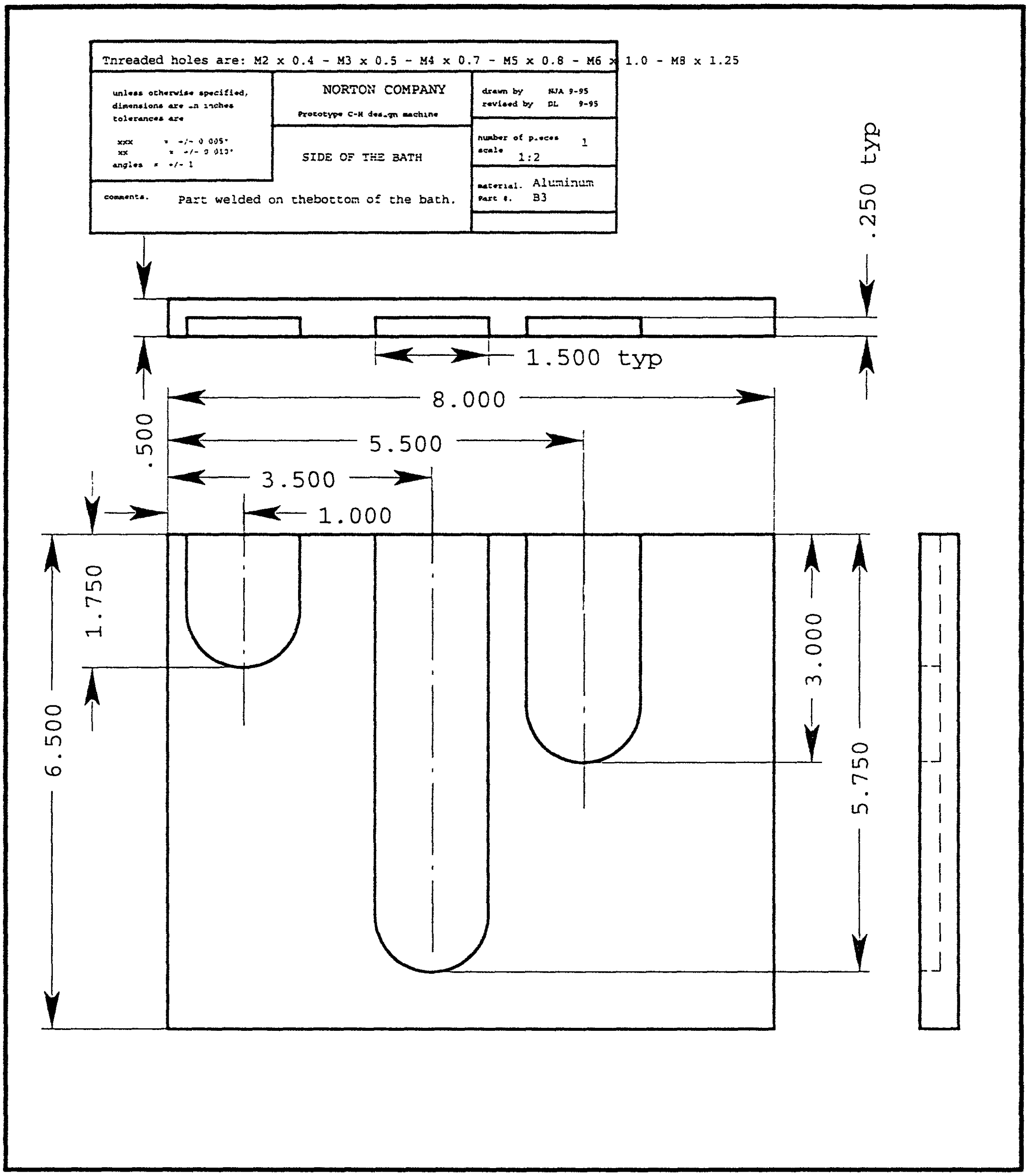

Figure A-15: Left side of the resin bath.

