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Concurrent Printing and
Thermographing for
Rapid Manufacturing-
Executive Summary

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Dated: September 2002

Abstract

The objective of the work reported in this Executive Summary and the five accompanying submissions was to develop systems of solid free form (SFF) manufacture capable of being used for mass production as well as for rapid prototyping (RP). This would be likely to have a major impact on commercial production methods, since existing commercial RP systems are far too slow for mass production and are limited in the range of materials they can use. This restricts them to specialised applications and the production of prototypes.

The methodology involved a literature search, followed by analysis and assessment. This pointed to printing and thermography as the most suitable technologies for further investigation. A major aim was to take advantage of existing technologies as far as possible. The main components of a prototype system were then analysed in order to identify necessary adaptations and improvements.

This generated a number of highly innovative developments that were then combined to produce a system involving concurrent printing, thermographing, annealing, stacking, registering, bonding and height adjustment of coatings (SFF layers) to form parts. To confirm the level of innovation and likely future development, assessment was made of current developments in the field of SFF manufacture and printing. Prospects for commercialisation were identified by reference to extensive market research relating to the system.

The concurrency of the system allows it to be substantially faster than commercial systems that are largely consecutive in their modes of operation (between 150 and 800 times faster than an SLA 5000). The use of the thermography allows a high deposition rate of a wide range of materials including thermopolymers, thermosets, metals, ceramics and glass. These advantages make the system very suitable for mass-production.

Financially, the system is likely to be relatively inexpensive (around £6,000 compared with £327,300 for an SLA 5000), since it makes use of existing highly developed and readily available technologies.

Several of these inventions have been patented and a company, "Rapid Manufacturing Systems Limited" has now been formed to exploit the innovations.

Declaration

This executive summary and the portfolio that it is concerned with are submitted for and as part of an Engineering Doctorate that was undertaken at the University of Warwick. The summary and portfolio have not been presented for any other degree and except where acknowledged, all of this work is my own.

Acknowledgements

I extend my thanks to Kevin Neailey (of the University of Warwick) for his mentorship during my doctorate, which allowed me to obtain the maximum benefit from the module and project work.

I am indebted to the EPSRC loan pool for the loan of the rheometer, the differential scanning calorimeter, the vibration pattern analyser and the thermal camera used during the project.

Special thanks are due to Richard Moffat (of the University of Warwick) and everyone in the University of Warwick's ATC workshops for their assistance in the project.

Thanks are given to Steve Windsor of Rover Group, and Bruno Le Razer and David Wimpenny of the University of Warwick for their editorial advice on the "The Future of Rapid Manufacture" submission.

Nomenclature

Acronym:	Name or title:
CMC	Carboxymethyl cellulose
CWSF	Cold water-soluble fabric
CMB	Controlled Metal Buildup
DSC	Differential scanning calorimeter
DPI	Dots per inch
DOD	Drop on demand
FDM	Fused deposit modelling
GSM	Grams per square meter (metre)
IR	Infra red
IPR	Intellectual property rights
LOM	Laminated object manufacture
m	Meter (metre)
mm	Millimetre
Pa. s	Pascal seconds
PAI	Polyamideimide
PEI	Polyetherimide
POD	Print on demand
PTFE	Polytetrafluoroethylene
PVA	Polyvinyl alcohol
PVAOH	Polyvinyl alcohol
RP	Rapid prototyping
KCl	Potassium chloride
Kg	Kilogram
KI	Potassium iodine
kW	Kilo watt
SLS	Selective laser sintering
SMART	Small Firms Merit Award for Research and Technology
SFF	Solid free form
SL	Stereolithography

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1. Introduction

This Executive Summary is concerned with a four-year study aimed at developing a solid free form manufacturing (SFF) system capable of being used for mass production as well as for rapid prototyping. The work has generated several patented inventions. Searches have confirmed their novelty and revealed no significant competitors. The potential market is large and mature enough to make it likely that commercialisation of such a system would be highly successful and a company, Rapid Manufacturing Systems Limited, has been formed to exploit the systems.

SFF manufacture is, essentially, the computer-controlled three-dimensional additive manufacture of parts. The commercialisation of such processes for use in Rapid Prototyping (RP) applications started in 1988 when 3D Systems introduced their Stereolithography systems. In the last fourteen years, a number of different commercial systems have been developed for specific RP applications. However, it is generally accepted that all of them are too slow to compete with processes such as injection moulding.

A new kind of SFF manufacturing system has been invented during the study that would be both relatively inexpensive and fast enough to compete with, or even surpass, the production rates of existing mass-production processes. Its inexpensiveness is due to its use of existing well-developed and readily available printing technology, and equipment that needs relatively little adaptation. Drawing on the inherent flexibility of SFF manufacture, this system offers industry and individual users unprecedented and affordable on-demand access to both one-off and high volume manufacturing capability. The system's novel ability to use concurrently the several techniques of thermal processing, annealing, part-height adjustment and part-bonding give it unprecedented high speed processing capabilities compared to competing SFF systems. This and the range of materials that it can use, provide the potential for manufacturing large volumes of parts out of mass-production materials.

1.1. Objectives

The initial objective of the study was to develop an SFF manufacturing system capable of meeting the requirements in respect of productivity to price ratios, ranges of materials from which parts can be made, resolution and accuracy for mass-production as well as rapid prototyping applications (see chapter 2). The objectives are thus of two kinds, technical and commercial.

1.1.1. Technical Objectives

The study began with a survey of the capabilities of existing commercial SFF systems (see Chapter 2) [1]. The submission, “Future of Rapid Manufacturing” reports on this. It demonstrated that thermography, direct imaging (DI), impact printing and jet printing were the most promising technologies to use. These findings generated further objectives.

It was decided that the capabilities of DI impact printers and jet printers needed to be examined with respect to their use in thermography (see section 3). Conventional inks were found to be unsuitable for use in thermography, so the next objective was to develop non-drying ink formulae for each type of printer (see section 3.1). The submission, “Printing” reports on this [2].

The next objective was to define an appropriate substrate for use in the system’s printer and thermographer (see section 1). The substrate had to be such that:

- It could be easily fed through the printers and the thermographer used in the study.
- It did not attract powder electrostatically onto its unprinted areas. Otherwise coatings with good definition could not be produced.
- It could stand up to the high temperatures and energy densities that might be involved in the thermographic process.

- Its removal from a coating did not unduly contaminate or damage the coating. This also necessitated setting the objective of defining a removal technique that would allow this.

The “Substrates” submission reports on this [3].

It became evident that the capabilities of thermography with respect to range of materials and speed of processing needed to be defined (see section 1). At the same time the objective of identifying suitable materials for making part and support coatings was set (see section 5.4 and 5.5). It was found that the conventional thermal processing involved in using the thermographer caused problems, and so the objective of inventing adaptations was set (see section 5.3). The submission “Solid Free Form Thermography” is concerned with this [5].

Having produced thermographic coatings using the types of materials and at the speeds required by mass-production applications, it was decided that a number of other objectives should be set as follows:

- Invention of methods for rapidly making a part by stacking, registering and bonding the coatings, that would also meet the criteria for range of materials and speed (see section 6.2.3).
- Creation of a method for adjusting the height of a part’s build, so as to prevent the building up of inaccuracies (see section 6.2.4).
- Evaluation of methods for releasing a part from the support material (see section 6.4).

The submission, “Stacking Registering and Bonding” covers the meeting of these objectives [6].

There were a number of developments in the field of SFF manufacture and printing publicised near to the study’s completion date, and the objective of assessing the implications of these in order to confirm the originality of the study was set (see chapter 7).

1.1.2. Commercial Objectives

To assess the following:

- The potential markets, the competition and the strengths and weaknesses of the new system with respect to competing systems, together with the potential effect on United Kingdom (UK) and overseas technologies of commercialising the system (see chapter 1).
- The potential of the new system to meet the price to productivity ratio necessary to compete with existing commercial SFF systems, and with any new mass-production processes that might be emerging (see sections 8.3.1 and 8.4).

1.2. Methodology

The methods used in the study were as follows:

- Commercial solid free form manufacturing systems, SFF research and printing technologies were examined to determine ways in which requirements necessary for mass production as well as rapid prototyping, such as price to productivity ratio, speed, range of materials, resolution and accuracy, might be achieved (see chapter 2) [1]. This was primarily a literature search and theoretical analysis to provide the necessary data, following which a number of new ideas were developed. The most suitable of these were broadly patented to secure the IPR for subsequent work (see chapter 5).
- Experimental work and theoretical analysis were used to define a novel and practical prototype system. Each experiment was repeated at least three times and subjected to statistical analysis in order to establish the significance of the findings. The theoretical analysis was based on conventional physical theories and laws. The methods used were as follows:
 - Speed and deposition rates of the DP2030 impact printers and jet printers used in the study were examined and the suitability of the printers' conventional inks for use in thermography was assessed. They were found either to dry too quickly or to produce unacceptable contamination of the coatings. The

rheological properties of the inks were determined and new ink formulae were developed which were rheologically similar but which in addition were non-drying and produced little contamination of the coatings. Scales, viscometers and a microscope were used in this assessment and development (see chapter 3) [2].

- The thermal properties of a substrate and the techniques used for removing substrate from coating are crucially important factors in SFF thermography. The types of substrate involved dictate the particular removal technique to be used and the point in the process at which removal is to be performed. Techniques may involve thermal, chemical or mechanical processes or combinations of these. Each technique was evaluated by analysing substrates representative of the different classes of substrate, each suited to a particular technique. This involved:
 - Differential scanning calorimeter (DSC) analysis of the thermal properties of the substrates in order to define the range of thermal processing that could be performed on them (see chapter 4) [3].
 - Ash content analysis of the candidate substrates for thermal removal which indicated the potential for their contaminating the coatings (see chapter 4) [3].
 - Assessment of print quality, feedability and background powder associated with the use of each substrate (see chapter 4) [3].
 - With the mechanical removal technique the coefficients of friction and wear-rate of the different substrates were compared, in order to define a substrate that could be peeled away easily from a coating (see chapter 4) [3].
- The thermographic process was then analysed. This involved a DSC analysis of the thermal properties of both conventional powder-coating materials and engineering materials that were judged likely to be suitable for use in SFF Thermography. Statistical analysis was undertaken of the weight, volume,

continuity and resolution of thermographed coatings and a theoretical assessment was made of a newly invented concurrent thermal processing technique that allowed the coating to be annealed, in comparison with conventional processing which does not allow for annealing (see chapter 5) [5].

- Experimental and theoretical analysis of a number of methods invented for the stacking and bonding of thermographed coatings was then undertaken in order to find which would be suitable for building high and accurate parts (see chapter 6) [6].
- Developments in the field of SFF manufacture and printing publicised near to the study's completion were assessed, to ascertain whether they brought into question the originality of the processes and techniques invented and the implications for the future development of the system were considered (see chapter 7).
- The potential productivity to price ratio of the new production system was then calculated and the markets, competition and strengths and weaknesses of the system were identified. The effect that commercialisation might have on UK and overseas technologies was assessed. The experimental and commercial data was then consolidated and interpreted to define a plan for commercialisation (see chapter 8).

1.3. Portfolio Synopsis and Plan

The five submissions covered by this Executive Summary are described below in order of submission. The Executive Summary was the final piece of work submitted.

- “The Future of Rapid Manufacturing”, is primarily concerned with a literature search and assessment of commercial SFF systems, SFF research and commercial and emerging printing technology that might be used to meet the productivity to price ratio, speed, range of materials, resolution and accuracy criteria for mass-production and rapid prototyping applications. This identified jet printing, direct imaging impact printing and thermography as the most suitable technologies to

use in a prototype system. This would be assessed in the subsequent experimental work aimed at defining capability in meeting criteria and suggesting adaptations that might be needed. The use of thermography in SFF manufacture was identified as being highly innovative (see chapter 2) [1].

- “Printing” describes the findings and experimental work involved in the analysis of impact and non-impact printing technologies. It also covers the development of novel non-drying ink formulae for use in the printers, so as to allow them to be used in conjunction with thermography to produce high coatings from a broad range of materials (see chapter 3) [2].
- “Substrates” is concerned with the findings and experimental and theoretical work involved in examining different types of substrates, in order to identify those with suitable thermal properties to allow a broad range of materials to be thermographically processed on them. The substrates needed to have a surface quality which would allow high-resolution print to be deposited on them and mechanical properties which would allow them to be fed through the printer and thermographer. The submission also described an innovative technique for removing the substrates from thermally processed coatings (see chapter 4) [3].
- “Solid Free Form Thermography” describes the findings and experimental and theoretical work involved in analysing the capability of conventional thermography for use in SFF manufacture and its suitability for mass-production and prototyping applications. The submission also describes the innovative adaptations that were needed to allow the criteria to be met (see chapter 5) [5].
- “Stacking Registering and Bonding” is concerned with the findings and experimental and theoretical work involved in an assessment of different ways of stacking, registering and bonding coatings, in order to form accurate parts at the speeds dictated by the criteria. This necessitated a high level of novel development that resulted in the invention of concurrent stacking, registering, bonding and height adjustment methods (see chapter 6) [6].

- “Concurrent Printing and Thermographing for Rapid Manufacturing- Executive Summary” summarises and consolidates the work and findings described in the previous submissions [1 to 3 and 5 to 6]. In order to define the study’s level of innovation and recommendations for commercialisation and future development, it extends the work and takes account of market research data and recent developments in the field of SFF manufacture and printing.

2. Current Technology

The following sections are concerned with the findings and recommendations contained in the report, Future of Rapid Manufacturing [1]. This defined the technologies most likely to meet the productivity to price ratio, speed, range of materials, resolution and accuracy criteria that would allow a production system to be developed for use in mass-production as well as for rapid prototyping applications. Research and experimental work described in the four other submissions [2 to 3 and 5 to 6] that accompany the Executive Summary are concerned with the evaluation of these technologies and the adaptations that may allow the criteria to be met.

2.1. Commercial Rapid Prototyping

It was shown that commercial RP systems are not capable of meeting all of the criteria that would allow them to be used for mass production [1], mainly due to their relatively slow build speed. It would take between 1 and 9 hours for some of the fastest systems to produce a single 30 x 40x 20mm part such as the bulb holder shown in Figure 1 [7].

It is generally known that build speeds can be increased by using a system to build a number of parts at the same time, nested next to one another, so that the total build time is divided between the parts. This is because it optimises the use of the volume in which the system can build parts (the build envelope), and it increases the utilisation of the material deposition method used. This has led some people to assert that a part such as that shown in Table 1 could be made at an overall rate of one every 0.08 hours if 300 parts were built on an SLA 5000 system. However, it would take 24 hours to build all of these parts, and during this time none could be extracted for post processing. This would result in a lot of unwanted work in progress, and if a particular end user required only one part it would substantially increase the lead times. Consequently, present commercial systems are not suitable for mass production applications.

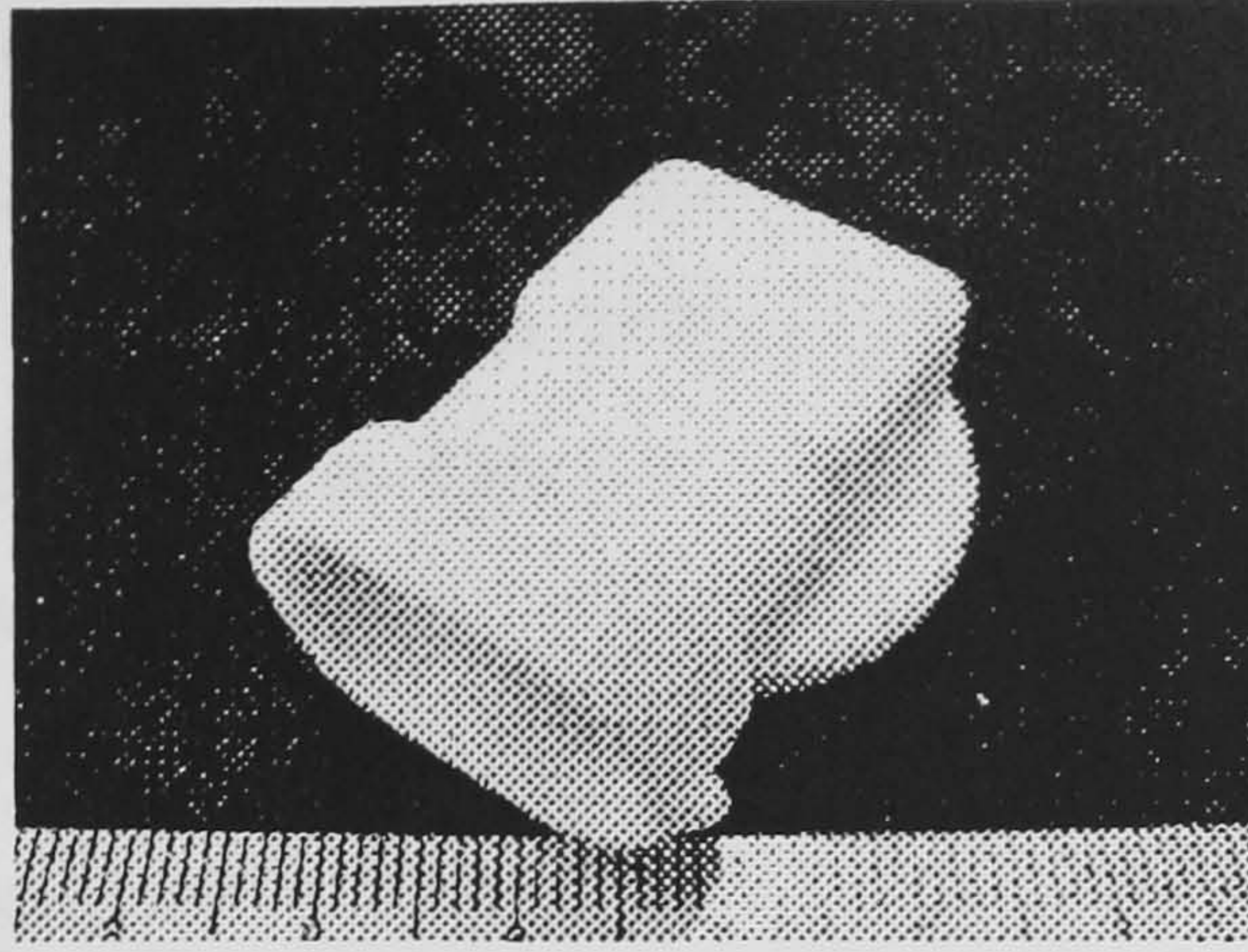


Figure 1: Bulb Holder [7].

Price / £	System	Material	Parts on the bed	Layer height / microns	Build time / minutes	Post process / minutes	Build time per part / minutes	Total time per part / minutes	Productivity per 1000 hours to price ratio / cm ³ per £
37,820	Z corp	ZP100	1	100	30	30	30	60	0.026
		Plaster	30		180	60	6	7.9	0.2
205,128	SLS	Duraform	1		60	300	60	360	0.0008
		Nylon	300		1800	1200	6	9.9	0.029
288,461	SLA 5000	SL5195	1		120	60	120	540	0.00038
			300		720	720	2.4	4.8	0.043
38,461	Actua	Thermojet 88	1	50	60	30	60	90	0.017
			30		480	240	15.9	23.4	0.066

Table 1: Build times for the Bulb Holder (see Figure 1) [7].

In Table 1 the price of the rapid prototyping systems was taken in mid January 1998, and build and post processing times were obtained from experimental evaluation of the system undertaken by Rover Group [7].

2.1.1. Research

Current research into solid free form manufacture was reviewed in "The Future of Rapid Manufacturing" submission and it was found to be primarily orientated towards developing systems for niche applications [1]. The bias is generally towards manufacturing parts for RP using different materials, or increasing the speed of existing commercial systems. The research systems were found to be based on

technology developed especially for them, and in many cases were the product of lengthy research projects. This indicated that it would be extremely costly and time consuming to develop them further to give them sufficient speed to compete with mass-production processes such as injection moulding. Even if there were resources to do this, the productivity to price ratio would probably be so high as to make them commercially unviable. The technology of many of the systems also limited them to using only a small number of materials or one class of material and this suggested that they might not be capable of using the materials dictated by mass-production applications. It was also judged that the technical problems associated with increasing the speed of the systems dramatically to enable them to compete with mass-production processes would in most cases be unsurmountable. Consequently, it was decided that the only way to produce a system that would meet the requirements was to have a fundamental re-think about the underlying principles of SFF manufacture and to invent a radically new type of system.

2.2. Printing Technology

The distance that vector- guided laser or knife cutting devices have to cover to cut out shapes increases dramatically with the complexity of the geometry, resulting in longer production times which are difficult to estimate because they vary with the shape. This is less of a problem with printing, and impact and some non-impact printers can produce a complex geometry in the same time that it would take them to produce a simple geometry. Consequently, because of these problems, cutting and vector guidance were discounted as candidate technologies for use in the prototype system and printing was selected [1].

Commercial RP systems such as 3D Systems Actua and Thermojet and Sanders Prototyping's Model Maker II are based on printing and they tend to have higher resolutions and accuracy than those based on other technologies. There are also substantially faster printing technologies that have not yet been used either in this study or in SFF manufacture that may further extend the range of materials for making parts [1].

A wide range of printing technologies was assessed, to define which would be suitable for use in solid free form manufacturing systems while meeting the criteria for mass production (see section 1.1). Computer to plate impact printing and non-impact jet printing were identified as the most suitable technologies to use [1] primarily because of the high printing speed of the impact printers and the flexibility of the jet printers with respect to on-demand printing. However, almost all of the printers were limited to using particular ranges of materials, and had relatively low deposition rates in relation to their linear printing speeds [1]. It was decided to examine processes that might overcome these difficulties. This pointed to thermography as the most suitable process for increasing deposition rates and the range of usable materials. Thermography involves:

- Deposition of printing inks onto the substrate.
- Dusting with a powder (which ideally adheres only to the ink).
- Vacuuming or shaking off any powder that has not adhered.
- Thermally processing the powder so that it melts or sinters to form a solid coating.

It is used in the printing industry to build up extremely thick decorative coatings on ink that has been printed onto substrates.

The properties of the particular powder used influence:

- the amount of powder which adheres to the printed ink;
- the effectiveness of the vacuuming or shaking process which removes any excess powder;
- the type of thermal processing needed to convert the powder into a solid coating;
- the properties of any parts constructed from thermographed coatings.

Current practice indicated that thermographic printers might produce coatings in a range of materials at rates sufficient for mass production applications. Table 2 shows a comparison of some of the fastest non-impact and impact printers that could be used in conjunction with thermography. It is assumed that thermography will allow 100 micron high coatings to be produced and that the bulb holders (see Table 2) could be formed at the same rate as the coatings. If this were the case the production rates for these parts might be substantially higher than if commercial rapid prototyping systems were used (see Table 1). Depending on the demand for the parts, it was calculated that the productivity to price ratio of a system based on thermography might be very much higher than that of the RP systems (see Table 1 and Table 2) and it was also found that there was a broad range of industrial and desktop printers suitable for meeting high and low volume demands. This justified proceeding with the experimental and theoretical work (see chapters 3 to 6).

Two issues became apparent:

- the productivity to price ratio of the industrial jet printers was substantially lower than that of the other printers and so it was decided this precluded their use.
- The very high initial capital cost of industrial impact printers made it impractical to consider them and in any case it was unlikely that their very high speeds would be required because the market for large volumes of duplicate SFF parts has not yet been established.

It was therefore decided to use desktop printers rather than industrial printers.

In Table 2 it is assumed that 100 micron high coatings are thermographed onto the print produced by the printers and that the bulb holders (see Figure 1) can be built at the same rate as this. The capital cost for the printers was taken between December 1998 to January 1999 when one BPS£ = approximately US\$1.56 [7].

Class	Type of printer & application	Manufacturer	Model	Price / £	Bulb holders per minute	Productivity per 1000 hours to price ratio / cm³ per £
Impact	Desktop screen printer	Duplo	DP2030	2,996	33	660
	Industrial litho printer	Man Roland	Uniset 70 with six colour towers and four black units	15,000,000	132866	531
Non-impact	Desktop jet printer	Canon	BJC4400WWF	152	1.7	671
	Industrial Jet printer	Scitex	HSP	960,000	545	34

Table 2: Comparison of some of the fastest non-impact and impact printers that could be used in conjunction with thermography.

3. Printing

Desktop impact and non-impact jet printers were selected for use in the study primarily because of their high productivity to price ratio and low cost (see Table 2). However, the following findings are also applicable to faster industrial printers.

A number of samples were printed using the study's jet printers and the DP2030 impact printer and these were weighed to find the weight of ink printed in a given area. Statistical analysis was used to define the significance and means for this data, and the deposition rates of the printers were calculated. It was assumed that all of the ink could be solidified and used to make SFF parts, because this gave the best-case scenario for the rates. This might be possible if inks were frozen or changed for UV curable inks with the same rheological behaviour. The means were then compared with the deposition rates calculated to be possible if the printers were used in conjunction with thermography (see Figure 2 and Figure 3). It was assumed that 100 micron high coatings were thermographed onto the print, because measurements of conventional thermographic coatings showed that this height could easily be achieved. This showed that the combined use of printers and thermography could give substantially higher deposition rates than the printers could achieve on their own, and this justified the previous selection of thermography. Furthermore stereolithography (SLA), fused deposit modelling (FDM) and lamination RP systems generally use layer heights that are around 100 microns high. This also allowed a comparison of build rates of the RP systems and systems based on the printers and thermography to be extrapolated. This indicated that if thermography were used in conjunction with the DP2030 printer the system might be between 80 and 160 times faster than an SLA5000 and 9 to 18 times faster than an Epson Stylus 900 printer (see Figure 1 to Figure 3, and Table 1).

Current practices with thermography also indicated that the range of materials would be greater than with the RP systems. Thermography is already used to make coatings with a variety of different materials such as thermoset, UV curable and thermopolymer resins and in some situations fillers such as glass, metal and ceramics are also added to give decorative effects. Depending on the resolution and thickness

required, these materials might be applied in the form of powders with particle sizes ranging from 20 to 500 microns in diameter. This also indicated the robustness and versatility of the thermographic process, which justified the adaptation of the printers for use in thermography [2].

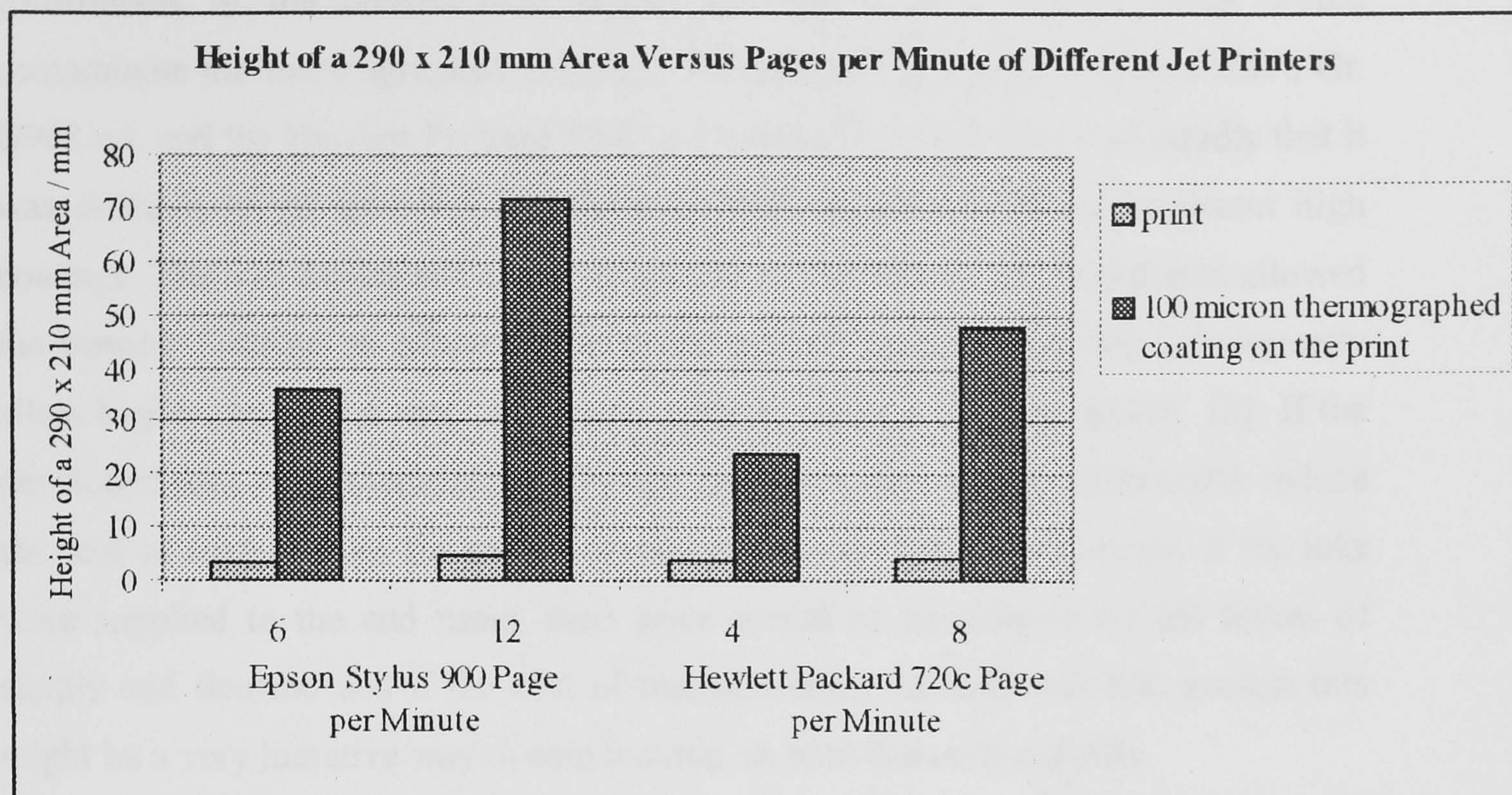


Figure 2: Cumulative thickness of the ink and thermographed coating produced in one hour by the jet printers [2].

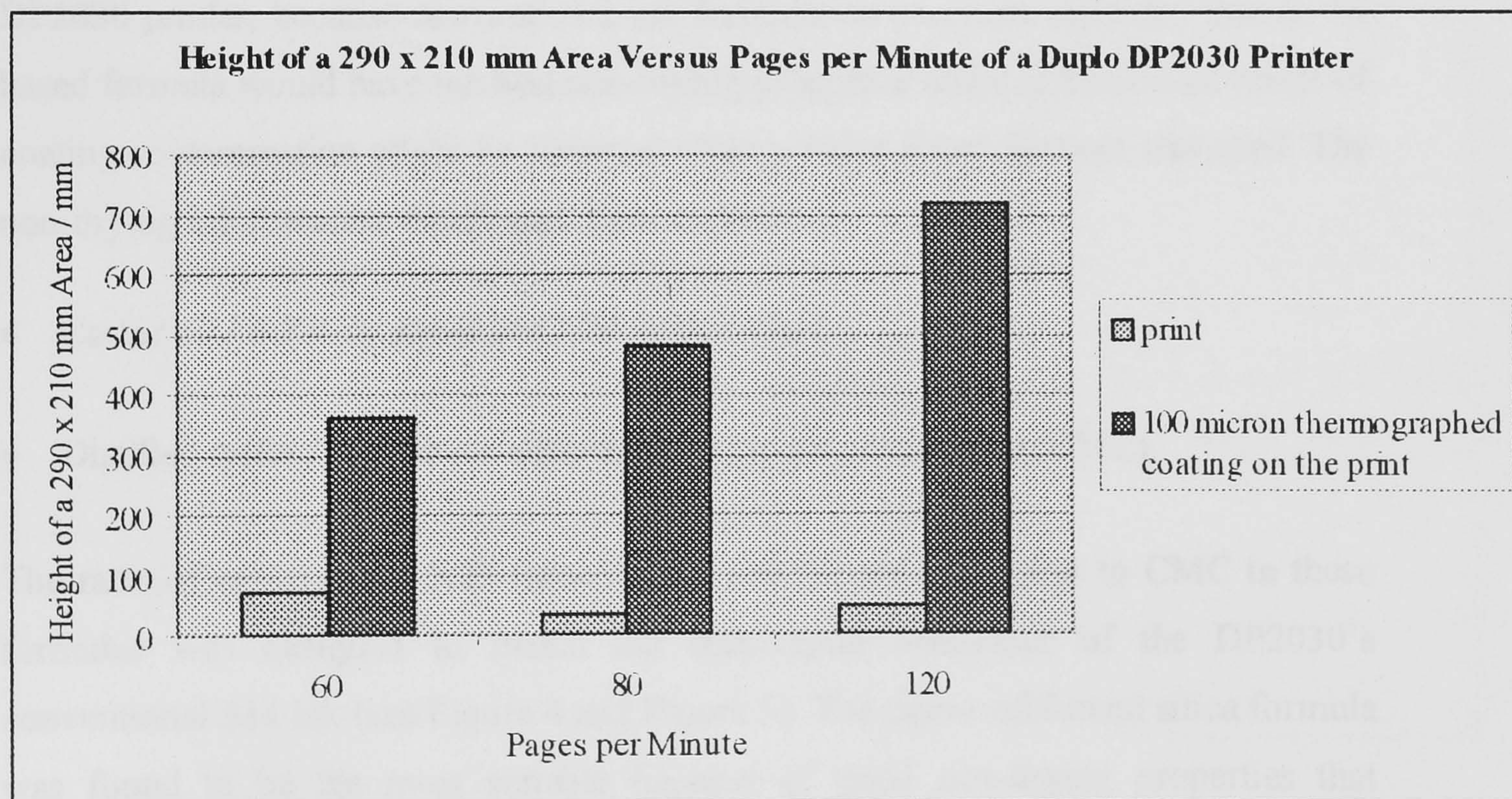


Figure 3: Cumulative thickness of the ink and thermographed coating produced in one hour versus pages per minute of the DP2030 printer [2].

3.1. Inks

As part of the study, non-drying ink formulae were developed for the jet printers and the Duplo DP2030 printer. This was necessary because analysis showed that the constituents of the conventional Duplo 514 ink such as carbon black would contaminate the thermographed coatings. The printed Epson Stylus Color 900's Gr. D968 ink and the Hewlett Packard 720C's 51645a ink tended to dry so rapidly that it was difficult to get powders to adhere to them in order to form consistent high coatings. The non-drying and sticky properties of the newly- developed inks allowed the powder coatings to adhere better to the printed patterns, and this subsequently allow higher deposition rates and more uniform coatings to be produced [2]. If the developed inks were manufactured by the end users, this might substantially reduce the cost of consumables for an SFF thermographic system. Alternatively, if the inks were supplied to the end users, their price would be determined by the forces of supply and demand and if the cost of manufacturing the inks was low enough this might be a very lucrative way to earn income, as with conventional inks.

3.1.1. Duplo DP2030 Formulae

An oil based ink formula and a water based ink formula were developed for use in the DP2030 printer, because conventional ink formulation practices indicated that an oil based formula would have the best non-drying properties and that the lowest levels of coating contamination might be obtained when a water based formula was used. The non-drying ink formulae developed were as follows:

- Castor oil / 6.5% by weight of N20 fumed silica.
- Distilled water / 2.7% by weight of carboxymethyl cellulose (CMC).

The ratio of castor oil to N20 fumed silica and the ratio of water to CMC in these formulae was designed to match the rheological behaviour of the DP2030's conventional 514 ink (see Figure 4 and Figure 5). The castor oil/fumed silica formula was found to be the most suitable because of good non-drying properties that prevented it from drying in the printer and clogging it. This increased the length of the periods that might be allowed between the printer's operation. During the study

the formula has been left in the printer for a number of months and this has not affected subsequent printer operation. This indicates that if this or a similar formula were used there would be little or no need for operators to clean the printer's internal mechanism. Castor oil was chosen as the non-drying constituent of the formula because, though classified as a non-drying oil, it contains a high proportion of ricinoleic acid, which has one double bond per molecule. Consequently, if the oil is heated in a particular way, it undergoes a chemical change resulting in another double bond being formed within the oil's molecule chains, giving it drying properties [8]. This means that the oil might be incorporated into the coating, either as a plasticiser or, after heating, as a solid resin.

It was found that if the water / 2.7% by weight of CMC formula was left in the printer for a number of days it would dry and block the printer's mechanism. This made it necessary to clean the mechanism each time the formula had been used. However, during thermography the formula's water content is evaporated away from the coatings and the small percentage of CMC would not unduly contaminate them. Consequently, if an application dictated that low levels of coating contamination were needed, it might be preferable to use the CMC formula rather than the castor oil formula, because the oil formula becomes incorporated into the coatings.

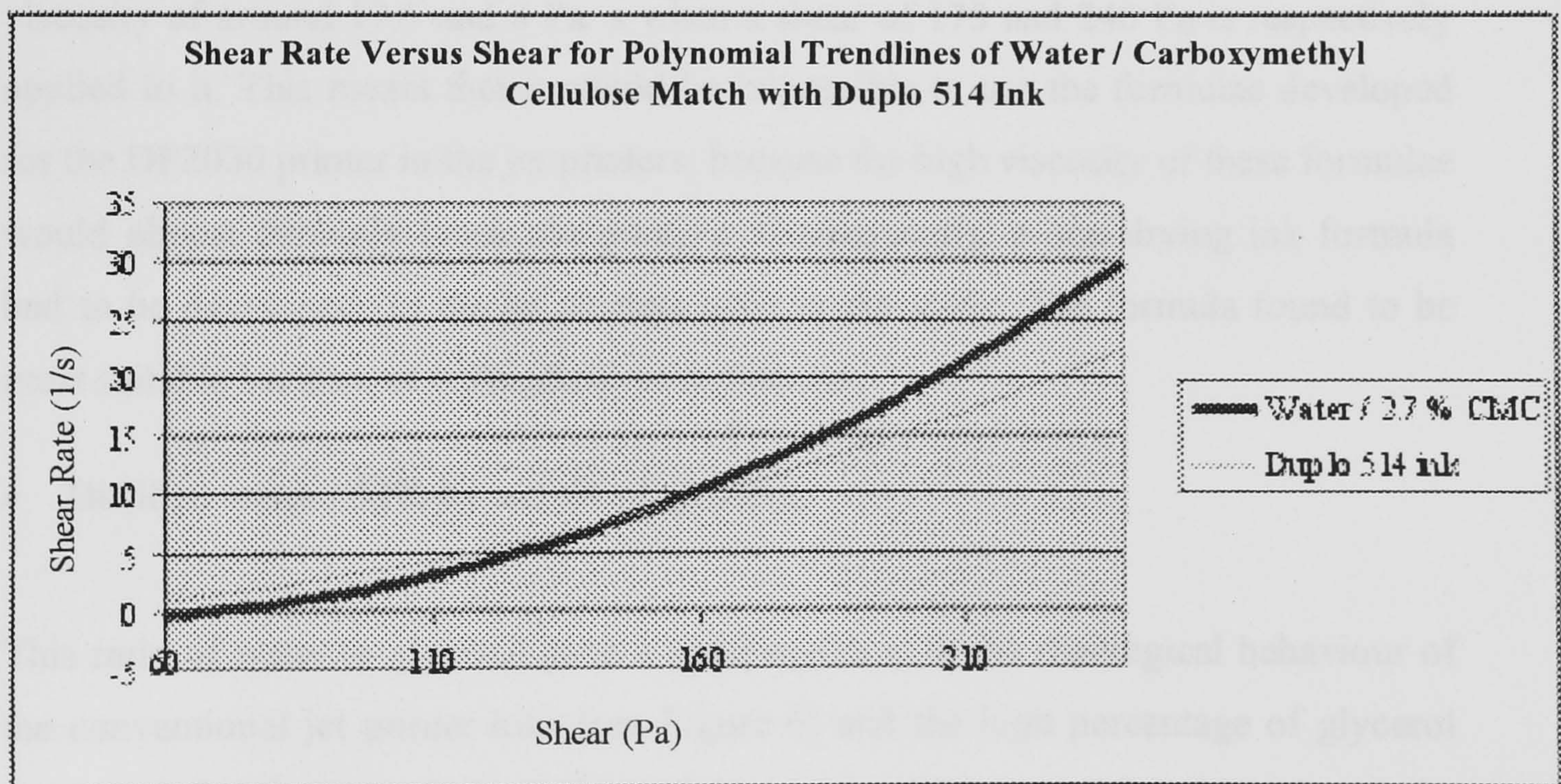


Figure 4: Shear rate versus shear for water / 2.7% CMC formula which roughly matches the viscosity of the Duplo 514 ink.

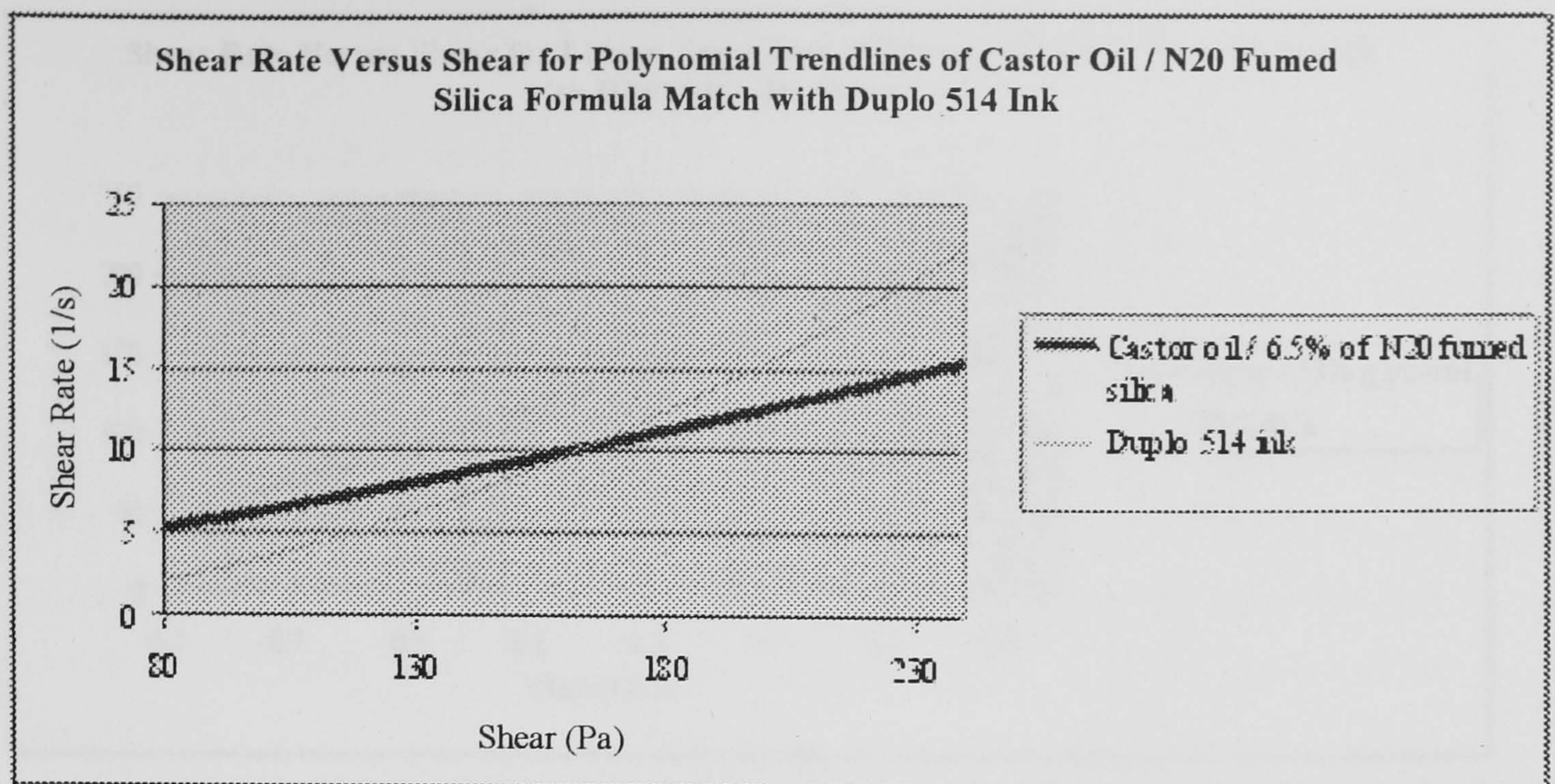


Figure 5: Shear rate versus shear for polynomial trendlines of castor oil / N20 fumed silica formula match with Duplo 514 ink.

3.1.2. Jet Printer Formula

The Hewlett Packard 51645a ink has a viscosity of 0.009 Pascal seconds (Pa. s) and the Epson compatible Gr. D698 ink has a viscosity of 0.011 Pa. S. They are both Newtonian liquids whereas the DP2030's 514 ink is a non-Newtonian liquid with a viscosity of around 17.5 and 8 Pa. s when a shear of 175 and 240 Pa is respectively applied to it. This meant that it would be impossible to use the formulae developed for the DP2030 printer in the jet printers, because the high viscosity of these formulae would almost certainly block the printers. Consequently, a non-drying ink formula had to be developed for the jet printers used in the study. The formula found to be most suitable because of its simplicity is as follows:

- Distilled water / 53% by weight of glycerol.

This ratio of water to glycerol gave a good match with the rheological behaviour of the conventional jet printer inks (see Figure 6) and the high percentage of glycerol prevented the formula from drying, giving it the sticky qualities that caused the thermographic powders to adhere to it when printed.