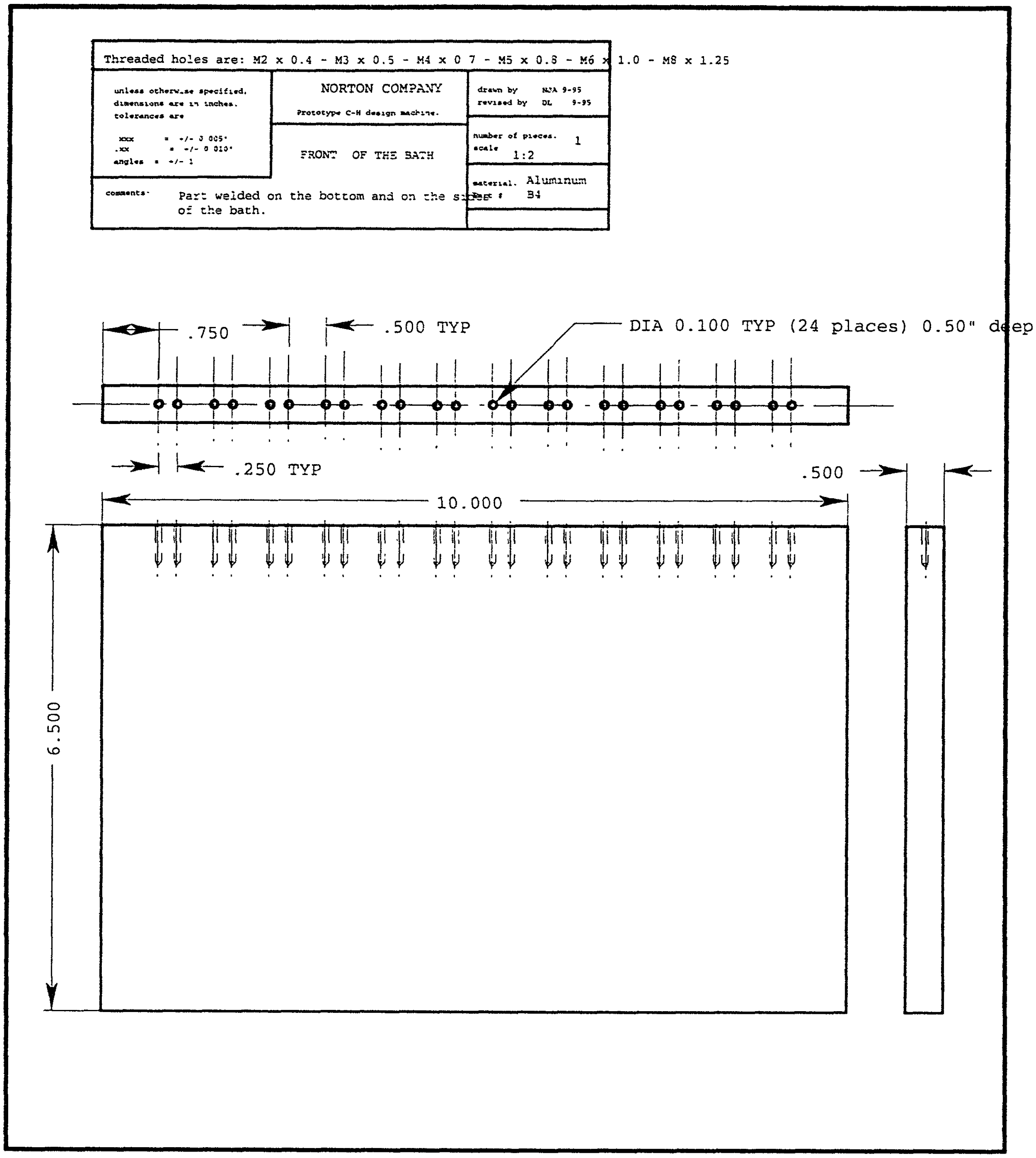

Figure A-16: Front of the resin bath.