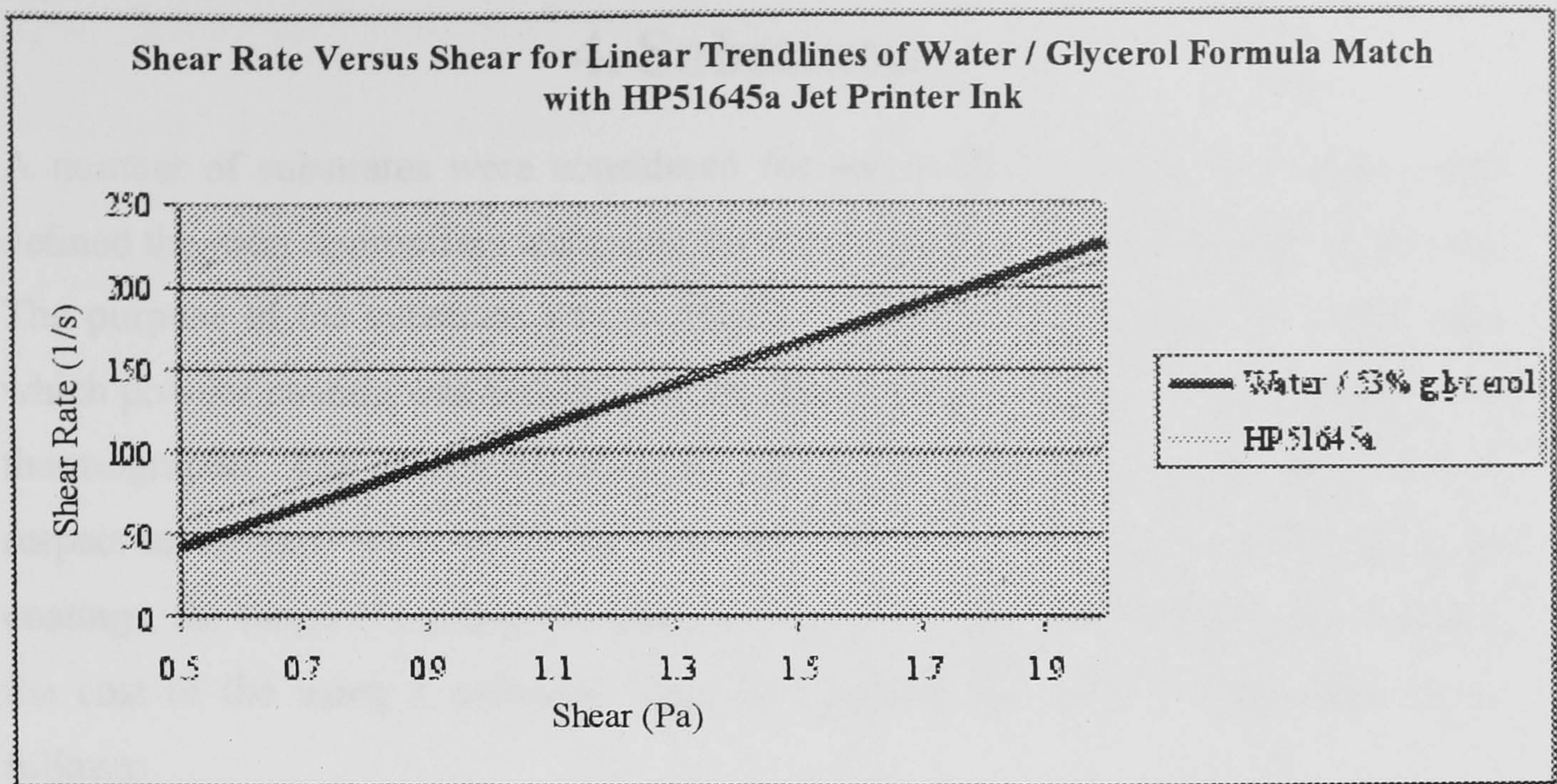


Figure 6: Shear rate versus shear for linear trendlines of water / glycerol formula match with HP51645a jet printer ink.

4. Substrates

A number of substrates were considered for use in thermography and this in turn defined the most appropriate technique for removing the coatings from the substrates. The purpose of the substrate was to receive and carry the printed ink pattern onto which powder coating was formed and thermally processed into solid coatings by the thermographer. The classes of substrate and the techniques that were assessed with respect to the ease with which the substrates could be removed from the processed coatings, the range of coating materials that could be processed on the substrates and the cost of the using a particular type of substrate and removal technique are as follows:

- Cellulosic substrates were evaluated with a thermal removal technique, because cellulosic paper is used in conventional thermography, and in the ceramics industry burning is commonly used to degrade and remove paper from transfer prints;
- Water-soluble substrates that are conventionally used in embroidery were used to assess the possibility of chemical removal, because they are based on polyvinyl alcohol which would allow the technique to be relatively environmentally friendly. Removal was achieved by using water to dissolve the substrates away from the coatings;
- Peeling was assessed as the most appropriate mechanical technique for removing substrates because it avoided damaging the coatings excessively. Other techniques such as sand blasting, tumbling, air blasting and water jetting were not considered because of likely damage to the coatings.

The incorporation of substrate material into a three-dimensional part was also examined, and it was found that this necessitate the use of a removal technique to selectively remove the uncoated areas of the substrate from the part.

4.1. Thermal Processing and Removal of Cellulosic Substrates

Differential Scanning Calorimeter (DSC) analysis, along with ash weight tests, suggested that the thermographer's thermal processing should be altered to make it similar to a batch oven, because conventional linear processing tended to cause drastically different thermal gradients to build up between the substrate and the coating. Experimental and theoretical analysis showed that in the worst instance the use of conventional processing caused the substrate to decompose before the coating was processed. This would be less likely to be the case within a batch oven because there would be more time for the gradients to even out.

This problem suggested a technique that might be used to remove the substrate material from the coated substrates that had been processed in a batch oven. In theory it might be possible to use linear heating units similar to those used in conventional processing, to build up different thermal gradients between substrates and coatings which could be used to decompose and remove the substrates from the coatings without damaging them. Unfortunately, there would be a residual problem because during the removal the areas underneath the coating would have a lower temperature than those being decomposed, so they would probably have to be incorporated into any parts subsequently built with the coatings. In addition, it is likely that when the substrate was removed there would be a substantial problem with maintaining the position and dimensional accuracy of the coatings, because after its removal the substrate would not be supporting the coatings.

It was calculated that the use of cellulosic substrates and thermal removal would be less feasible if a batch oven were used to supply the heat for the removal, because there would be far less disparity between the thermal gradients of the substrate and the coatings than with the linear heating unit. The temperatures required to decompose the substrates would almost certainly decompose many types of polymer coatings. This would not be a problem if the coatings were made of high temperature materials such as metal, glass or ceramics. It was calculated that in these instances the substrate would decompose before the sintering or melting temperatures of the materials were met. Once the substrate had been decomposed the temperature might be increased to allow the sintering or melting in order to produce solid coatings. This

might allow substrates to be printed, coated stacked and registered with one another bringing the coatings into the required relationship to form a part. The batch oven heating could then be used to decompose the substrates and bond the coatings together to form a part.

Figure 7 shows the substrate ash volume versus the thermographed coating thickness for a cubic metre of thermographed substrates heated to 600 degrees centigrade that might be expected if this were done. The actual volume of ash would be affected by different part geometries, firing schedules and atmospheres, so at best Figure 7 only gives a comparison of the ash content of the different substrates. The CF21NW filter paper has the lowest ash volume in all cases. Above a 75 micron coating thickness, the 12 gsm 5 micron thick paper has the next lowest ash volume, but below this thickness the cigarette paper 30131 had lower ash volume. This is probably because the thinner substrates have higher densities as follows:

- 50 micron CF21NW filter paper has a density of 440 kg per m³;
- 20 micron cigarette paper 30131 has a density of 900 kg per cm³;
- 5 micron thick wrapping paper has a density of 2400 kg per cm³.

It was assumed that the high density of the thin substrates might cause interfacial bonding problems between the coatings if short coatings were produced on thin substrates, because the high density of these substrates would tend to cause carbon ash to be left at the interfaces. However, it was speculated that the substrates could be perforated prior to use to improve the bonding.

The major problem with using a batch oven to remove the substrates and bond the coatings is that the heating schedules associated with firing large parts tend to involve long periods [4], and it was decided that this might substantially reduce the speed of the system. This, combined with the fact that areas of substrate would probably be left on the polymer coatings and that it would be difficult to maintain their position and accuracy after the removal, indicated that it would be prudent to define thermal removal and cellulosic substrates as unsuitable for use in the system.

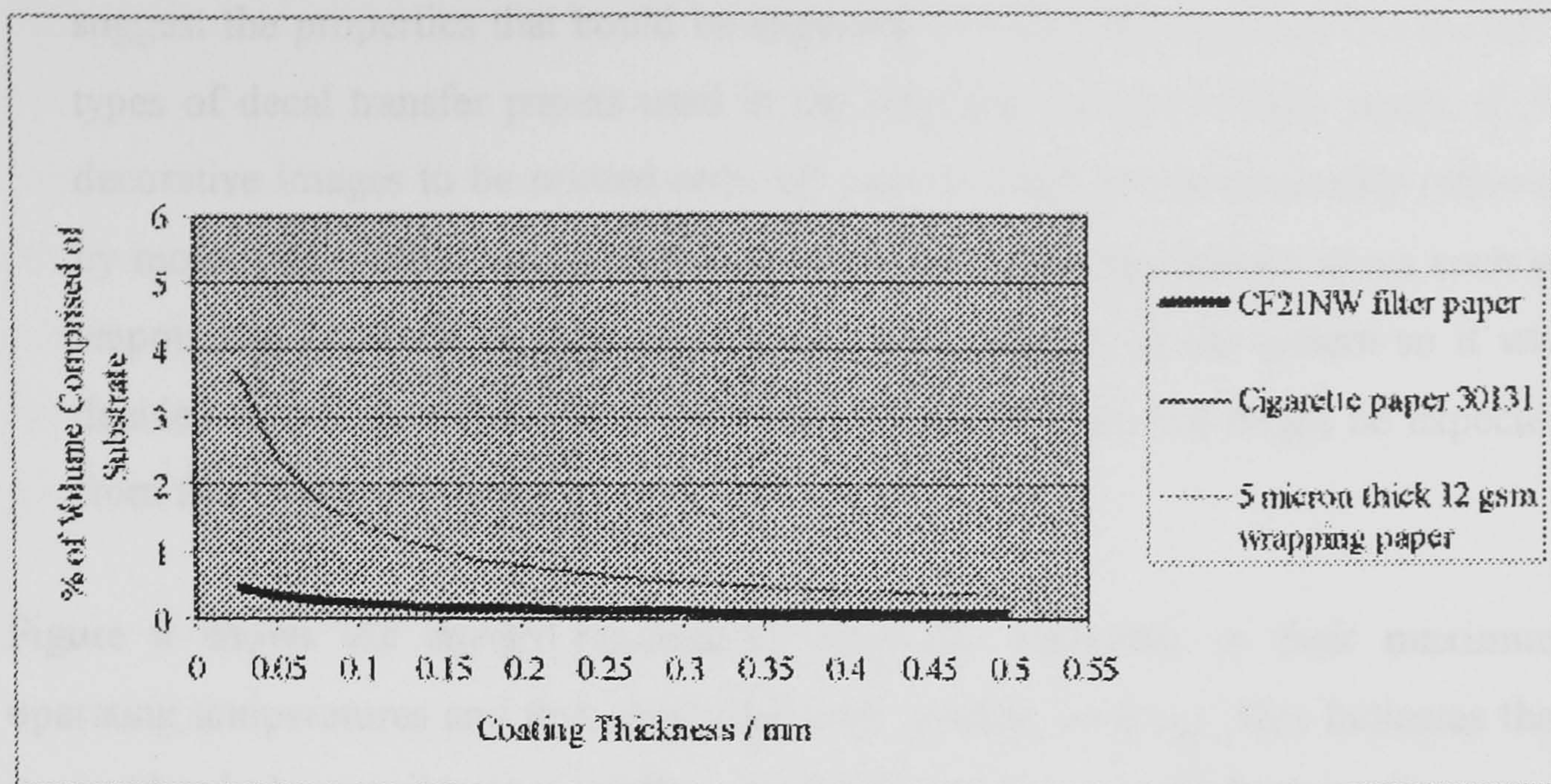


Figure 7: Substrate ash volume versus thermographed layer thickness for a cubic meter of thermographed substrate heated from 20 degrees centigrade to 600 degrees centigrade in 20 minutes [3].

4.2. Chemically Removable Water Soluble Substrates

Three types of chemically removable water-soluble substrate were assessed and it was found that they were un-suitable for use and as a result the chemical removal technique was rejected for use. The reasons for rejection are described below and the substrates assessed were as follows:

- CWSF cold water soluble non-woven (63.2 gsm 80 micron thick), selected because its structure is similar to that of the paper that printers normally use;
- Woven, water soluble PVA OH (26.9 gsm 55 micron thick), selected because it is hot water soluble (at 90 degrees centigrade), so it might be more stable during the thermal process involved in the thermography, and the spaces between its warp and weft give a fine distribution of holes which might allow a proportion of a coating to pass through, making possible the construction of parts made of substrate and coating. Hot water solubility might also add to the stability of the thermographic process, because it is less affected by water in the atmosphere and the ink;
- CE001 film cold water-soluble PVA OH (24.8 gsm 20 micron thick) was selected because it is the thinnest available water-soluble film. The thinness may also

suggest the properties that could be expected of PVA OH layers in use in many types of decal transfer papers used in the ceramics industry. These layers allow decorative images to be printed onto the papers which are subsequently released by moistening with water in order to transfer images onto pottery items such as teapots and plates. This type of process might be used in the system so it was decided to use data obtained on the film to extrapolate what might be expected from these types of papers.

Figure 8 shows the energy required to raise the substrates to their maximum operating temperatures and that associated with melting coatings. This indicates that it would only be possible to partially melt the 160 to 171 micron thick coatings on a CE001 or woven PVA OH substrate before the substrate began to melt, causing deformation and possible contamination of the coating. However, if the CWSF substrate were used, it is possible that the coatings could be totally melted without any deformation or contamination from melting. Since the M9372 and Gloss Supaflow coatings that are conventional laser printer toner and thermographic powder respectively are designed to melt when relatively small amounts and densities of energy are applied, it was evident that it would be unlikely that coatings requiring high energy densities for melting could be processed on the CE001 or woven PVA OH substrates, and so it was decided not to use these substrates.

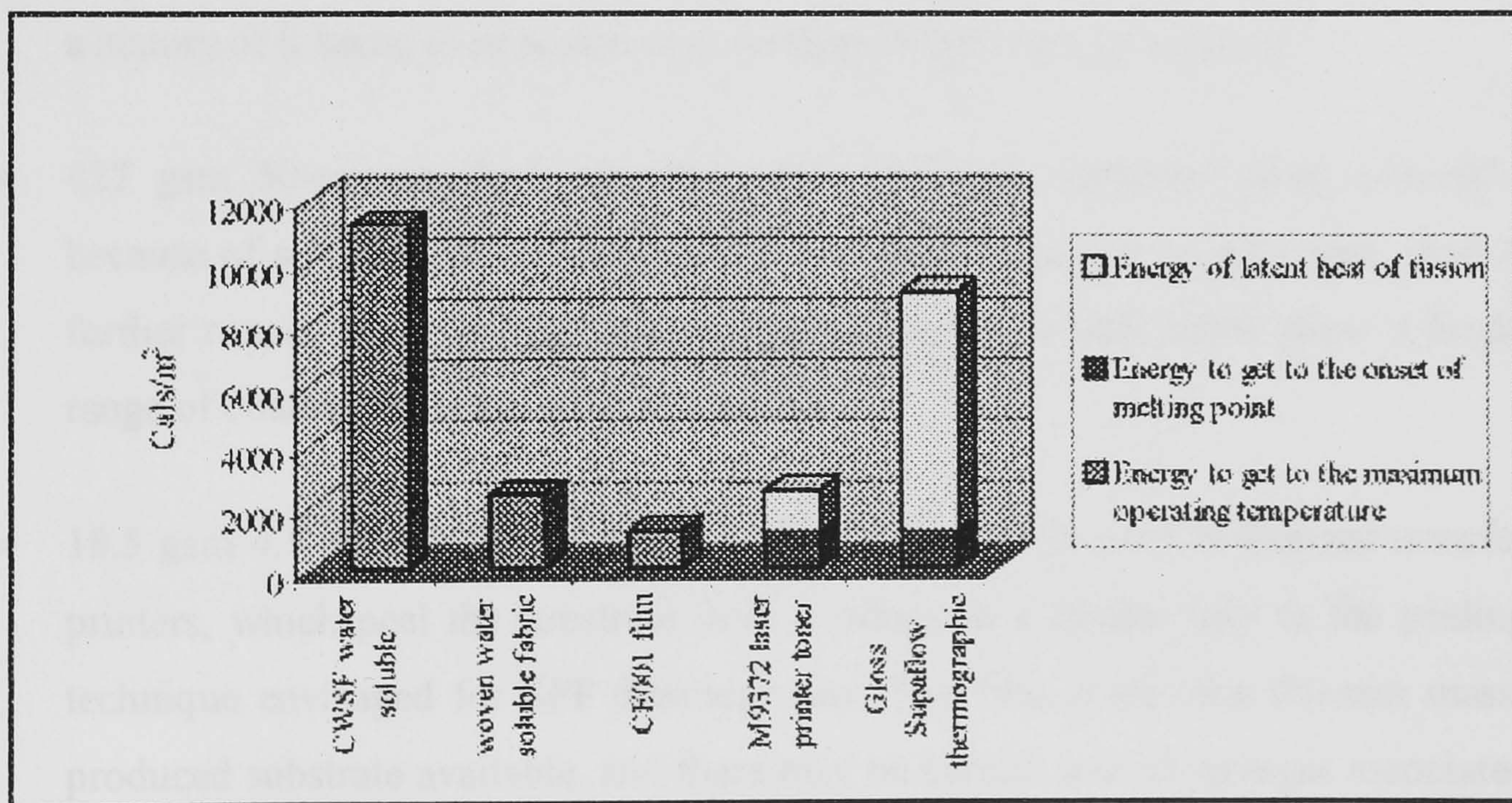


Figure 8: Energy involved in raising the substrates to their maximum operating temperatures and that associated with melting a 160 to 171 micron high coating of M9372 and Gloss Supaflow.

This left the CWSF cold water soluble non-woven substrate. A number of thermographic coatings were produced on this, but it was found that the substrate contained paper pulp that interfered with removing the substrate. Even when the substrate had been totally dissolved, pulp fibres would adhere to the coatings. In addition, the initial porous nature of the substrate tended to absorb and disrupt the structure of coatings. Consequently, it was decided that this substrate also was unsuitable for use.

4.3. Peeling Substrates Off Coatings

Because of the preceding observations and considerations, peeling the substrates off the coatings seemed to be a possible method, since the non-stick coatings assessed were more capable of withstanding high temperatures and energy densities than the other substrates. Conductive PTFE coated glass fibre belting was found to be the most suitable substrate, because it had a low background powder problem and its low coefficient of friction, made it relatively easy to peel away coatings [3]. In due course it may be useful to locate a similar product with a smoother surface, which would allow smoother and more accurate coatings to be made. The peelable substrates assessed and the main reasons for their selection are as follows:

- 236 gsm 100 micron thick conductive PTFE coated glass fibre belting, because it has the lowest coefficient of friction of any of the available substrates and there is a history of it being used as non-stick belting in the printing industry;
- 427 gsm 50-micron thick stainless steel 302 fully hardened shim, primarily because of a history of it being used in non-stick belting or transfer foils, with a further reason being its high temperature properties, which might allow a broad range of coating materials to be processed;
- 18.5 gsm 4.5 micron thick polyester film, because it is used in thermal transfer printers, which peel the substrate from coatings in a similar way to the peeling technique envisaged for SFF thermography. The film is also the thinnest mass-produced substrate available, and there may be certain cost advantages associated with thinness.

The conductive PTFE coated glass fibre belt melts at between 310 and 373 degrees centigrade and the maximum operating temperature of PTFE is around 260 degrees centigrade. This would allow it to be used in the processing of all but the highest temperature polymers.

The coefficients of static and dynamic friction for stainless steel are around 0.8 and 1.06 respectively and for PTFE they are around 0.04 and 0.5 respectively. The stainless steel and PTFE are similar to the conductive PTFE glass fibre belting and the stainless steel shim substrates, so it was evident that it would be easier to peel coatings off the PTFE belting than the shim.

Figure 9 indicates the substrates with the lowest background powder problem. It had already been decided for other reasons not to use the cellulosic papers and water-soluble non-woven (see sections 4.1 and 4.2). Because of its thermal, peelable and low background powder properties it was decided that the PTFE coated glass fibre belting was the most suitable substrate for use.

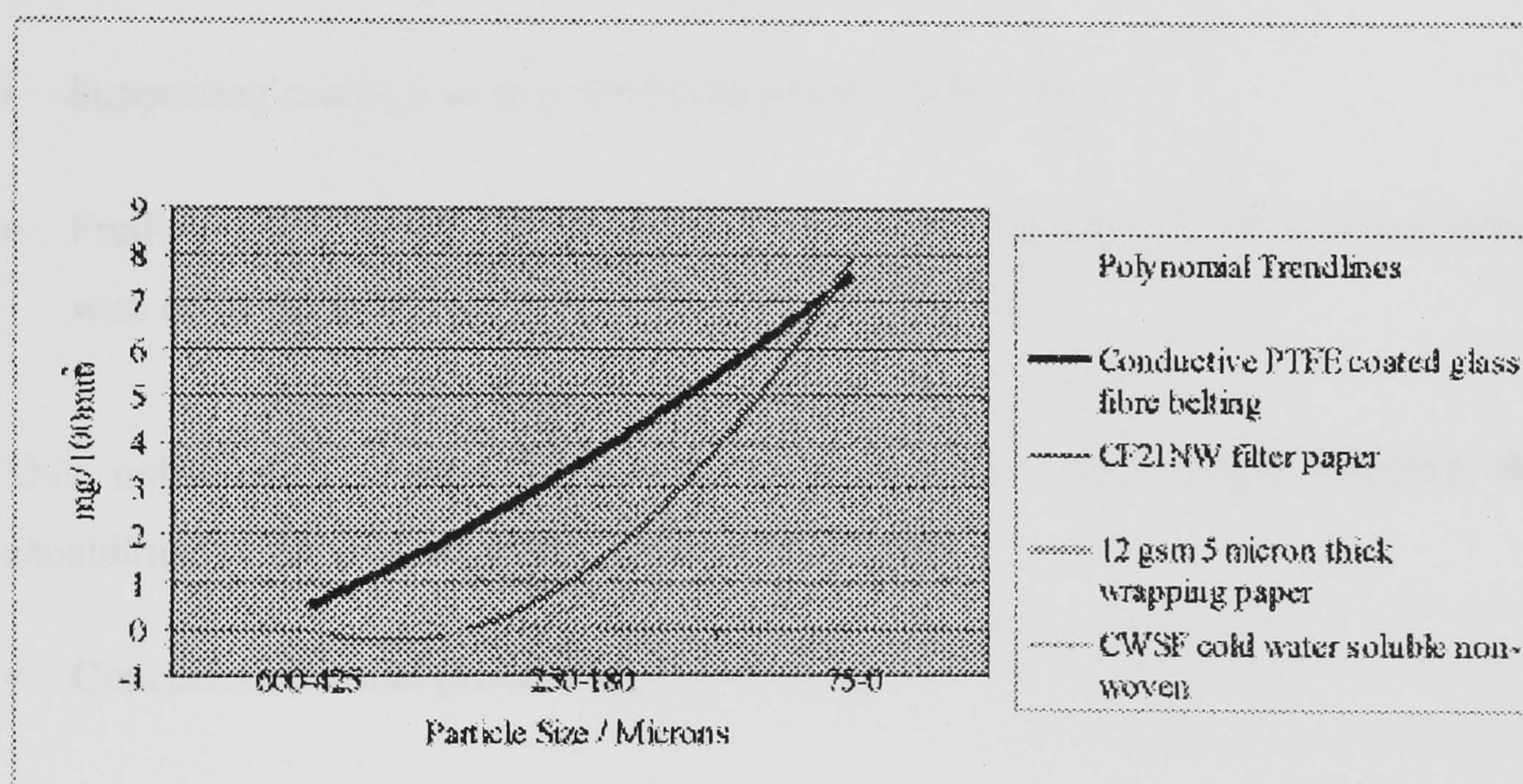


Figure 9: Weight of Mowiol 4-88 background powder per 100 mm² for versus Mowiol particle distribution for a number of substrates that have low background problems.

5. Thermography

The Solid Free Form Thermography submission [5] is concerned with thermographic coating of print (see section 2.2). Thermography is used in the printing industry to build up extremely thick coatings, on patterns of ink that have been printed onto substrates. This capability was the main reason for selecting it for evaluation, because it allowed the deposition rates of the printers used in the prototype system to be substantially increased (see section 2.2 and chapter 3). It was decided to evaluate the thermographic process's capability with respect to the following:

- Controlling and achieving the required continuity of coating.
- Producing multiple slice coatings on a substrate.
- Thermally processing the coatings.
- The use of engineering materials that may be more suitable than conventional thermographic materials as SFF support or part material.
- Supporting coatings as they are being peeled off substrates.
- Producing the height, resolution and accuracy requirements of coatings made with different materials.

This indicated a number of innovative adaptations which might improve the capabilities of the thermographic process, as follows:

- Concurrent thermal processing;
- Annealing of coatings;
- Compressing the coatings during the thermal processing.

The findings and recommendations derived from the Solid Free Form Thermography submission [5] are summarised in the following sections.

5.1. Coating Continuity

Powder coatings are produced by dusting thermopolymer, thermoset, metal or ceramic powders onto a printed ink pattern on a substrate, any powder that does not adhere to the ink being vacuumed or shaken off and recycled. In many cases, to ensure coatings with the required continuity, jet printer speeds needed to be slowed. For example, instead of printing 12 pages per minute the Epson Color Stylus 900 was at best capable of printing 4 pages per minute, otherwise discontinuities were formed (see Figure 10).

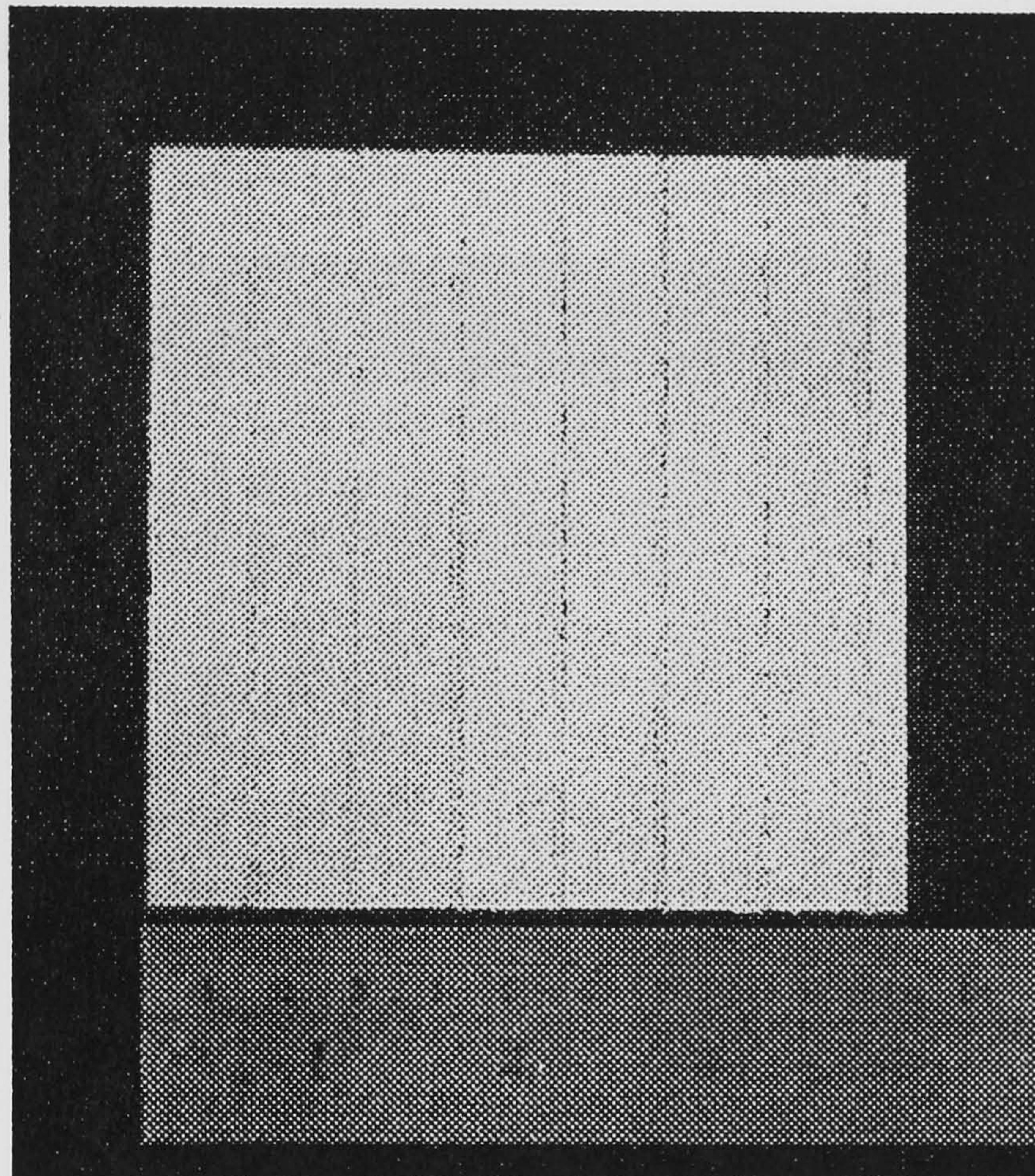


Figure 10: Dusted coating of 100 mm² printed by a Epson Stylus Color 900 using distilled water / 53% glycerol formulae instead of conventional ink and printed with mode: speed, ink: black settings onto PTFE coated glass fibre belting.

Mode speed (12 page per minute) ink black printer settings were used to produce the coating shown in Figure 10. The substrate used was conductive PTFE coated glass fibre belting (see section 4.3) and in Figure 10 and Figure 11 the powder used for the coating was a 212 to 75 micron distribution of Texicote 1050™ (saturated polyester carboxyl terminated). The light area is the coating and the black area is the uncoated

PTFE coated glass fibre belting. The intermittent black vertical lines in the coating are caused by the speed mode of the printer, and would tend to cause breaks in the final coating. If molten coatings were capable of spreading over these lines, this high level of spread would have a detrimental effect on the resolution and accuracy of the final coating. In view of this, it was decided not to use the speed setting of the Epson Stylus 900 printer.

Figure 11 shows a powder coating deposited onto print produced with the Epson stylus 900 using color black settings. The continuity of this coating was far superior to that shown in Figure 10, and it was decided that this would be sufficient to produce a melted and solidified coating, with a high degree of continuity. Consequently, the quality setting was used for producing print for all of the subsequent coatings.

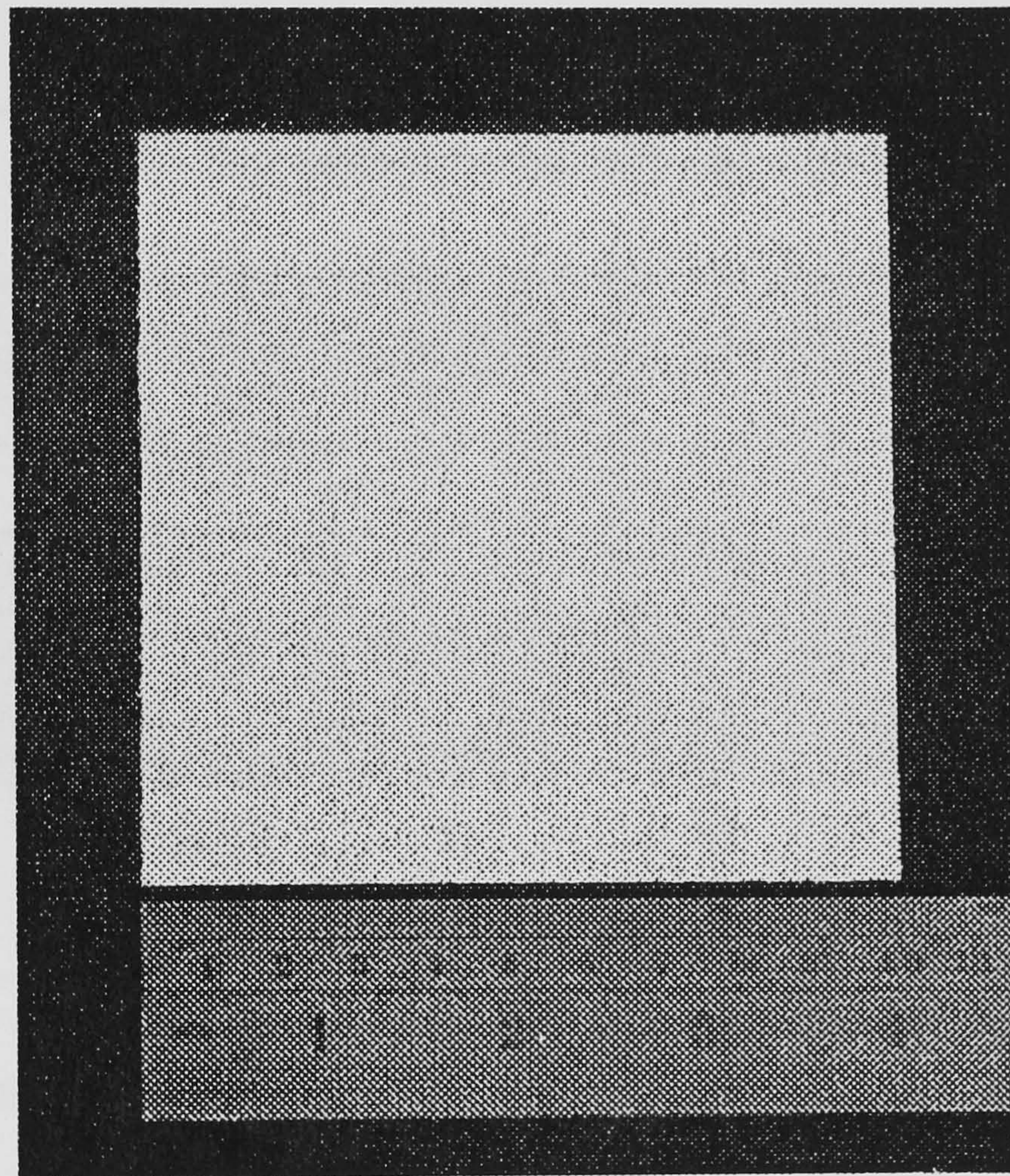


Figure 11: Dusted coating of 100 mm² printed by a Epson Stylus Color 900 using distilled water / 53% glycerol formulae instead of conventional ink and printed with mode: quality, ink: black settings onto PTFE coated glass fibre belting.

As the complexity of the STL files increased their slicing and printing became substantially more demanding in terms of time, memory and processing power.

Moreover demands associated with dissimilar geometries described by different files are difficult to predict, and so a number of experiments were performed to examine this problem. The Epson Color Stylus 900 printer and a Toshiba Satellite laptop with a 4 GB hard disc, 64 Mb RAM, 233 MHz CPU and a USB port connection with the printer was used in these experiments. Each experiment was repeated three times, and the associated means were used to generate Figure 12 to Figure 15. Figure 12 shows that the time taken to slice and print a part goes up as the number of slices increases. This meant that it took more than 25 seconds to make a print-out when 30 slices were made of the part. However, if duplicate print-outs were made and the Duplo DP2030 printer was used instead of the Epson this would not be a problem, because, without affecting the printing speed, the sliced files can be converted to postscript, sent to the printer and processed so that they are ready for imaging the printer's masters (screens).

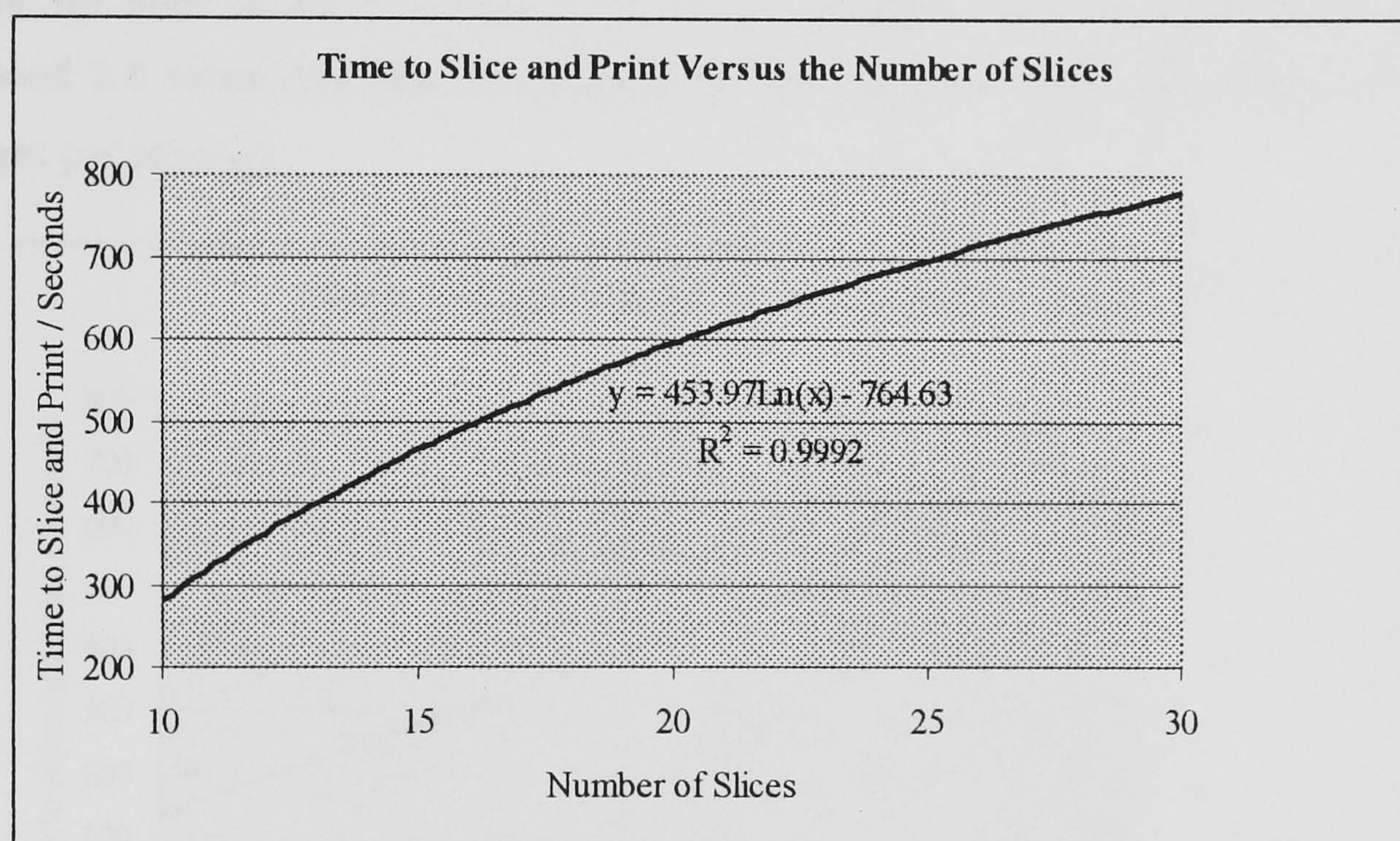


Figure 12: Shows the time taken to slice and print a part versus the number of slices made.

In Figure 12 the number of print outs that corresponds to slices is one more than the number of slices shown, because the slicing was performed within the part. The quality print setting was also used for these print outs and the part was made of 11432 polygons which the slicing software reduce to 11236 polygons (see Figure 12). The part had a maximum size of 84mm in x, 32 mm in z and 92 mm in y (see Figure 12).

Figure 13 shows that as the number of the polygons in a part increase it takes longer to slice and print the part. It was calculated that for a part with 884 polygons and a density of 0.00176 polygons per mm³ it would take 12 seconds to produce each print-out if 10 slices were made. For a part with 39546 polygons and a density of 0.68 polygons per mm³ it would take 62 seconds to produce each print-out if 10 slices were made. This caused a high degree of variability in slicing and printing time when the Epson Color Stylus was used. This type of problem was found to be substantially less important when the DP2030 printer was used, because the slicing and processing of the sliced images could be performed in parallel with the printing. It was also found that when duplicates of the part with 39546 polygons and a density of 0.68 polygons per mm³ that had been sliced in ten places were printed it only took 14 seconds to produce each duplicate print. This was because processed slice images were stored in a temporary memory ready for printing and so there was little or no need for them to be processed. Even so, the printing speed was still found to be around 2.8 times less than that quoted by the manufacturers of the Epson (12 A4 pages per minute).

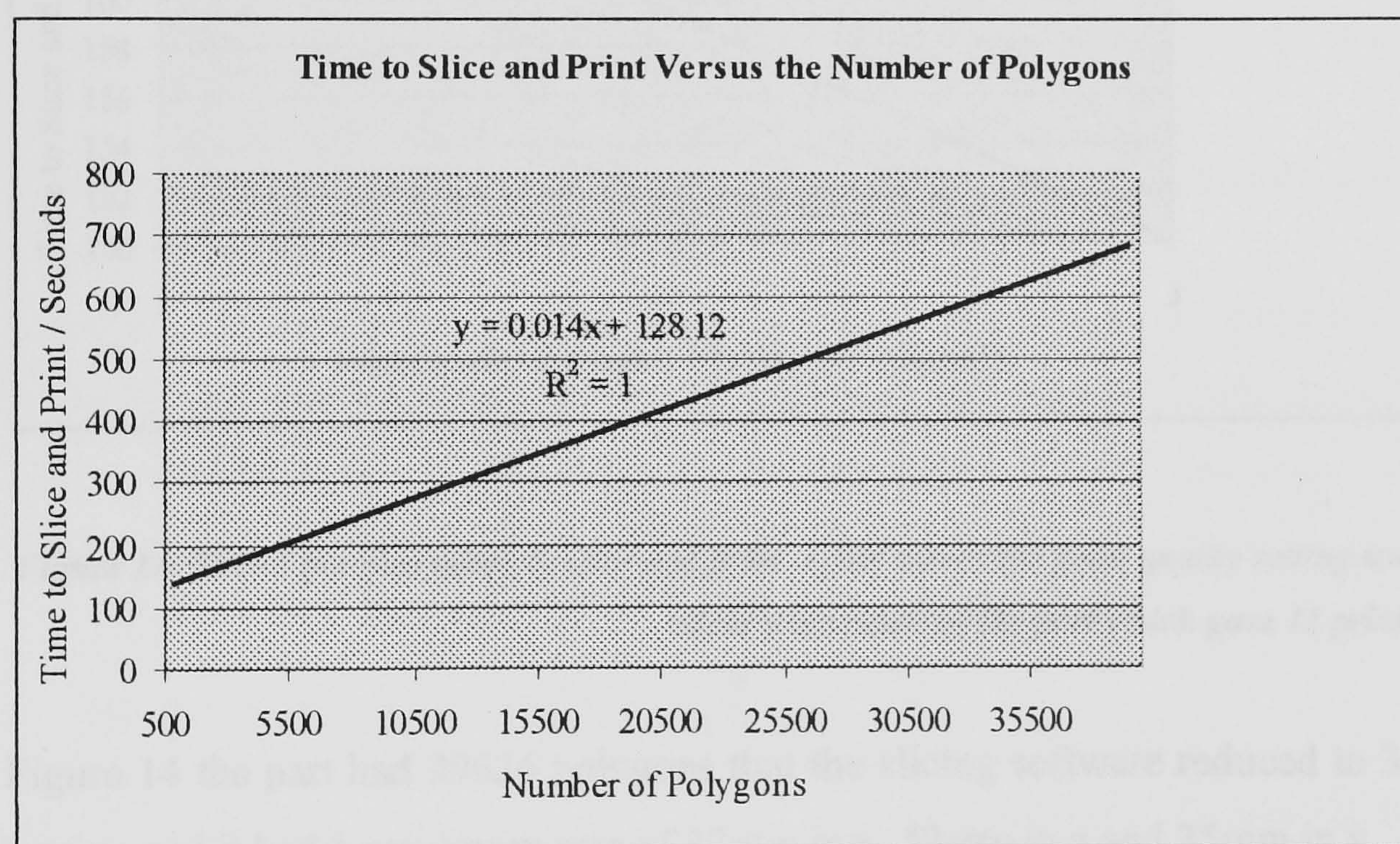


Figure 13: Shows the time taken to slice and print parts versus the number of polygons that the slicing software reduced the parts to having.

In Figure 13 ten slices were made of each part which gave 11 print outs for each part and the quality print setting was used. The first part had 1804 polygons that the

software were reduced to 884 polygons, and it had a maximum size of 98mm in x, 44mm in z and 116mm in y. The second part had 11432 polygons that were reduced to 11236 polygons, and it had a maximum size of 84mm in x, 32 mm in z and 92 mm in y. The third part had 39626 polygons that the were reduced to 39546 polygons, and it had a maximum size of 32mm in x, 52mm in z and 35mm in y (see Figure 13).

The time for printing duplicates became longer when the print quality setting of the Epson had to be changed from speed to quality in order to ensure the continuity of the powder coatings (see Figure 14). This was probably because more processing was required to produce the higher resolution quality print than the speed print.

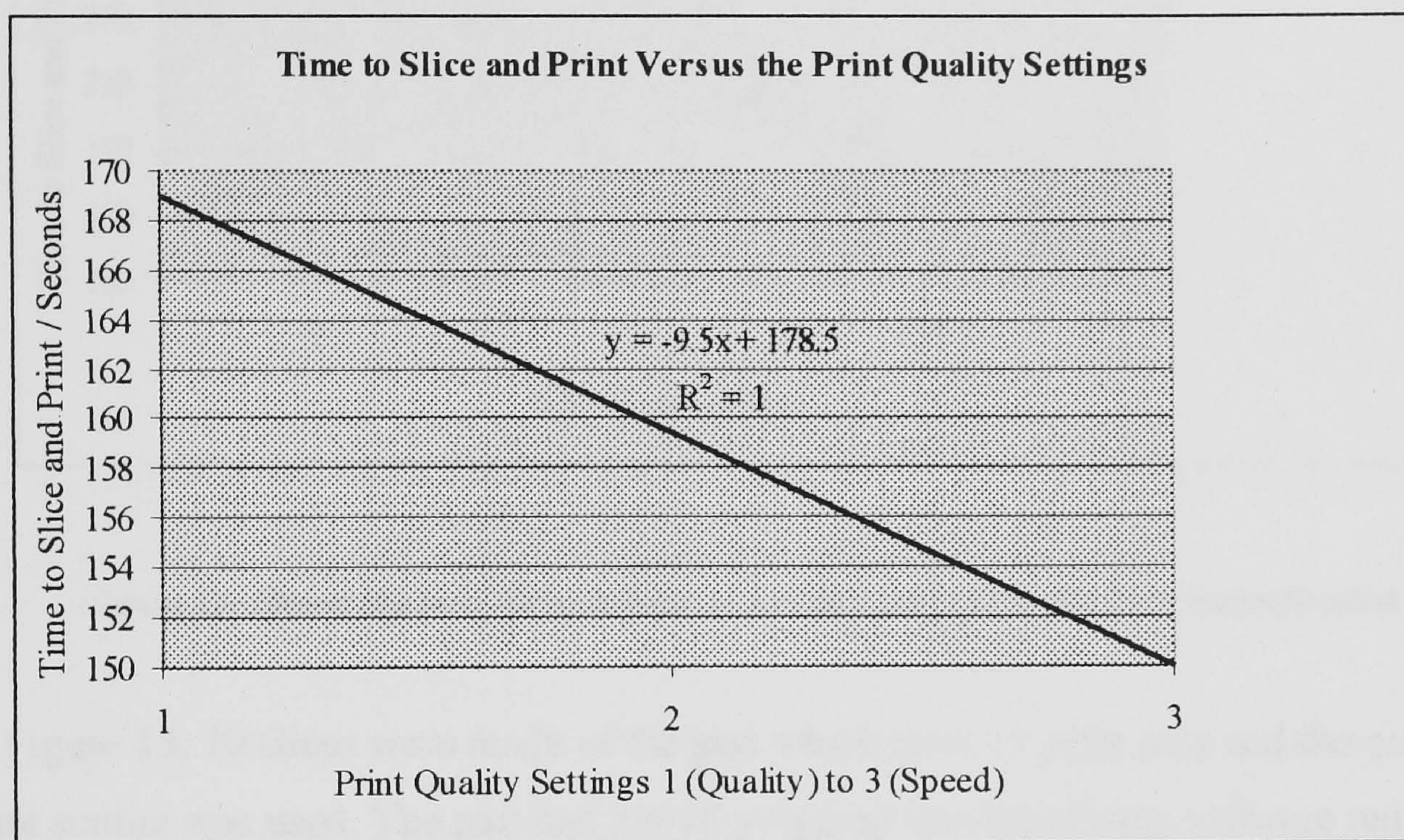


Figure 14: Shows the time taken to slice and print a part versus the print quality setting used. 10 slices were made of the part which gave 11 print outs.