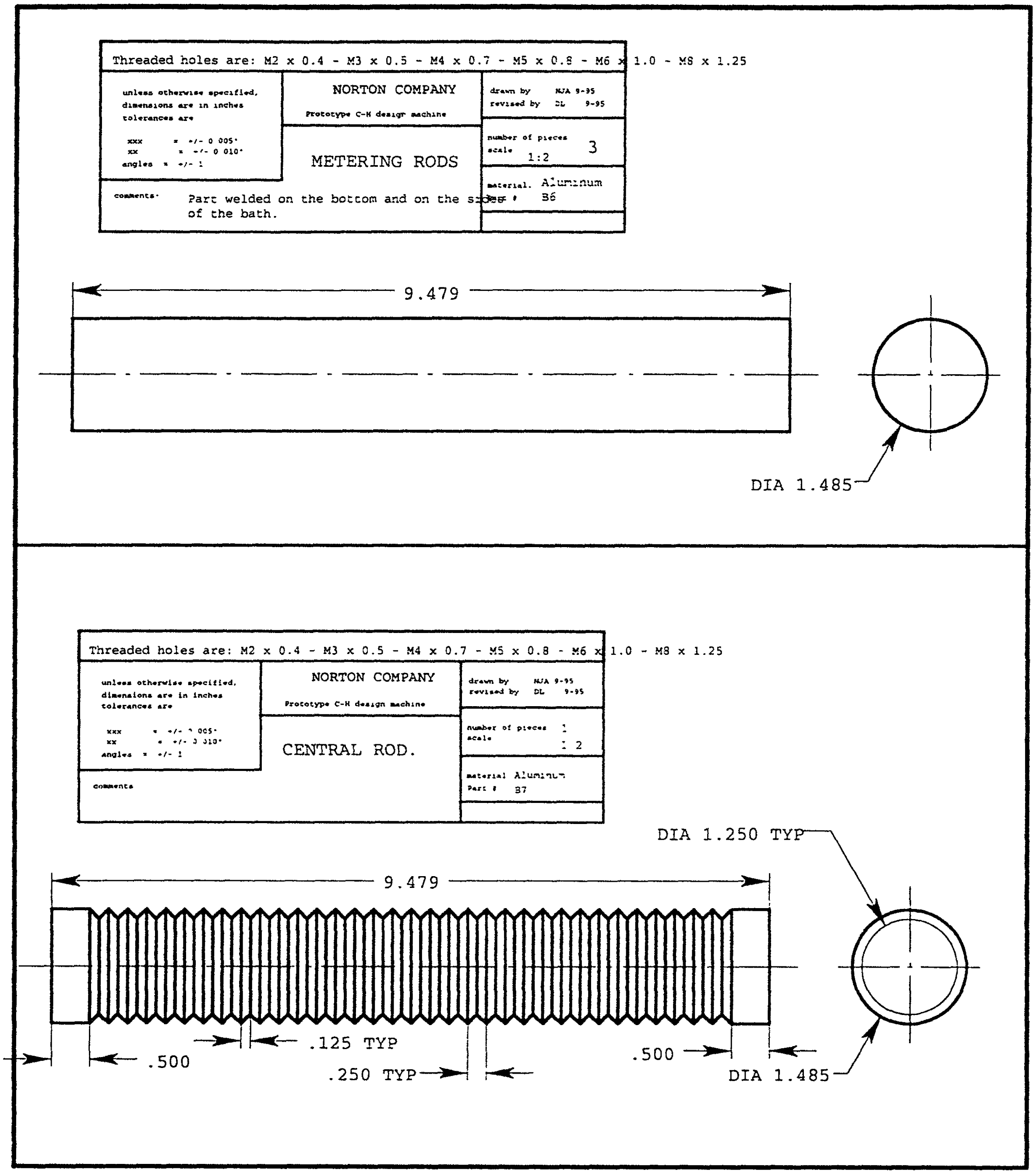

Figure A-17: Guiding and metering rods of the resin bath.

Appendix B

Finite Elements Analysis Datasets.

The first analysis determines the stresses and strains in a thin wheel supported by a ring and under a uniform pressure load, the second calculates the same parameters for a disc rotating at high speed.

Each analysis is comprised of two parts. The first one, called *main*, defines the position of the origin and knots as well as the type of elements and the load applied to the system. The second dataset, called *plot*, defines the axis and displays the results.

```
* Supported circular plate under pressure load (main)
*
* fileunits list=8 log=7 echo=7
* fcontrol heading=upper origin=upperleft
* control plotunit=percent height=1.25
*
fileunits list=8
control plotunit=percent height=1.25
fcontrol size=iso iso=-4.5 xsf=10 ysf=5
workstation sys=12 colors=rgb background=white
colors ori=inverse el=inverse bc=inverse xya=inverse xyl=inverse ve=inverse
fcontrol heading=upper
*
database create
head 'Supported circular plate under pressure load'
*
master idof=100111 reaction=yes
printout vol=max ipric=0 iprit=0 ipdata=3 cardimage=no
porthole form=yes file=60
*
coordinate
entries node y z
1 to
3 .0 .05
4 .5 to
6 .5 .05
*
material 1 elastic e=2.e11 nu=.3
*
egroup 1 twodsolid axisymmetric results=tables
```

```
stresstable 1 3 4 7
gsurface 6 3 1 4 el1=10 el2=1 nodes=8
*
loads pressure type=lines
6 3 1.0 1.e6 1.e6
*
fixboundaries 2 type=lines / 1 3
fixboundaries 3 / 5
*
frame heading=upper
mesh nodes=11 element=1 bcode=all
lvector dep=push output=all
*
adina
*
end
*
```

```
* Supported plate under pressure load (plot)
*
* fileunits list=8 log=7 echo=7
* fcontrol heading=upper origin=upperleft
* control plotunit=percent height=1.25
*
fileunits list=8
control plotunit=percent height=1.25
fcontrol size=iso iso=-4.5 xsf=10 ysf=5
workstation sys=12 colors=rgb background=white
colors ori=inverse el=inverse bc=inverse xya=inverse xyl=inverse
colors def=inverse ve=inverse st=inverse
fcontrol heading=upper
*
* Database command to load or open the adina-plot database
*
database create formatted=yes
* database open
*
frame
mesh original=1 deformed=0 nodes=11 subframe=2211
mesh original=1 deformed=0 nodes=10 elements=1 bcode=all subframe=2111
lvector var=p2dpress output=all depiction=push yshift=-5
*
frame
mesh original=2 dmax=5 lines=-99 subframe=2211
esegline radial
0.0 0.0 0.0 0.0 0.5 0.0
list esegline
list eline
```

```
axis 1 0.0 0.0 0.0 0.0 0.5 'radial distance'
axis 2 0.0 0.0 0.0 0.0 14.0e07 'stress'
list axis
*
lgraph radial yvar=stress-xx time=1.0 xaxis=1 yaxis=2 output=all,
symbol=1 subframe=2111 timelabel=no
lgraph radial yvar=stress-yy time=1.0 xaxis=-1 yaxis=-2 output=all,
symbol=2
lgraph radial yvar=stress-yz time=1.0 xaxis=1 yaxis=2 output=all,
symbol=5
text xp=40 yp=50 color=green string='<1> stress-xx'
text xp=40 yp=47 color=green string='<2> stress-yy'
text xp=40 yp=44 color=green string='<5> stress-yz'
*
zmax number=5 variables=y-displacement z-displacement
zlist tstart=1.0 variables=y-reaction z-reaction
*
control eject=no linpag=10000
fileunits list=9
npoint center node=2
plist center var=z-displacement
epoint center el=10 point=3
plist center var=stress-xx stress-yy
*
end
*
```

```
* Analysis of a rotating tubular shaft (main)
*
fileunits list=8 log=7 echo=7
fcontrol heading=upper origin=upperleft
control plotunit=percent height=1.25
*
* fileunits list=8
* control plotunit=percent height=1.25
* fcontrol size=iso iso=-4.5 xsf=10 ysf=5
* workstation sys=12 colors=rgb background=white
* colors ori=inverse el=inverse bc=inverse xya=inverse xyl=inverse ve=inverse
* fcontrol heading=upper
*
database create
head 'Analysis of a rotating tubular shaft'
*
master idof=101111
analysis static mass=consistent
printout vol=max ipric=0 iprit=0 ipdata=3 cardimage=no
porthole form=yes file=60
*
coordinate
entries node y z
1 .16
2 .25
3 .16 .02
4 .25 .02
*
material 1 elastic e=1.e7 nu=.33333 density=2.54e-4
*
```

```
egroup 1 twodsolid axisymmetric
stresstable 1 6 8 9
gsurface 4 3 1 2 el1=8
*
loads centrifugal omega=1.e4 bz=1
*
frame
mesh nodes=11 elements=1 bcode=all
*
adina
*
end
*
```

```
* Analysis of a rotating tubular shaft (plot)
*
fileunits list=8 log=7 echo=7
fcontrol heading=upper origin=upperleft
control plotunit=percent height=1.25
*
* fileunits list=8
* control plotunit=percent height=1.25