In Figure 14 the part had 39626 polygons that the slicing software reduced to 39546 polygons, and it had a maximum size of 32mm in x, 52mm in z and 35mm in y.

It was also found that when duplicates of the part with 39546 polygons and a density of 0.68 polygons per mm³ were printed with different magnifications that the time needed to print them went up with magnification. It took 14 seconds to print one slice of the part with its original maximum size of 32mm in x, 52mm in z and 35mm in y, and when the size was magnified by 7.5 times it took 26 seconds to print a slice. This

is far less than that quoted by the manufacturer for the quality speed setting and so it is recommended that even if a very small number of duplicates are need the DP2030 printer should be used instead of the desktop jet printers, because its printing speed (120 pages per minute) is not so badly affected by magnification and print quality requirements.

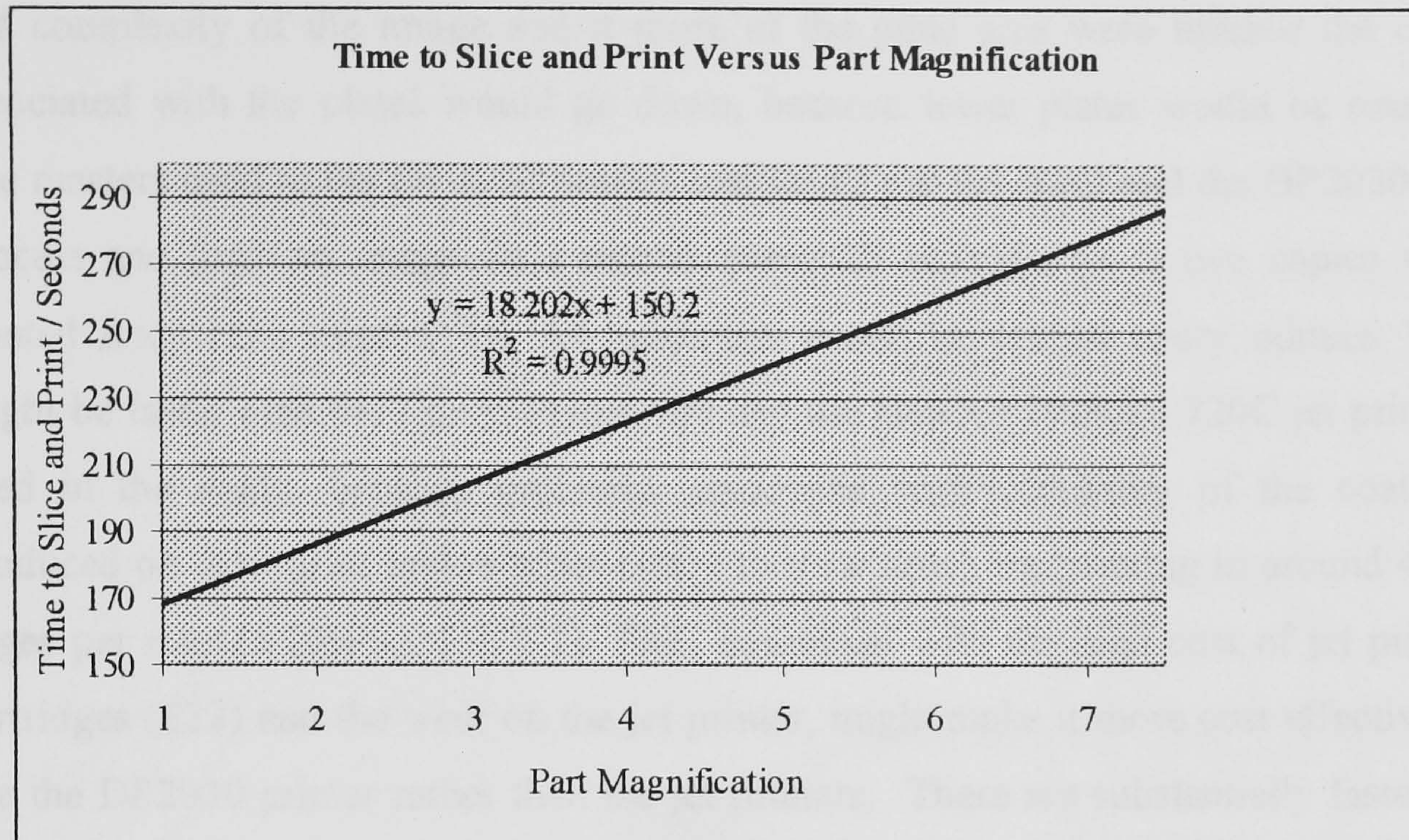


Figure 15: Shows the time taken to slice and print a part versus the part magnification used.

In Figure 15, 10 slices were made of the part which gave 11 print outs and the quality print setting was used. The part had 39626 polygons that the slicing software reduced to 39546 polygons, and it had an un-magnified maximum size of 32mm in x, 52mm in z and 35mm in y.

5.2. Multiple Slice Coatings on a Substrate

Most RP systems deposit form and process coatings consecutively one on top of another so that they are on different parallel planes. With SFF thermography it is possible to form and process all or a large number of the coatings required for a part on the substrate so that they are on the same plane. This reduces the number of plates, masters or screens used by the impact printer and increases the efficiency of the thermal processing, because more of the substrate's surface is coated and so more of

the energy is involved in processing the coatings rather than in merely heating the substrate. The coatings may then be assembled and bonded to form the part.

In this instance, it would almost certainly be faster and more cost effective to use impact printing rather than desktop jet printing. With many impact printers the time required to form an image on a plate, master or screen is fixed, irrespective of the size and complexity of the image and if more of the plate area were utilised the costs associated with the plates would go down, because fewer plates would be needed. The masters used in the DP2030 printer cost £0.12 per A4 sheet and the DP2030 can process and form an image on a master every 25 seconds. So if two copies were printed from each master, 4.6 A4 substrates could be printed every minute. This might be faster than the Epson Stylus 900 and the Hewlett Packard 720C jet printers used in the study, because problems associated with continuity of the coatings produced on their print makes it necessary to slow down the printing to around 4 A4 pages per minute (see section 5.1). This, combined with the high cost of jet printer cartridges (£22) and the wear on the jet printer, might make it more cost effective to use the DP2030 printer rather than the jet printers. There are substantially faster jet printers used in industry, but this does not invalidate this assessment because there are even faster impact printers and plate making processes.

It may still be useful to use the jet printers because of their four colour printing capability which may be used to impart pictures to the coatings. It was calculated that if the DP2030 printer were used to do this it would be around 3.5 times slower than the jet printers because the number of masters that it would have to image would be increased by a factor of 4 in order for the colours to be printed. The cost of its masters would also be increased by a factor of 4, and so in this instance the jet printers might be a less expensive option. Even so, it is apparent that jet printing would be suitable only for producing coatings for one-off or very small numbers of parts, primarily because there is likely to be a high degree of wear on printer components [5].

5.3. Conventional Thermal Processing Versus Stack Processing

On a theoretical level, it has been shown that heating the coatings in parallel in a stack (see Figure 16) would be substantially easier to control than the thermographic

process's conventional linear heating, which involves feeding coated substrate consecutively through an infra red emitter section (see Figure 17 and section 5.3.1). It was also shown that if the coatings were processed in a stack that also contained conductive plates (see Figure 16), the heat might be efficiently recycled, which would allow for dramatically higher processing rates (see section 5.3.2). The recycling produces a geometric increase in the rates. Consequently, it is recommended that heating the coatings in a stack should be seriously considered as an adaptation to the process (see section 5.3.3).

It was assumed that after the coatings had been processed and cooled a collation machine would be used to separate (de-collate) the various components of the stack.

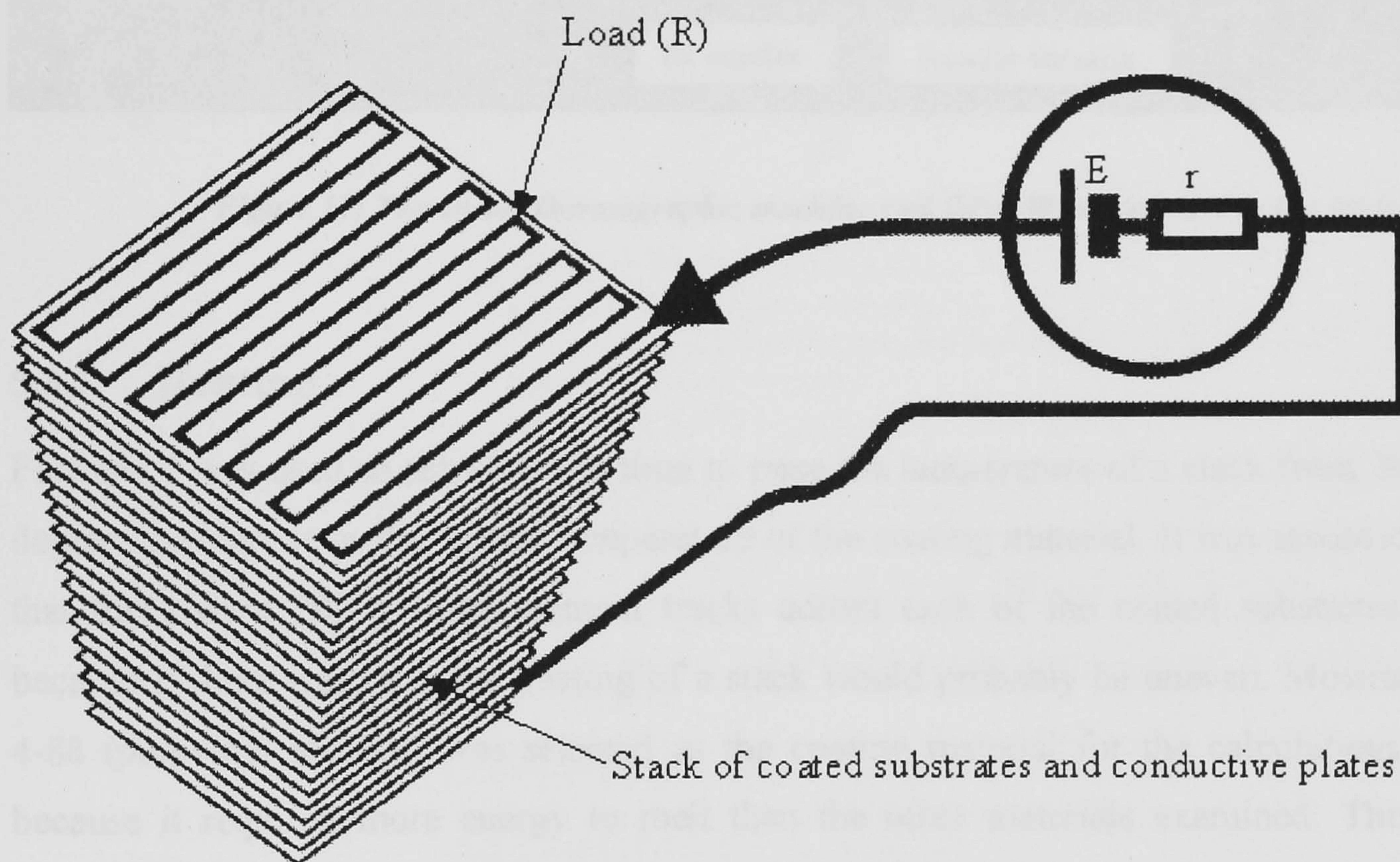


Figure 16: Using electrical resistance heating elements embedded in the substrates of a stack of coated substrates to raise the temperature of the stack to the coating's melted temperature.

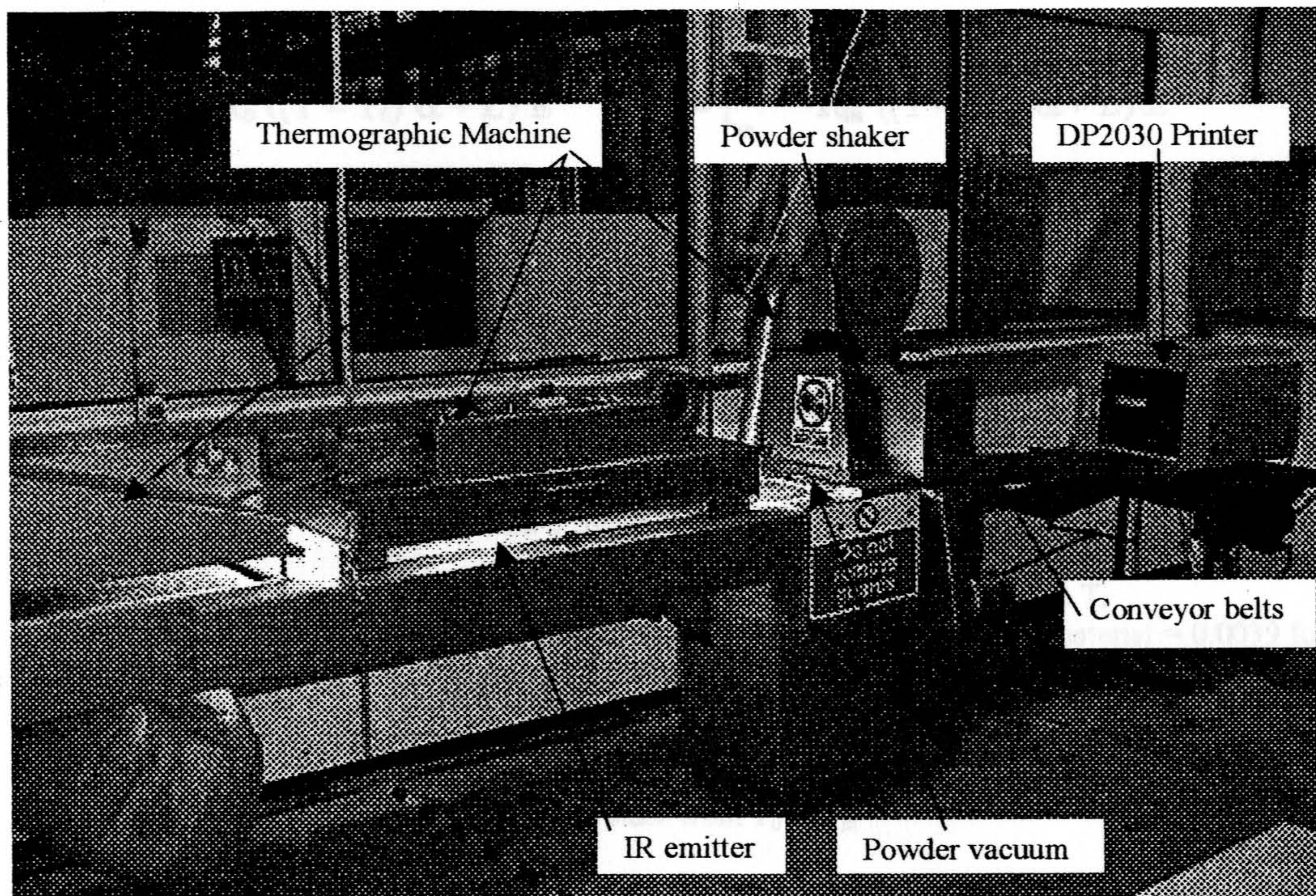


Figure 17: The 14 kW thermographic machine and DP2030 printer used in the study.

5.3.1. Heating

Formula 1 was used to calculate the time to raise the temperature of a stack from 20 degrees centigrade to the melted temperature of the coating material. It was assumed that there were 200 parallel element tracks across each of the coated substrates, because if there were less the heating of a stack would probably be uneven. Mowiol 4-88 (polyvinyl alcohol) was selected as the coating material for the calculations, because it required more energy to melt than the other materials examined. This meant that the calculations would indicate the maximum time to raise the temperature of a stack to the melted temperature of a coating material.

If the cooling needs to be accelerated, this could be achieved by using stacks of coatings laminated between substrates and sandwiched between cooling plates, in a similar arrangement to that shown in Figure 16. The product of Formula 2 was added to Formula 1's K_c and K_f so that the time required to raise the stack of coatings could be calculated.

$$t = \int_{T_0}^{T_m} \frac{K_c (r + R_0 ((T - T_0) \alpha + L))^2}{R_0 ((T - T_0) \alpha + L) E^2} dT + \int_{T_m}^{T_1} \frac{K_c (r + R_m ((T - T_m) \alpha + L))^2}{R_m ((T - T_m) \alpha + L) E^2} dT$$

Where:

- t = the time to raise the temperature of the stack from T_0 to T_1
 T_0 = start temperature of the stack = 20°C
 T_m = onset of melting temperature of the coating material = 127°C for Mowiol 4-88
 T_1 = melted temperature of the coating material = 226°C for Mowiol 4-88
 r = internal resistance of the EMH / $\Omega = 2.4$ for 100A
 R_0 = resistance of the element at the start / $\Omega = \rho_r L / A$ where: ρ_r = the resistivity of the element's material = 2.8×10^{-10} for aluminium and 1.7×10^{-10} for copper
 T = increments of temperature from T_0 to T_m and from T_m to T_1
 α = temperature coefficient of resistance of the element's material = 0.0039 for aluminium and 0.0043 for copper
 L = length of the element
 E = EMH / volts
 K_c = heat capacity of the stack from T_0 to T_m =

$$K_c = \rho_p L A cp + \frac{CP_c \rho h L w}{n} + \frac{CP_c \rho_c h_c L w}{n}$$

Where:

- ρ = density of the coating material / (g / cm^3)
 h = height of the coating = 500 microns
 n = number of parallel wire tracks across a coated substrate = 200
 w = width of the stack = 20 cm
 ρ_s = density of the PTFE coated glass fibre belting substrate / (g / cm^3) = 2.36
 cp_s = specific heat of the PTFE coated glass fibre substrate / (j/g per °c) = 1.05
 h_s = height of the PTFE coated glass fibre belting substrate = 100 microns
 CP_c = specific heat of the coating material / (j/g per °c) = 2.435 for Mowiol 4-88

- K_1 = heat capacity of the stack from T_m to T_1 =

$$K_f = \rho_p L A cp + \frac{FP_c \rho h L w}{n} + \frac{CP_c \rho_c h_c L w}{n}$$

Where:

- FP_c = Latent heat of the coating material converted to j/g per °c = 0.946 for Mowiol 4-88

Formula 1: Time required to raise the temperature of a stack from 20 degrees centigrade to the melted temperature of the coating material.

It was demonstrated that it would take around 250, 310 and 370 seconds to raise the temperature of stacks with 500 micron high graphite, aluminium and copper plates respectively. This is assuming the element is aluminium, and that 6kW is supplied to the element, which allows 77 coatings to be raised to the required temperature in this time, and that 500 micron high 20cm² Mowiol 4-88 coatings are being processed. This gives a processing rate of around 0.31, 0.25 and 0.21 coatings per second, for stacks with graphite, aluminium and copper plates respectively. 6kW is the power that could be expected in households and offices, so these sorts of rates that could be achieved in such settings. In industry, the maximum power that could be delivered to an element would be around 600 kW, so the rates would be a hundred times greater.

$$\frac{Cp_g \rho_g h_g L w}{n}$$

Where:

Cp_g	=	specific heat of the plate material / (j/g per °c) = 0.709, 0.385 and 0.897 for graphite, copper and aluminium respectively.
ρ_g	=	density of the plate material / (g / cm ³) = 1.8, 8.96 and 2.698 for graphite, copper and aluminium respectively.
h_g	=	height of the plate / cm = 0.05
L	=	length of the element in Formula 1
w	=	width of the stack in Formula 1
n	=	number of parallel element tracks across a coated substrate in Formula 1

Formula 2: formula for defining the specific heat of the cooling plate setup that needs to be incorporated into K_c and K_f of Formula 1.

Formula 3 and Formula 4 were used to calculate processing times for conventional thermographic processing. It was found that these times were similar to those associated with processing the coatings in a stack. It was assumed that stack processing would be more easily controlled than conventional processing, because there would be less likelihood of radically different thermal gradients building up between the substrates and the coatings.

$$e_d = \frac{100 e s (x + \Delta x)}{a l x}$$

Where:

e_d	=	energy density required to melt the coating / mw
s	=	coated substrates traverse speed through the emitter section / (mm/s)
e	=	energy required to melt a mm ² of coating with a height of x / joules = 121.771 for Mowiol 4-88
Δx	=	difference in the height of the coating being processed / mm
a	=	% of energy absorbed = around 95 for the thermographer in the study when it has warmed up
x	=	height of the coating that was used to calculate e / mm = 0.132
l	=	emitter length / mm

Formula 3: Energy density required for melting the coating material.

$$P = \frac{e s w (x + \Delta x)}{10000 a x}$$

Where:

P	=	emitter power required for melting the coatings / kW
w	=	the emitter width / mm = 269

Formula 4: Emitter section power required for melting the coatings (see Formula 3).

5.3.2. Conventional Thermographic Cooling

It was decided that time might be needed for annealing, curing, coalescing, spreading or levelling the coatings. Consequently, Figure 18 was generated to show the speed at which the temperature of PTFE coated glass fibre substrates with melted Mowiol 4-88 coatings would fall in conventional processing from the melted temperature (226 degrees centigrade) to 20 degrees centigrade, for different coating heights. Figure 18 was derived from calculations made with Formula 5. It was assumed that the surfaces of the coated substrates were kept at room temperature (20 degrees centigrade), by the forced convection generated by the thermography machine's meter long air-blower cooling section (see Figure 17). The situation would probably be similar if an air-blower were not used, because the traverse of the coated substrates also produces forced convection. Figure 18 indicates that it would take around 1.68 seconds to lower the temperature of a 500 micron high coating on the substrate, and 0.2 of a second for a 50 micron high coating. This suggests that if annealing, curing, coalescing, spreading or levelling time were required after the

coatings had been melted, a unit would need to be added to the thermographic machine to maintain the coated substrates' temperature for the appropriate time.

If the coatings were 132 microns high and made of Mowiol 4-88, and a 406mm traverse were used (as calculated with Formula 3 and Formula 4), assuming the temperature needed to be maintained for 20 seconds an 8.12 meter unit would be needed. If the unit were to have the same warm-up time as the emitter section, it would need to have a similar energy density. When it had warmed up it could use a lower energy density to maintain its temperature. During the warm up, around nine times as much power would needed, compared with when the unit was not used. If the 406mm traverse were used, the addition of the unit to the thermographic machine would add 20 seconds to the total traverse time through the machine. Consequently, if the processing became more discontinuous, the addition would increasingly reduce the rate at which the coatings were processed. If the unit and a 406 mm traverse were used the total traverse time would be around 25 seconds. Consequently, it was decided that the addition of such a unit would make conventional processing too slow for use with SFF thermography for in mass-production.

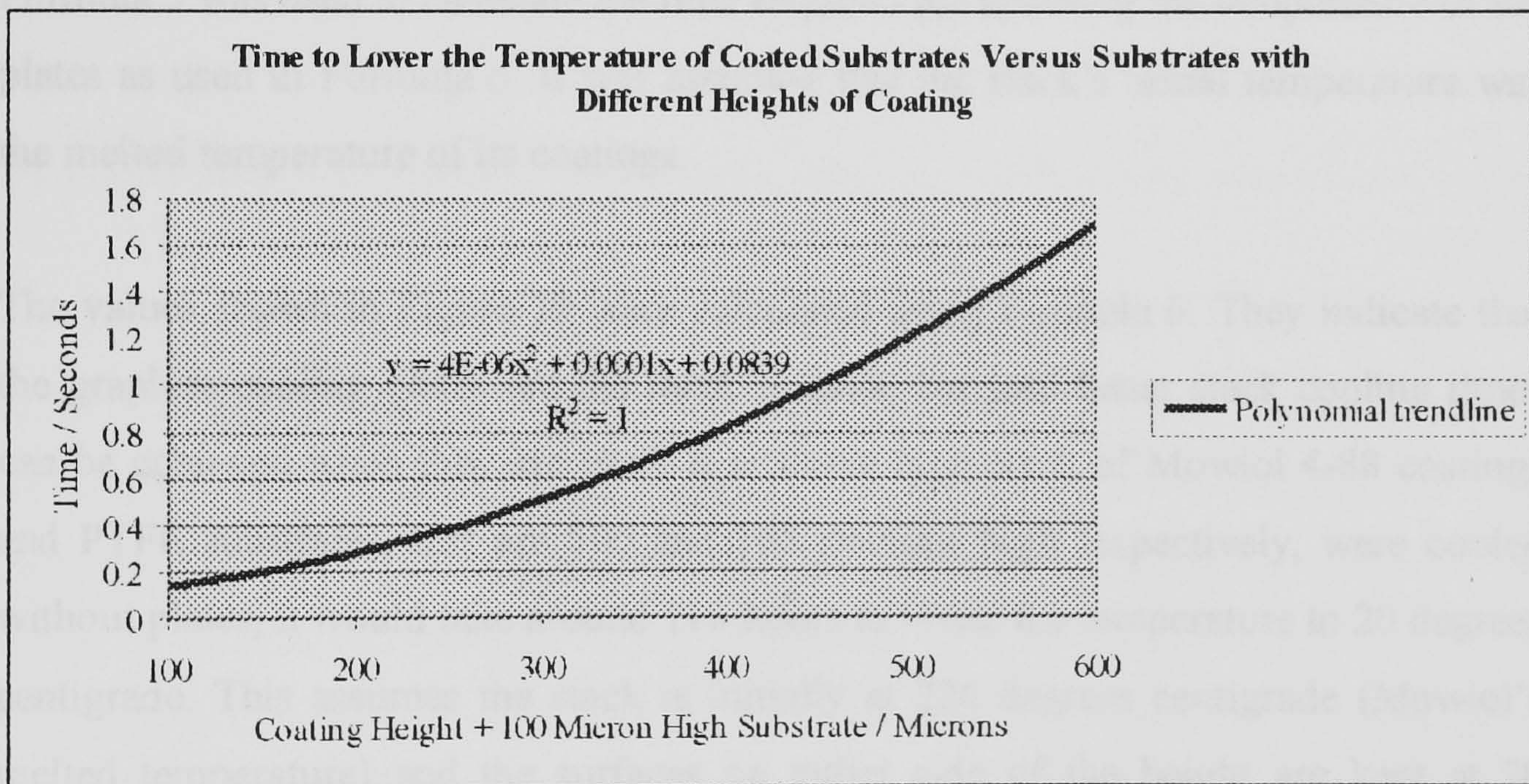


Figure 18: Time to lower the temperature of coated substrates from the melted temperature of the coating (226 degrees centigrade for Mowiol 4-88) to 20 degrees centigrade versus substrates with different coating heights.

$$\frac{\partial U(x,t)}{\partial t} = c^2 \frac{\partial^2 U(x,t)}{\partial x^2}$$

Where:

U = temperature / centigrade = 127, 156 and 160 for the onset of melting for Mowiol 4-88, indium and nylon 12 respectively. 226, 178 and 198 for the melted temperature for Mowiol 4-88, indium and nylon 12 respectively.
x = height / mm
t = time / seconds
 c^2 = conductivity =

K / (cp ρ)

where:

K = coefficient of thermal conductivity / (w mm⁻¹c⁻¹) = 1.96, 0.401 and 0.237 for graphite, copper and aluminium respectively.
cp = specific heat / (j/g per °c) = 0.709, 0.385 and 0.897 for graphite, copper and aluminium respectively.
ρ = density / (g / mm³) = 0.0018, 0.00896 and 0.002698 for graphite, copper and aluminium respectively.

Formula 5: Temperature formula [5].

5.3.3. Stack Cooling and Recycling

Formula 6 was used to calculate the time needed to lower the temperature of a stack. Formula 5 was used to calculate the time required for lowering the temperature of the plates as used in Formula 6. It was assumed that the stack's initial temperature was the melted temperature of its coatings.

The values shown in Figure 19 were calculated using Formula 6. They indicate that the graphite cooling plates are the most suitable, because faster stack cooling times can be achieved when they are used. If a 20 cm high stack of Mowiol 4-88 coatings and PTFE substrates, that are 500 and 100 microns high respectively, were cooled without plates, it would take around 118 hours to lower the temperature to 20 degrees centigrade. This assumes the stack is initially at 226 degrees centigrade (Mowiol's melted temperature) and the surfaces on either side of the height are kept at 20 degrees centigrade. It is also assumed that the coatings and substrates are in series with respect to the surfaces (see Formula 5). This confirms the assessment that the cooling would be substantially faster if plates were used.

$$t_c = t_l + \frac{t_l (e h l w \rho + 2 c p_s h_s l (-T_0 + T_m) w \rho_s)}{c p h_p l (-T_0 + T_m) w \rho_p}$$

Where:

t_c	=	time to lower the stack from 20 degrees centigrade to the melted temperature of the coating material / seconds
t_l	=	time to lower the plates from the melted temperature of the coating material to 20 degrees centigrade / seconds (see Formula 5)
t_m	=	time to raise the stack from 20 degrees centigrade to the melted temperature of the coating material / seconds
t_r	=	time to raise the plates from the 20 degrees centigrade to the melted temperature of the coating material / seconds (see Formula 5)
ρ_p	=	density of the plate material / (g / cm ³) = 1.8 for graphite, 8.96 for copper, 2.698 for aluminium
h_p	=	height of the plate / cm = 0.1
l	=	length of the stack / cm = 20
w	=	width of the stack / cm = 20
cp	=	specific heat of the plate / (j/g per °c) = 0.709, 0.385 and 0.897 for graphite, copper and aluminium respectively.
T_m	=	melted temperature of the coating material / centigrade = 226
T_0	=	start temperature of the stack / centigrade = 20
ρ	=	density of the coating material / (g / cm ³) = 1.337
h	=	high of the coating / cm = 0.05
e	=	energy required to melt a gram of coating / j = 656.448
ρ_s	=	density of the PTFE coated glass fibre substrates / (g / cm ³) = 2.36
h_s	=	height of the PTFE coated glass fibre substrates / cm = 0.01
cp_s	=	Specific heat of the PTFE coated glass fibre substrates / (j/g per °c) = 1.05

Formula 6: Time to lower a stack from the melted temperature of the coating material to 20 degrees centigrade.

Figure 20 shows the relationship between the time required to lower a stack's temperature and the stack's plate height to coating and substrate height ratio. This indicates that even when the ratio is quite low, relatively fast cooling times can be achieved in spite of the stack being quite wide. The increase in time due to the reduction in the ratio indicates that the plates are less able to conduct the heat away from the stack when the ratio is small. As long as there is sufficient coolant to maintain the temperature of the blocks, the stack could be as high or long as required and the times would still be applicable. In the simplest cooling arrangement, water could be used as the coolant, so this method could prove relatively inexpensive.

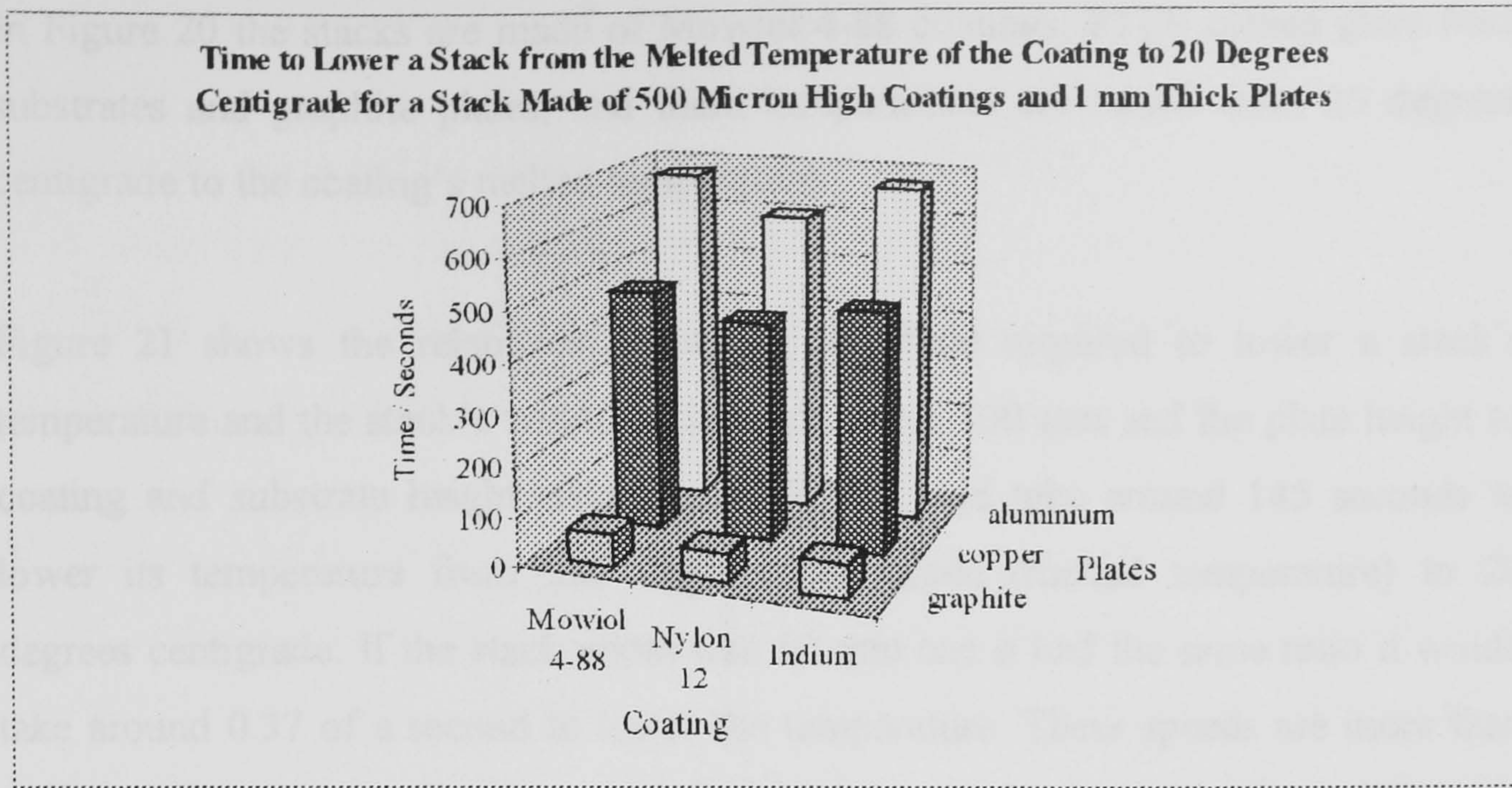


Figure 19: Time to lower the temperature of a stack from the melted temperature of the coatings to 20 degrees centigrade.

In Figure 19 the stack is comprised of 500 micron high coatings laminated between two 100 micron high PTFE coated glass fibre substrates, and the laminates are sandwiched between two highly conductive plates. Where the plates are in contact with two cooling blocks kept at the 20 degrees centigrade.

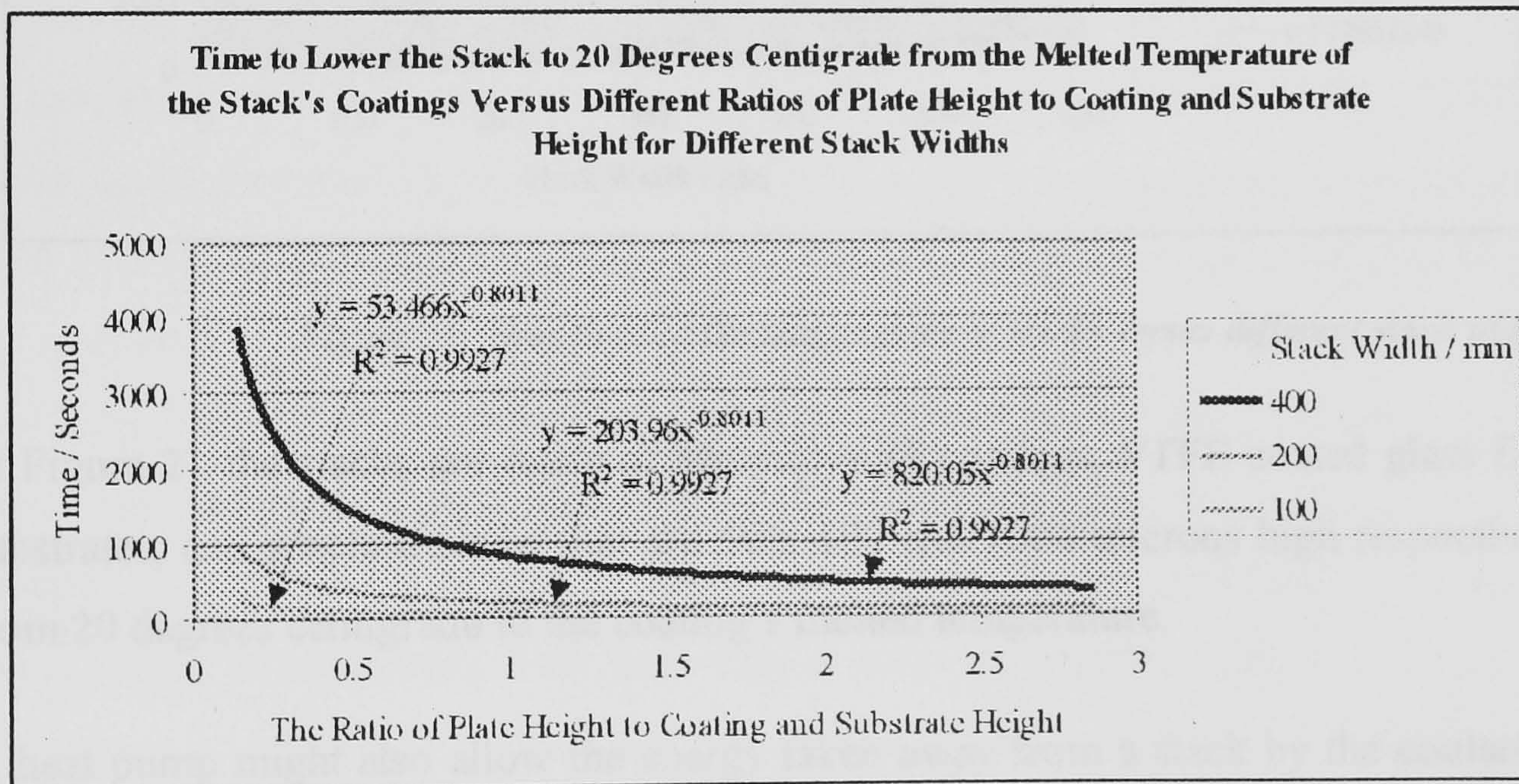


Figure 20: Time to lower the temperature of stacks of coatings substrates and plates versus different Ratios of plate height to coating and substrate height.

In Figure 20 the stacks are made of Mowiol 4-88 coatings, PTFE coated glass fibre substrates and graphite plates, and their temperatures are raised from 20 degrees centigrade to the coating's melted temperature.

Figure 21 shows the relationship between the time required to lower a stack's temperature and the stack's width. If the width were 200 mm and the plate height to coating and substrate height ratio was 1.42, it would take around 145 seconds to lower its temperature from 226 degrees centigrade (melted temperature) to 20 degrees centigrade. If the stack width was 10 mm and it had the same ratio it would take around 0.37 of a second to lower the temperature. These speeds are more than sufficient for mass-production applications because, as long as enough coolant were supplied, the stack could be as high or as long as required.

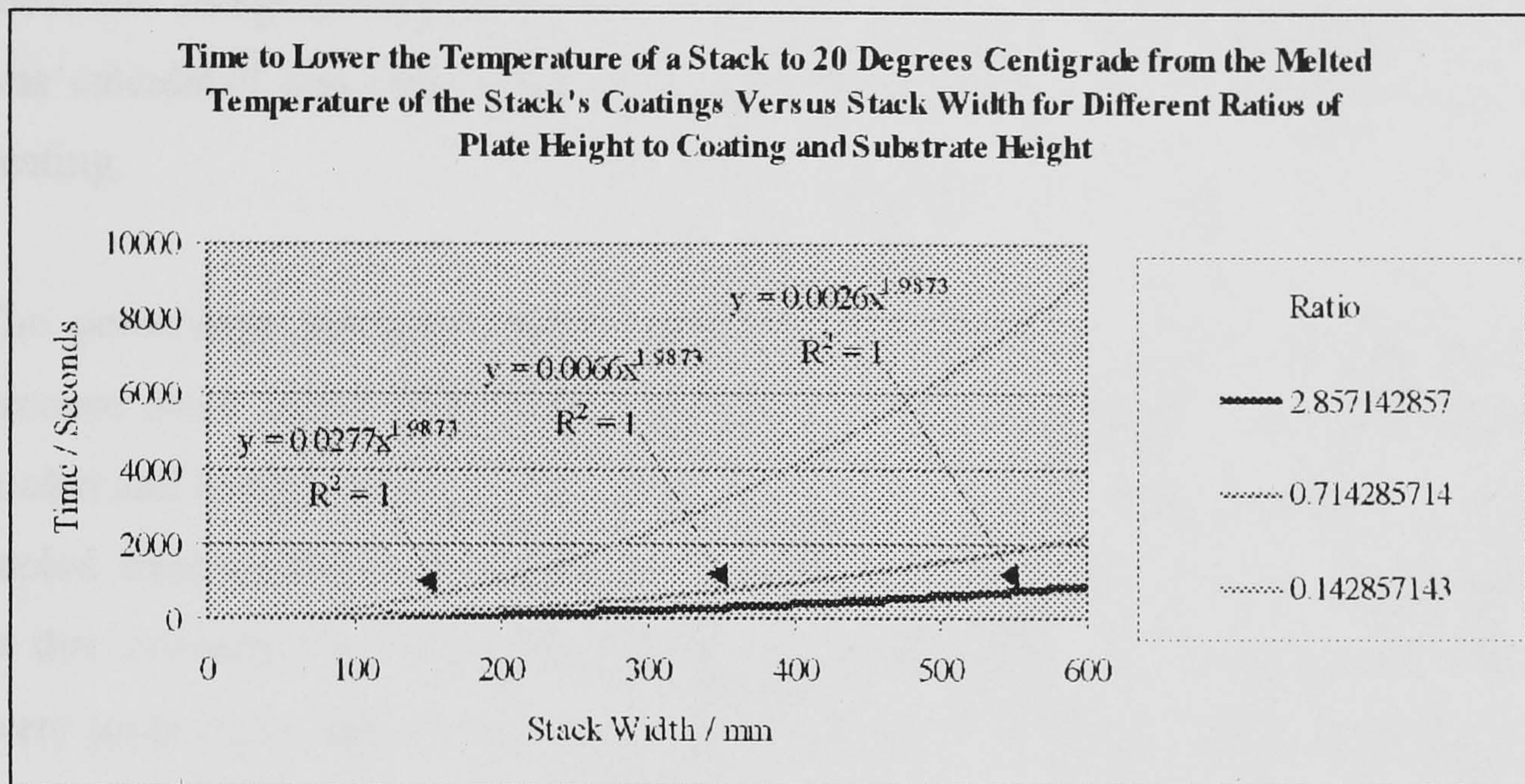


Figure 21: Time to raise the temperature of stacks versus different stack widths.

In Figure 21 the stacks are made of Mowiol 4-88 coatings, PTFE coated glass fibre substrates, and graphite plates that are 500, 100 and 1000 microns high respectively from 20 degrees centigrade to the coating's melted temperature.

A heat pump might also allow the energy taken away from a stack by the coolant to be used in maintaining the temperature of another stack. According to heat pump theory, this would be a very efficient way of maintaining the temperature (see Formula 7). The coefficient of performance indicates the number of joules that would be used in maintaining the temperature for a consumption of 1 joule of pump work

done. The efficiency would reduce as the temperature of the stack being cooled got lower, so it would be at its most efficient when there was only a slight difference between the temperatures of the stacks (see Figure 22). The efficiency is still around 2.43 even when the temperature of the stack being cooled reaches 20 degrees centigrade, and this confirms that it would be an efficient method for maintaining the temperature, (see Figure 22).

It was calculated that if this arrangement were used to maintain a stack's temperature at 499 degrees Kelvin, the average coefficient would be around 14.3 for every joule consumed in pumping. Alternatively, hot stacks that needed to be cooled could be placed next to the stacks that needed to be heated, so that heat would be transferred. Assuming the stacks are comprised of Mowiol 4-88 coatings, PTFE coated glass fibre substrates and graphite plates that are 500, 100 and 1000 microns high respectively, it was calculated that this might allow 53% of the power to be recycled for use in heating.

The percentage increases as the ratio of plate and substrate to coating reduces, because more latent heat is involved. When the temperatures of the stacks being cooled and heated reach equilibrium, a heat pump could be used to take heat from the cooled stack to help with heating or maintaining the temperature of the other stacks. In this instance the average coefficient of performance would be around 9.86 for every joule consumed in pumping. This might allow 95.24 percent more power to be used in processing than if heat transfer and heat pumping were not used, resulting in the processing rate for the coatings being increased by 95.24 percent. This is assuming that the energy losses are relatively insignificant. If the heat were used in maintaining the temperature of a stack at 499 degrees Kelvin, the average would be around 3.21, and so the efficiency would be less than in raising the temperature of a stack. Other arrangements with heat pumps could be used to further increase the percentage of power that could be used in processing. The increase might even exceed 100%, though it would probably be difficult to achieve this because of heat losses. It would also involve lowering the temperature of the cooling stacks to well below their initial ambient temperature. Consequently, at this stage it may be more

efficient to use a pump to transfer heat from a stream of cold water rather than from the stacks.