* fcontrol size=iso iso=-4.5 xsf=10 ysf=5
* workstation sys=12 colors=rgb background=white
* colors ori=inverse el=inverse bc=inverse xya=inverse xyl=inverse
* colors def=inverse ve=inverse st=inverse
* fcontrol heading=upper
*
* Database command to load or open the adina-plot database
*
database create formatted=yes
* database open
*
frame
mesh original=1 deformed=0 node=11 subframe=2211
mesh original=1 deformed=0 el=1 subframe=2111
*
esegline shaft
0 .16 0.01 0 .25 0.01
list esegline
list eline
nsegline radius
0 .16 0.02 0 .25 0.02
list nsegline
```

```
list nline
*
userdata analytical-stress-xx radius stress-xx
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
userdata analytical-stress-yy radius stress-yy
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
userdata analytical-stress-zz radius stress-zz
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
userdata analytical-uy radius uy
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
```

```
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
0 0 / 0 0 / 0 0
*
axis 1 0.0 0.0 0.0 0.16 0.25 'radius'
axis 2 0.0 0.0 0.0 0.0 1500.0 'stress-xx'
axis 3 0.0 0.0 0.0 0.0 100.0 'stress-yy'
axis 4 0.0 0.0 0.0 0.0 500.0 'stress-zz'
axis 5 0.0 0.0 0.0 0.0 2.1e-5 'y-displacement'
list axis
*
alias yc y-coordinate
alias eyc element-y-coordinate
frame heading=upper
lgraph shaft eyc stress-xx subframe=2122 output=all symbol=1,
sskip=6 xaxis=1 yaxis=2 timelabel=no
ugraph analytical-stress-xx output=all symbol=2 sskip=8,
xaxis=-1 yaxis=-2
text xp=30 yp=45 color=green hei=1.0 string='<1> finite elements'
text xp=30 yp=42 color=green hei=1.0 string='<2> analytical solution'
*
lgraph shaft eyc stress-yy subframe=2121 output=all symbol=1,
sskip=6 xaxis=1 yaxis=3 timelabel=no
ugraph analytical-stress-yy output=all symbol=2 sskip=8,
xaxis=-1 yaxis=-3
text xp=30 yp=45 color=green hei=1.0 string='<1> finite elements'
text xp=30 yp=42 color=green hei=1.0 string='<2> analytical solution'
*
lgraph shaft eyc stress-zz subframe=2222 output=all symbol=1,
```

```
sskip=6 xaxis=1 yaxis=4 timelabel=no
ugraph analytical-stress-zz output=all symbol=2 sskip=8,
xaxis=-1 yaxis=-4
text xp=30 yp=45 color=green hei=1.0 string='<1> finite elements'
text xp=30 yp=42 color=green hei=1.0 string='<2> analytical solution'
*
lgraph radius yc y-displacement subframe=2221 output=all symbol=1,
sskip=6 xaxis=1 yaxis=5 timelabel=no
ugraph analytical-uy output=all symbol=2 sskip=8,
xaxis=-1 yaxis=-5
text xp=30 yp=45 color=green hei=1.0 string='<1> finite elements'
text xp=30 yp=42 color=green hei=1.0 string='<2> analytical solution'
*
* check listing
*
control eject=no linpag=10000
fileunits list=9
nline some-nodes
1 / 2
eline some-points
8 6 / 1 8
llist some-nodes tst=1.0 var=yc y-displacement
llist some-points tst=1.0 var=eyc stress-xx stress-yy stress-zz
*
end
*
```

Appendix C

Overview of Norton Company

Norton Company built its first grinding wheel factory in 1886 on land now occupied by a portion of its plant complex in Worcester, Massachusetts. In 1858, Franklin B. Norton, a master potter from Bemington, Vermont, had founded the pottery business whose grinding wheels operation was to become a diversified global corporation.

Today, Norton *is* a diversified multinational corporation with four main products: abrasives, advanced ceramics, chemical process products and performance plastics. In addition, the company does promising research in diamond films.

Norton's abrasive products include bonded abrasives (grinding wheels used on metal, glass, ceramic and plastic materials), coated abrasives (sandpaper for products made of iron, steel, wood, brass and aluminum), and superabrasives (diamond and cubic boron nitride grinding wheels used as precision cutters in metalworking markets).

With more than 16,000 employees in twenty countries worldwide, Norton employs close to 9,000 people at about forty locations throughout the United States and Canada. Its headquarters is in Worcester, Massachusetts.

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