Considering that the coefficient of heat transfer of insulating materials is very low, the rate of heat loss from the stacks would be extremely low if they were insulated. Coefficients of $0.2 \text{ W/m}^2\text{K}$ are common for many types of 100 mm thick mineral and glass wool, and so a 0.2 m^3 insulated stack would lose 0.016 and 0.036 joules per second from 2 and 4 sides respectively. Depending on the arrangement of the stacks and the heating and cooling blocks, it might be possible to reduce the requirement for insulation. In some instances, it might be possible to surround some stacks so that they did not need insulating. If 6 kW of power were used to heat the stacks the losses would probably be insignificant. The fact that the heat can be recycled may allow a linear build-up of stack processing, and this may have a dramatic effect on the rate at which the coatings can be processed and the capacity for their production.

If it took 248 seconds to heat a stack and then the stack's heat were to be transferred to another stack there would be over 14 and 348 stacks being processed after an hour and 24 hours had elapsed respectively. The limiting factor to this progressive build up is the degree of heat loss from the insulated surfaces. In theory the surface area needs to exceed 30000 m^2 before the energy losses exceed the 6kW of unrecycled power used in the heating. This would equate to a 31 m^3 cube of stacks or an oblong block of stacks measuring around $387 \times 387 \times 0.2$ meter. It would take around 29 years to build up enough area to reach the 6kW limit, and so it is assumed that it has an insignificant effect on the rate at which coatings are processed. If the heat were recycled as described, the processing rates for 500 micron high 20 cm^2 Mowiol 4-88 coatings might be around 4, 110 and 750 coatings per second after 1, 24 and 168 hours had elapsed respectively. This assumes that 6kW is supplied for the heating, which is the sort of power that can be found in households or offices, and after a month of continuous processing the rate might be around 3000 coatings per second. If an industrial 600 kW supply were used the rate would be around 100 times greater than this.

There would almost certainly be substantial problems with supplying and handling such large volumes of material, and this might cause the rates to be lower than those

calculated. In addition, the recycling would work best with a continuous throughput, and it would become increasingly inefficient as the throughput became more intermittent. A heat storage unit could be used in place of a stack to compensate for this, but such a unit could only recycle half the energy at best that direct recycling between the stacks could achieve.

$$\frac{Q_1}{Q_1 - Q_2} = \frac{Q_1}{Q_1 - Q_2} = K$$

Where:

- Q_1 = heat of the stack that needs to be kept at temperature
- Q_2 = heat of the stack being cooled
- T_1 = temperature of the stack that needs to be kept at or raised to this temperature / Kelvin
- T_2 = temperature of the stack being cooled / Kelvin
- K = coefficient of performance

Formula 7: Definition of the coefficient of performance for a reversible heat pump [5].

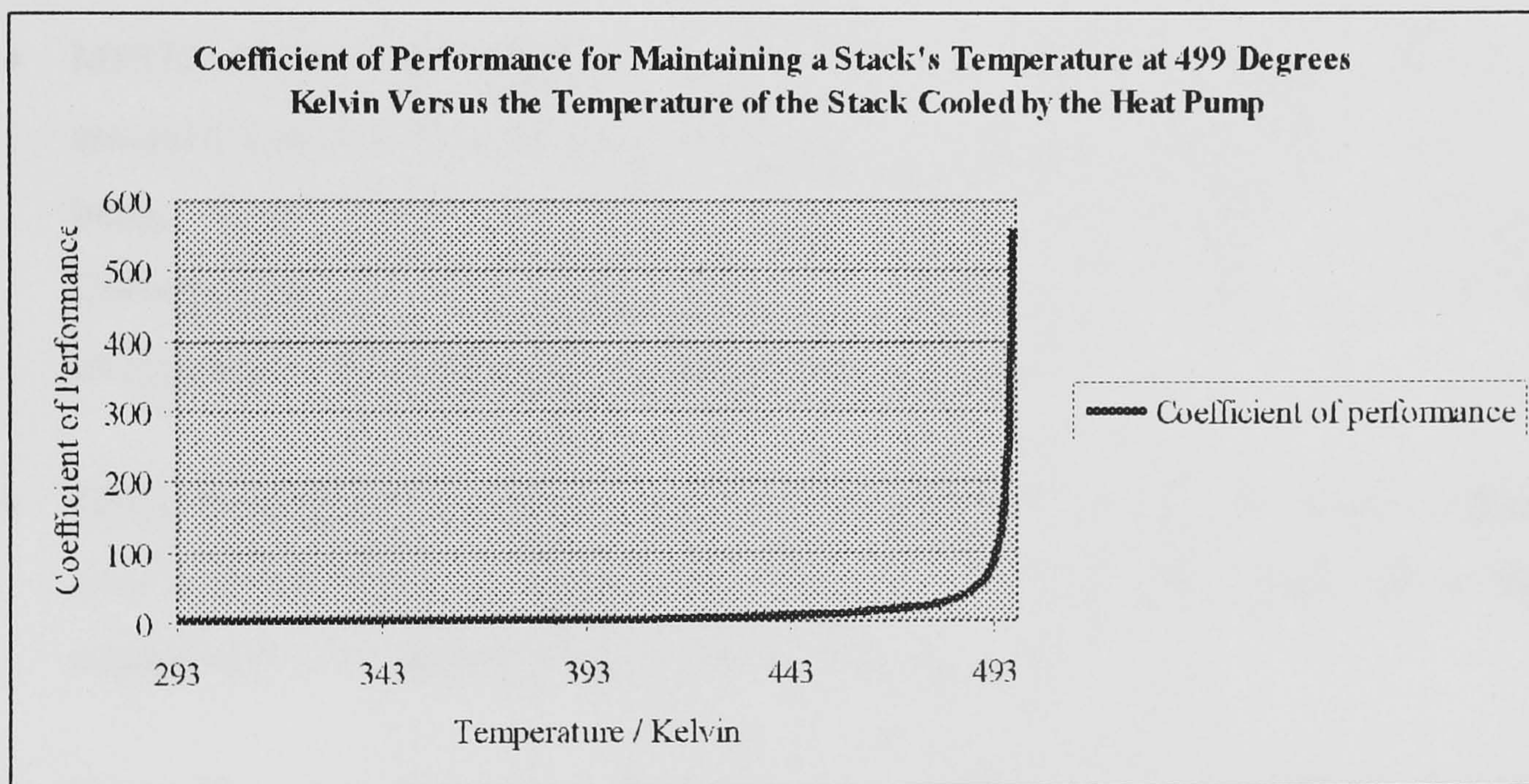


Figure 22: Coefficient of performance for maintaining a stack's temperature at 499 degrees Kelvin versus the temperature of the stack cooled by the heat pump.

5.4. Coating Materials

Coatings were made out of thermopolymers such as nylon (see Figure 23), polyethylene, polystyrene and acrylic, thermosets such as epoxy polyester, carboxypolyester and phenolic, metals such as bronze (see Figure 24), stainless steel

and solder and ceramics such as porcelain, molochite and zirconium silicate. This confirmed that thermography can be adapted to produce coatings of materials far more suitable for structural mass production applications than conventional thermographic or toner coating materials, which are brittle and have extremely low melting points (see Table 3) [5]. The exact formulae of conventional coating materials is not known, because the type and percentage of fillers, pigments, flow and levelling agents tend to be commercial secrets. Even so, most thermographic materials are based on polyester / co polyester resins, and toners tend to be based on polyester or styrene acrylate resins. In comparison to nylon and polyethylene these materials tend to have a low % of elongation break (see Table 4), and this is the cause of their apparent brittleness.

If DMC polyester were used, its high flexural modulus might compensate for its low % of elongation break. The conventional coating materials analysed and the reasons for selecting them are as follows:

- M9372 polyester resin toner is used in Lexmark desktop laser printers and it was assumed that this type of application would require the coating to be capable of being fused with relatively low temperatures and amounts of energy. Consequently, it was decided that this coating would indicate the lower temperatures and energy needed to process a coating.
- Gloss Supaflow is a general-purpose thermographic powder designed to flow over a broad range of temperatures and energy levels. This would allow the capabilities of a general-purpose coating to be defined.
- Laser Resist thermographic powder is intended for use in producing coatings resistant to the temperatures and energy involved in many types of electrophotographic printers. This would allow the principles underlying the resistance to be defined.

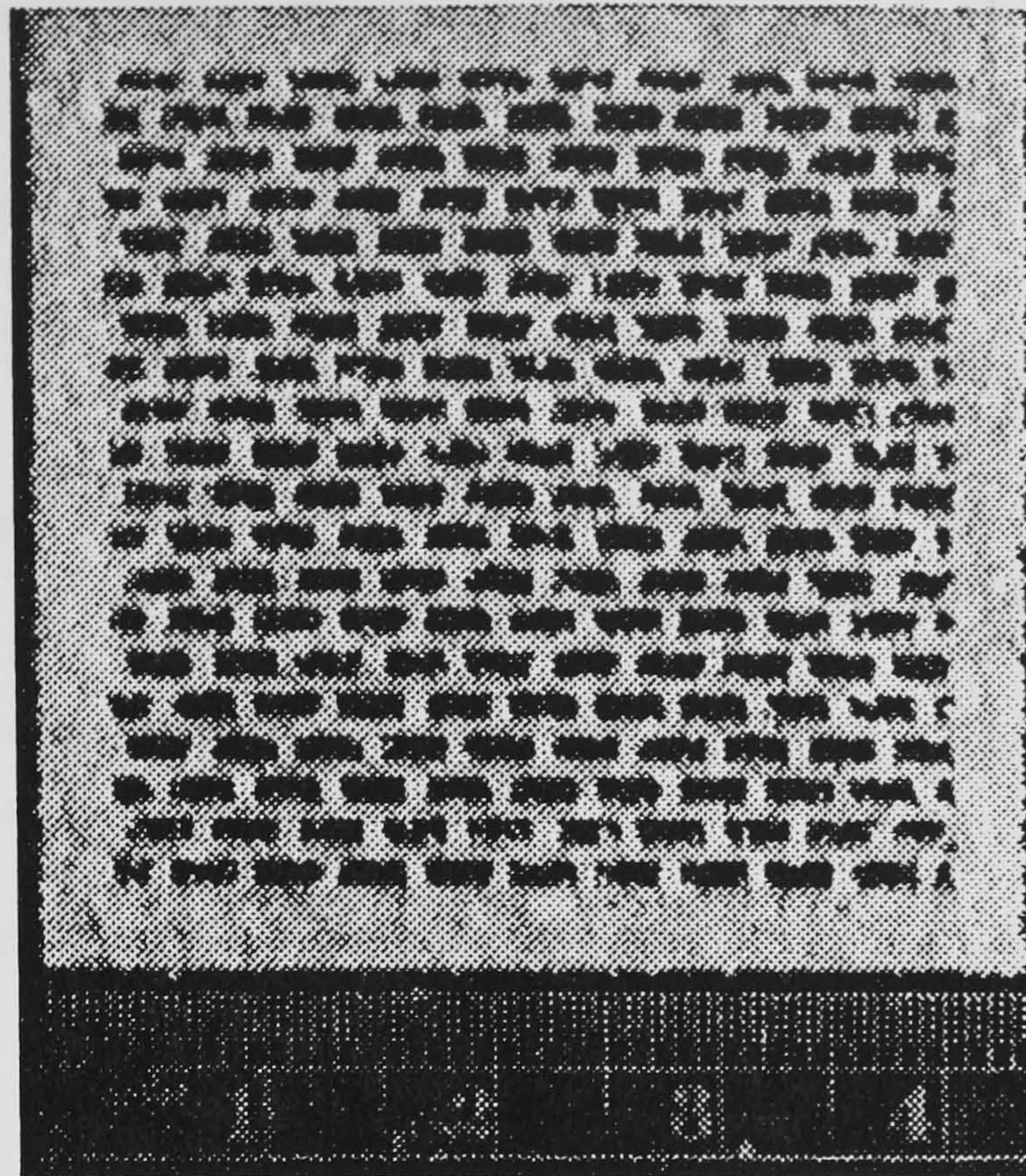


Figure 23: A 40 mm² 720 micron high (or thick) over thermographed coating produced with a 5 to 40 micron distribution of nylon 12 and a 40 to 250 micron distribution of Microcoat nylon 12.

The coating shown in Figure 23 has an average height (or thickness) of 720 microns and it was thermographed once with a 5 to 40 micron distribution of nylon 12 and then twice with 40 to 250 micron distribution of Microcoat nylon 12.

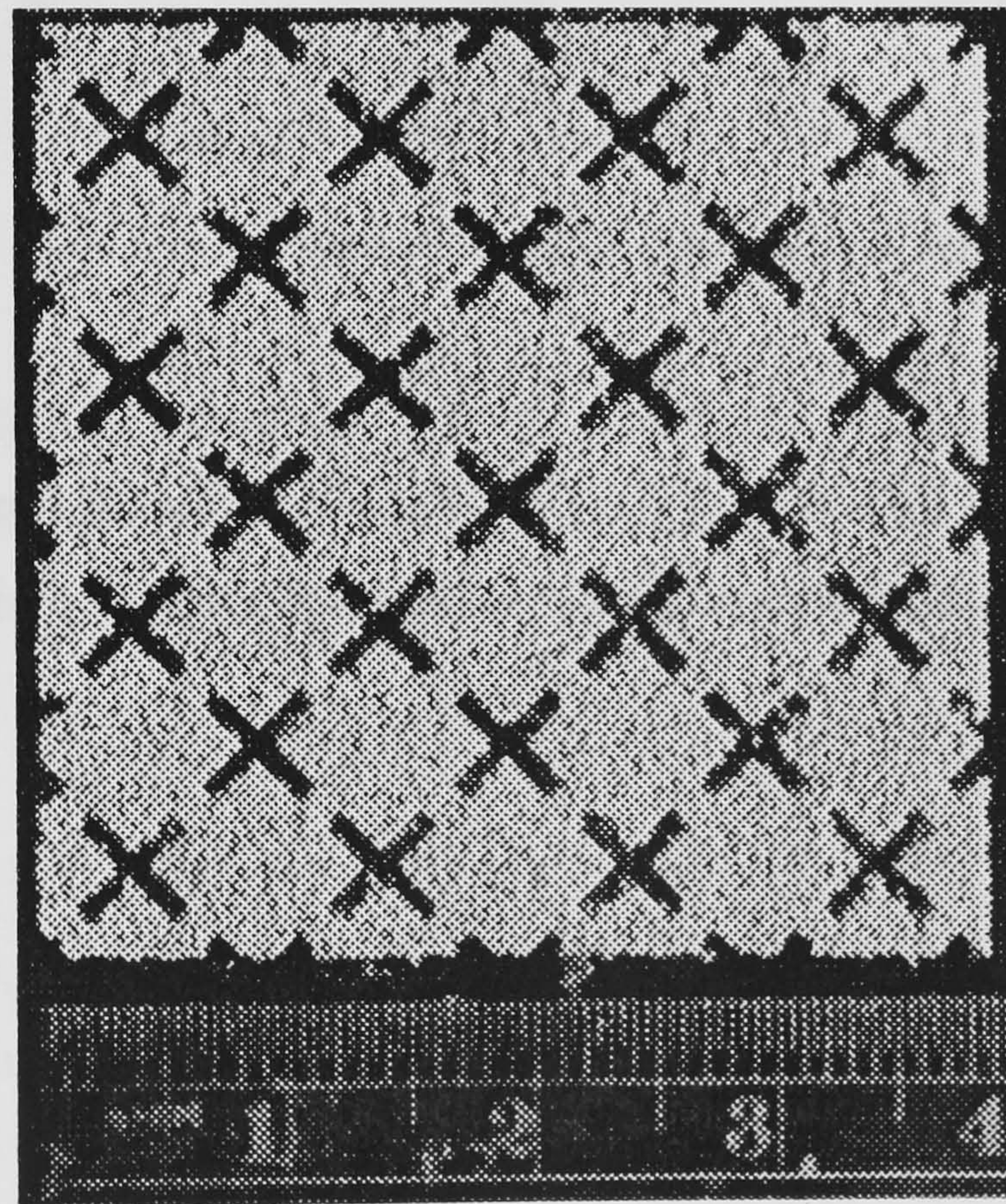


Figure 24: A 40 mm² 1370 micron high (or thick) over thermographed coating produced with 180 - 300 micron distribution of spherical bronze, bound with a -50 micron distribution of Mowiol 4-88 (PVA).

The coating shown in Figure 24 has an average height of 1370 microns and it was alternately thermographed with the PVA and bronze. This was repeated until there were three coatings of each of these.

Printing Materials	Melting onset point / °C	Melting / °C	Peak melting / °C	Ending melting / °C	Melting ends / °C
M9372 laser printer toner	69	72	78	84	87
Gloss Supaflow	43	53	67, 101 (two peaks)	117	121
Laser Resist	44	68	79	90	94

Table 3: Melting thermal transitions involved in DSC plots of Laser Resist and Gloss Supaflow thermographic powder and M9372 laser printer toner [5].

	Tensile strength (MN/m ²)	Flexural modulus (GN/m ²)	% Elongation at break
Polyethylene (HD)	32	1.2	150
Nylon 66	70	2.8	60
Acrylic	70	2.9	2
Styrene	40	3	1.5
DMC (polyester)	40	9	2

Table 4: Mechanical properties of different coating resins [9].

Colour and tonal coatings have also been produced and composite coatings made of sections containing different materials have been formed with over-thermographing. This may substantially broaden the number of applications for the systems.

5.5. Support

In many situations, it was necessary to thermograph a water-soluble resin around the most delicate coatings, so that the resin supported the coatings when they were peeled off the substrates (see Figure 25). When this was not done it was found nearly impossible to peel the coatings off without irreparably damaging them [5].

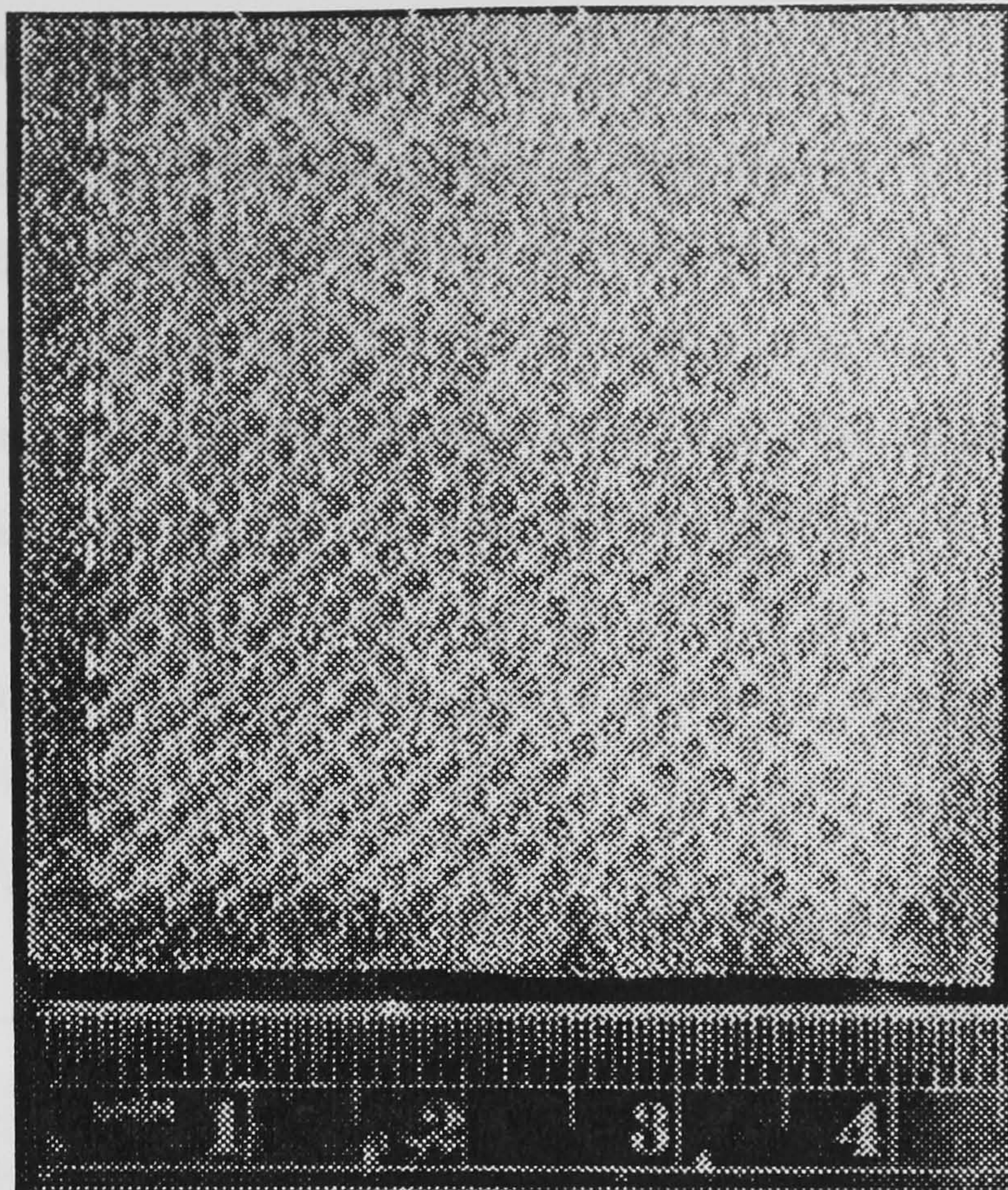


Figure 25: A 40 mm² coating made of water insoluble part material (gold coloured material) and water-soluble support material (clear or white lattice).

Figure 25 shows a coating made with a 50 to 80 micron distribution of E2016 methyl methacrylate / n butyl methacrylate (water insoluble resin) and a -50 micron distribution of Mowiol 4-88 (water soluble resin). The Mowiol is the gold coloured material and the E2016 is the clear or white lattice. The former is 100 microns high while the latter is 150 microns high.

5.6. Height

It was found that, depending on the particle distributions used and the type of material, coating heights ranging from 50 to 750 microns were achieved in one pass. The 50 micron coatings were produced when SB 0425 polystyrene powder with a mean particle size of 25 microns, fine (5 to 40 micron) powder coating of nylon 12 or low density polyethylene with a mean particle size of 25 microns were used, and the 750 micron coatings were achieved when 180 to 600 micron bronze spheres were used. However, in many cases the coatings needed to be over printed and thermographed again to improve the mechanical properties of the coatings so that they could be peeled off the substrates easily [5].

5.7. Resolution

Dependent on the particle distribution used, coating resolutions ranging from 42 to 1000 dots per inch (dpi) have been achieved in the study. The 42 dpi was achieved with 600 micron bronze spheres and the 1000 dpi with powder that had a 25 micron mean (see Figure 26). This also demonstrates that thermography is capable of producing coatings with a broad range of powder particle sizes, and this could be used to increase the deposition rates [5]. Figure 27 is an example of an SB 0425 polystyrene coating made with a mean particle size of 25 microns. It was calculated that the coating has a resolution of around 1000 dpi. Similar resolutions have been achieved with polyethylene, nylon and polystyrene.

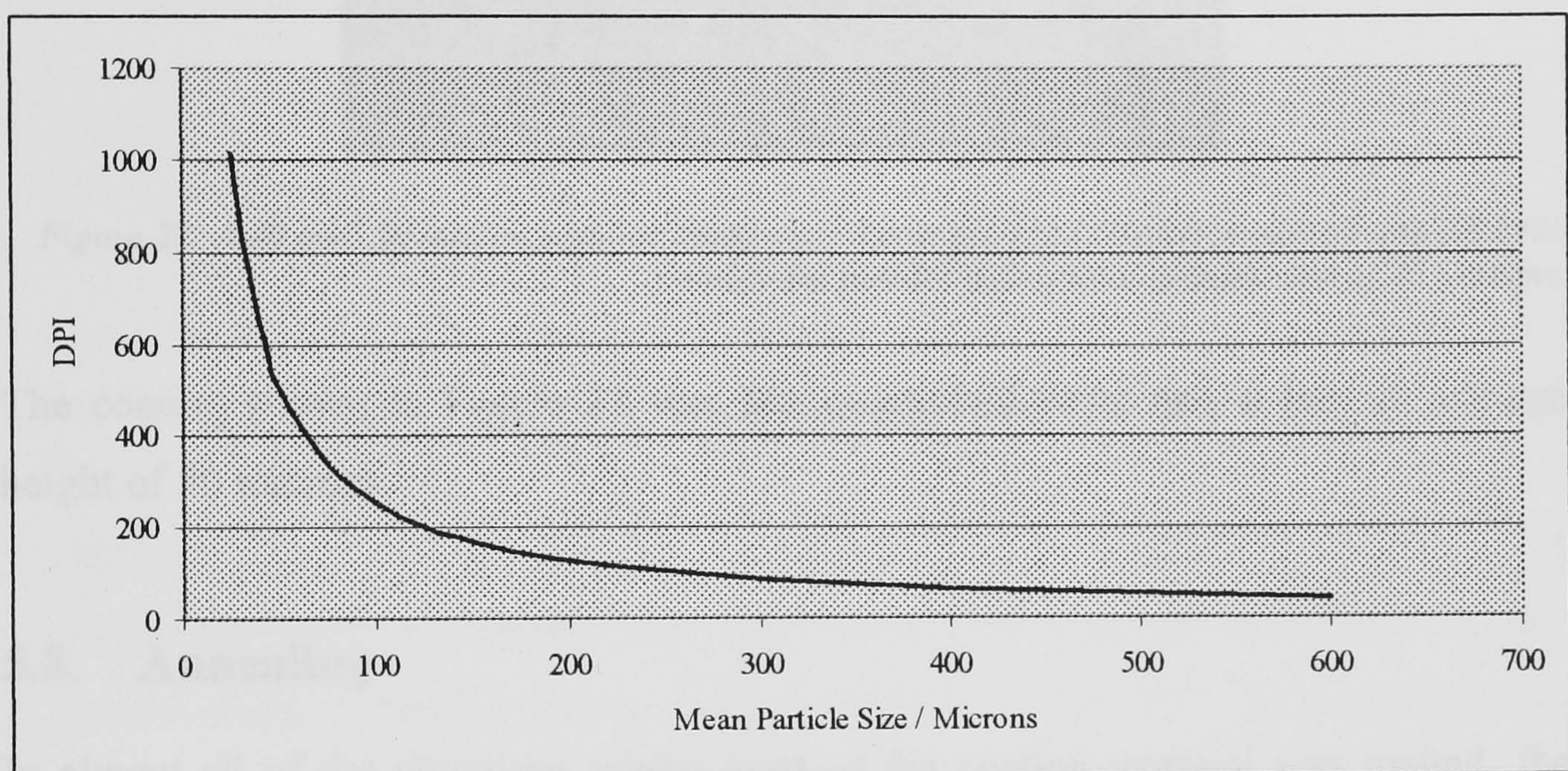


Figure 26: Coating resolution versus mean particle size of the powder coating.

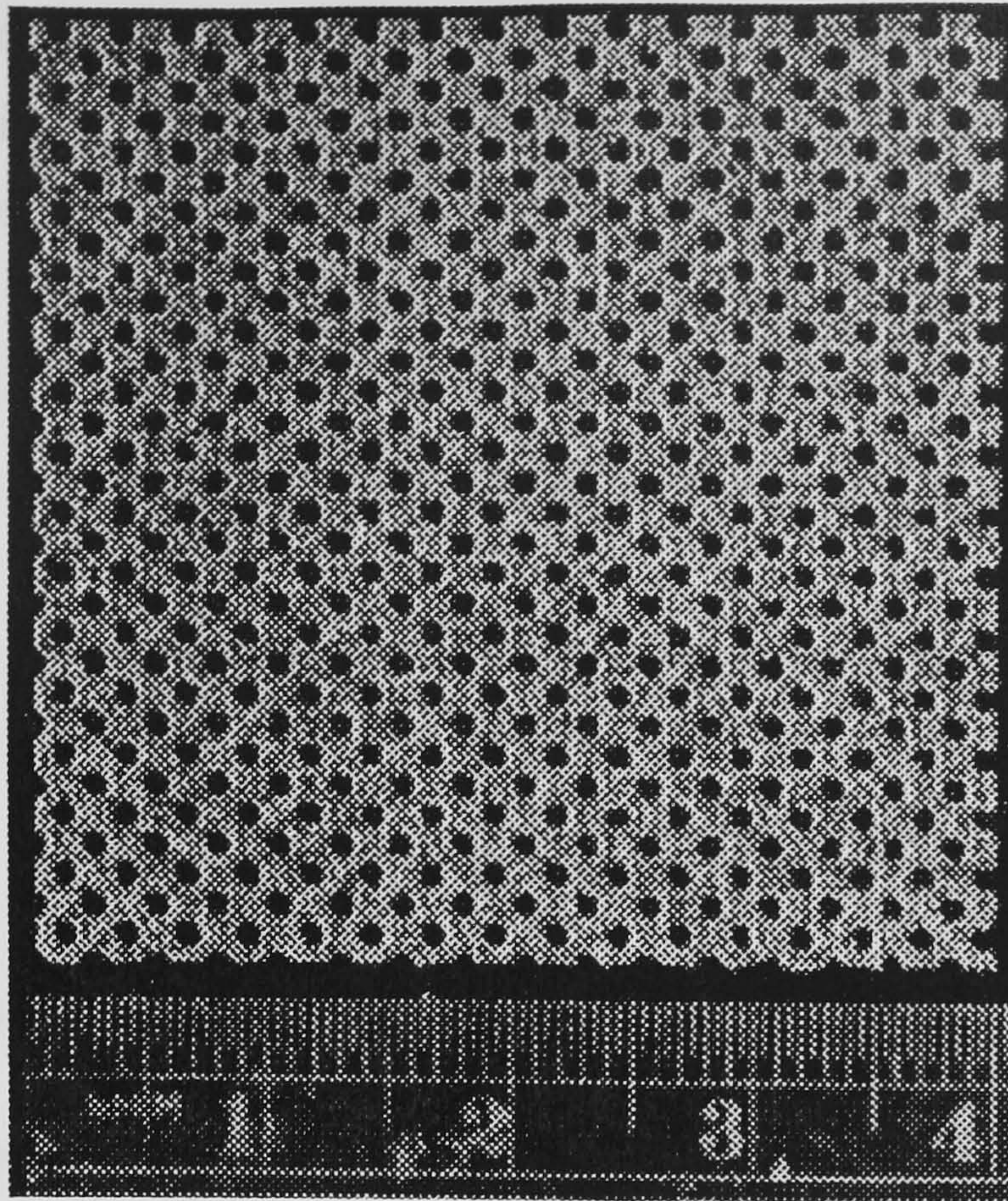


Figure 27: A 40 mm² 50 micron high (or thick) over-thermographed coating produced with SB 0425 polystyrene powder with a mean particle size of 25 microns.

The coating shown in Figure 27 was thermographed twice and it has an average height of 50 microns.

5.8. Annealing

In almost all of the situations where most of the coating material was melted, the coatings then needed to be clamped flat and annealed for 2 minutes to remove stress and prevent distortion. In the worst situations, when this was not done, coatings would curl up and peel off the substrates [5]. Consequently annealing must be considered as an extremely important part of the process. It is recommended that further study should be undertaken to define schedules to optimise the annealing for each of the coating materials.

The need for annealing is well known and with many types of manufacturing processes it is crucially important that it be used to remove stress, because otherwise these processes cannot make parts that have the accuracy and durability dictated by many applications. Stresses can arise from a number of sources, but key causes

include differential flow patterns in moulding, sharp wall transitions, different wall thicknesses, machining, polishing, hammering, flexing and compressing [11 and 12]. If SFF systems were to be speeded up for use in mass-production, similar problems with stress would almost certainly become a substantial limiting factor on the speed of the systems unless fast annealing processes were developed and the processing of coatings in a stack may allow for this development (see section 5.3 and 5.3.3).

Usually annealing is a secondary operation that can remedy certain stress imbalances. It is accomplished by exposing the part to elevated temperatures for extended periods of time.

The benefits that may be obtained from annealing are as follows:

- Improved Chemical Resistance: as in parts made of polycarbonate and polysulfone [10].
- Smoother Surface Finishes: PEI like many amorphous (transparent) plastics may be annealed to minimize stress crazing; Torlon® PAI also benefits from this [10].
- Better Flatness & Tighter Tolerance Capability: extremely close-tolerance parts requiring precision flatness and non-symmetrical contours sometimes require intermediate annealing during their manufacture. For this the manufacturing process needs to allow intermittent annealing [10].

Table 5 shows a typical annealing schedule and environment for removing moulded or machined stress from nylon 66 parts. If this data were related to 100 micron high SFF thermographed coatings the heat-up time would not be needed because the coatings would already be molten. The hold time would be 28 seconds and, considering its comparatively low height, it might be possible to allow it to cool in 2 seconds or less. Extended cooling periods tend to be associated with preventing excessive thermal gradients from causing stress or thermal shock damage in the coating or part [11 and 12]. As remarked earlier, since the time involved in annealing can affect manufacturing efficiency and production rates it is recommended that the

different requirements and methods for annealing be investigated further to define their potential effect on SFF thermography.

	Heat Up	Hold	Cool Down	Environment
Nylon 66	4 hours to 176 degree centigrade	30 minutes per 6 mm thickness	10 degrees centigrade per hour	Oil or nitrogen

Table 5: Annealing schedule and environment for removing the stress from nylon 66 parts [10].

5.9. Compression

Compression was considered as an addition to the thermographic process that would increase the density of a coating. It was decided that except where fine powders are being used, it is preferable not to use compression, because the distortion that it causes increases as the volume of material displaced by the compression increases particularly when coarser powders are used. Software could possibly be developed to alter the printed image in order to compensate for this, but it would probably take a lot of time to perfect. At present, it is expedient to over print and re-thermograph the coatings to increase density [5].

6. Stacking Registering and Bonding

The Stacking Registering and Bonding [6] submission is concerned with the construction of three-dimensional parts made of thermographed coatings. It was decided that joggers similar to those used in the pad and book making should be used for the stack and registering involved in forming high parts out coatings. This necessitated the invention and use of a two-dimensional support structure, which involved surrounding each part coating with a support containing edge features (lay edges) that are the male or female counterpart of a registration feature within the jogger. The supports may be formed by the SFF thermographic process or by another process and they allow the coatings to be placed in the jogger and vibrated so that the edge features (lay edges) of the supports fall concurrently into register on the jogger's feature thus registering the supported part coatings. A novel method for bonding the coatings in parallel also needed to be invented and assessed, because of the use of the concurrent registering. A description of the main findings and recommendations derived from this submission are summarised in the following sections.

6.1. The Need for Stacking and Bonding

The need for peeling the coatings away from their substrates was assessed. It was found that, dependent on the materials used, it was possible to make 1.5 mm parts by over-printing and re-thermographing the coatings (over thermographing them). This means that as long as the parts are around 1.5 mm high, there may be no need to resort to peeling off coatings and stacking and bonding them. This has allowed short and low relief parts to be made without stacking and bonding [6]. There is a large market for parts such as gaskets, circuit boards, floorings and labels that would fit into this height range [13 to 19]. It is likely that over thermographing might be used to replace processes such as etching, stamping, embossing and cutting. Figure 28 shows that even parts made of disconnected components can be made in this way.

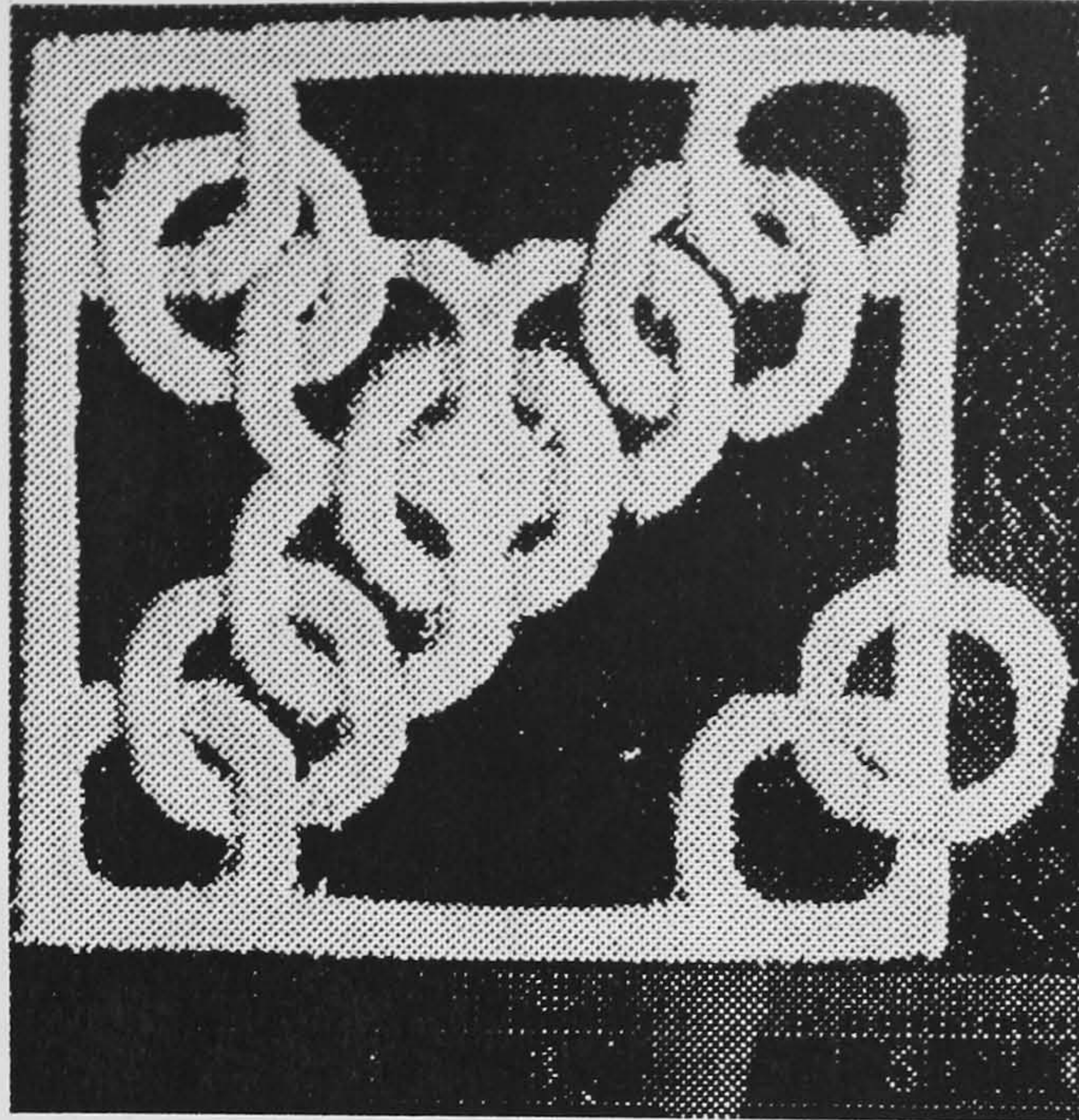


Figure 28: A 50mm² 750 micron high (or thick) part made of disconnected polyethylene components that were produced by over thermographing.

In Figure 28 the sections of the coating that would otherwise connect were over thermographed with Aquazol (Poly (2-ethyl-2-oxazoline)) so that the Aquazol could be washed away with water to release the components.

6.2. Placing and Registering Coatings

It was found that if parts higher than 1.5 mm were needed they could be produced by peeling the substrates away from the coatings and stacking and bonding the coatings. Two methods were examined, consecutive lamination and the parallel stacking, registering, peeling and bonding of coatings with paper joggers. Joggers are commonly used in book and pad making and they have not previously been used in SFF manufacture. Joggers usually work by vibrating the pages in parallel onto a right angle edge and then the pages are bound to form books or pads [6].

6.2.1. Consecutive Lamination

Figure 29 shows a system of two lamination units. The first unit uses a roll of coated substrate (1) that unwinds and feeds coated substrate under a transfer roller (2) thus transferring the coating to the stack (3) held on the flat base (4). The stripped substrate is then wound onto a roll (5). The second unit (6) transfers a coating on top of that previously transferred by the first unit (1, 2 and 5). The stack and flat base move (7) relative to the units, to allow the transfer, or the units may move (7) instead [6].

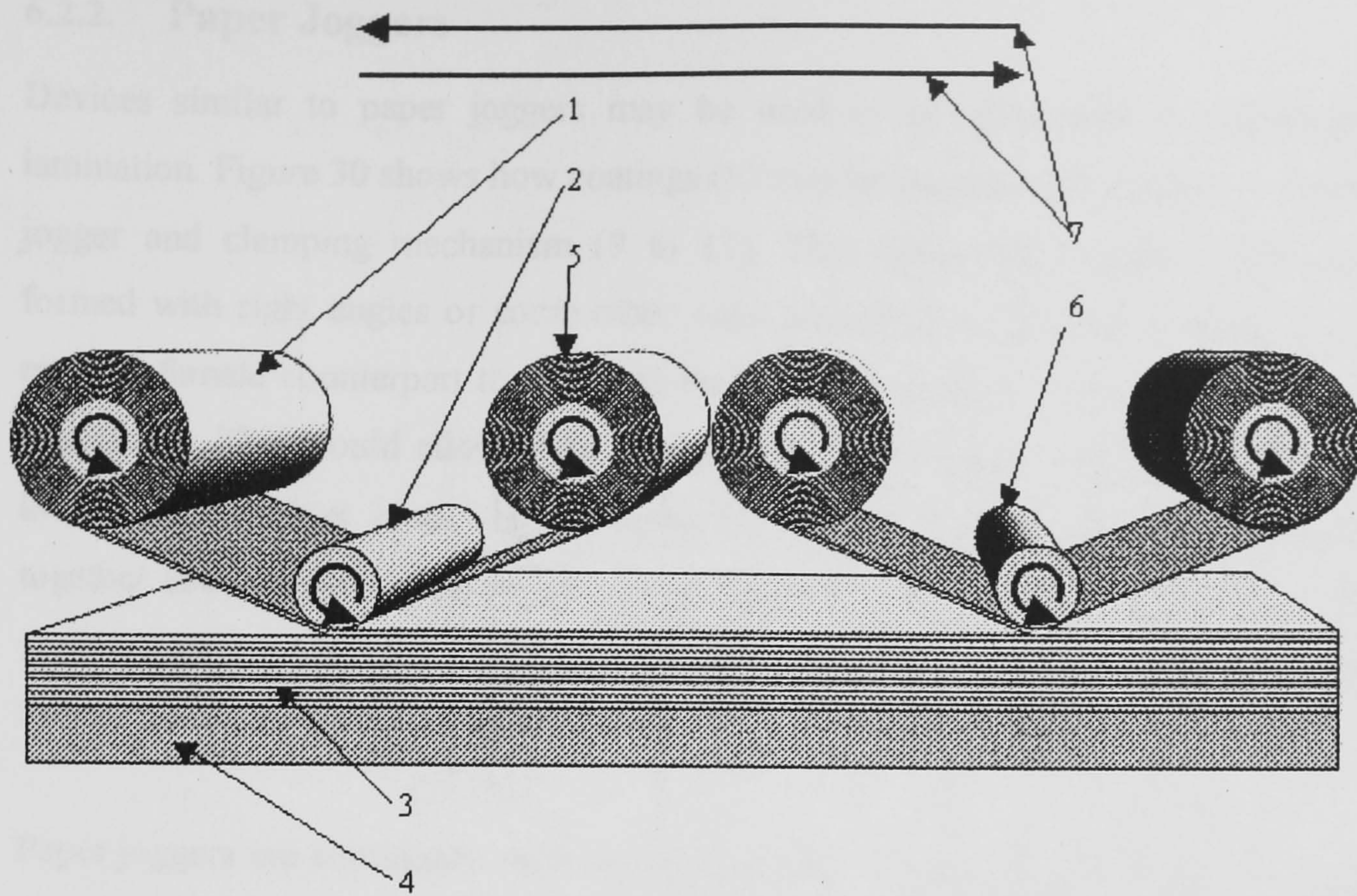


Figure 29: Multiple transfer lamination system [6].

In theory, as many lamination units as required could be used. Consequently, the time taken to construct a part would be limited only by the number of units possible in the length of the system, and its relative traverse speed in relation to the stack. A feed system, similar to that used in cut sheet paper feeders, could be used instead of the roll to roll laminating unit shown, and in this instance, the time would be limited by the relative traverse time of the units [6].

The practicality of using multiple units goes down as the number of units increases, because of the capital cost and set-up times. In addition, it is probable that the time required to compensate for misregistration or inaccurate transfer, and the costs of resultant waste would increase [6].

The geometry of many types of parts may require 1000 or more layers to be laminated on top of each other. If a system were to be capable of laminating all of these coatings in series, there would nearly always be a lot of work in progress, and if it were used intermittently its under-utilisation would increase dramatically. This would probably have a detrimental effect on lead times, manufacturing flexibility and inventory control. Consequently, it was decided that it was inappropriate to use consecutive lamination or transfer for stacking and registering the coatings [6].

6.2.2. Paper Joggers

Devices similar to paper joggers may be used as an alternative to consecutive lamination. Figure 30 shows how coatings (8) may be registered in parallel in a paper jogger and clamping mechanism (9 to 11). This necessitates coatings (8) being formed with right angles or some other edge feature (lay edges) that would be the male or female counterpart to a feature made by the jogger's base (10 and 11) (see Figure 30). This would allow them to be placed in the jogger and vibrated, so that they settle in register. In the study, a clamp (9) was then used to force the coatings (8) together and to hold them in register (see Figure 30) [6]. The parallel nature of this approach necessitated the invention of a method for bonding the coating in parallel and this is described in section 6.2.3.

Paper joggers are commonly used in book and pad making, and clamps would need to be added to them so that they were similar to Figure 30. If necessary, the registered coatings could then be bonded while they were in the jogger, or the clamped coatings could be removed to another device or to an area where the bonding could be performed. Depending on the sheet material being registered, many types of desktop paper joggers can register 500 sheets in less than 5 seconds. If this method were used to stack and register coatings, it would be very fast because everything would be performed in parallel. Depending on their sheet capacity, joggers tend to be priced at between £150 and £600, so it might be relatively inexpensive to register coatings in this way [6]. The capacities of many types of office paper joggers are limited to registering 500 40 to 100 grams per square meter A4 sheets. However, multiple bin joggers capable of registering 10 or more stacks that are each composed of 500 sheets are available, and if these were used the registering rates might be substantially increased [6]. The parallel nature of this registration necessitated the invention of a method for bonding the coating in parallel and this is described in section 6.2.3.

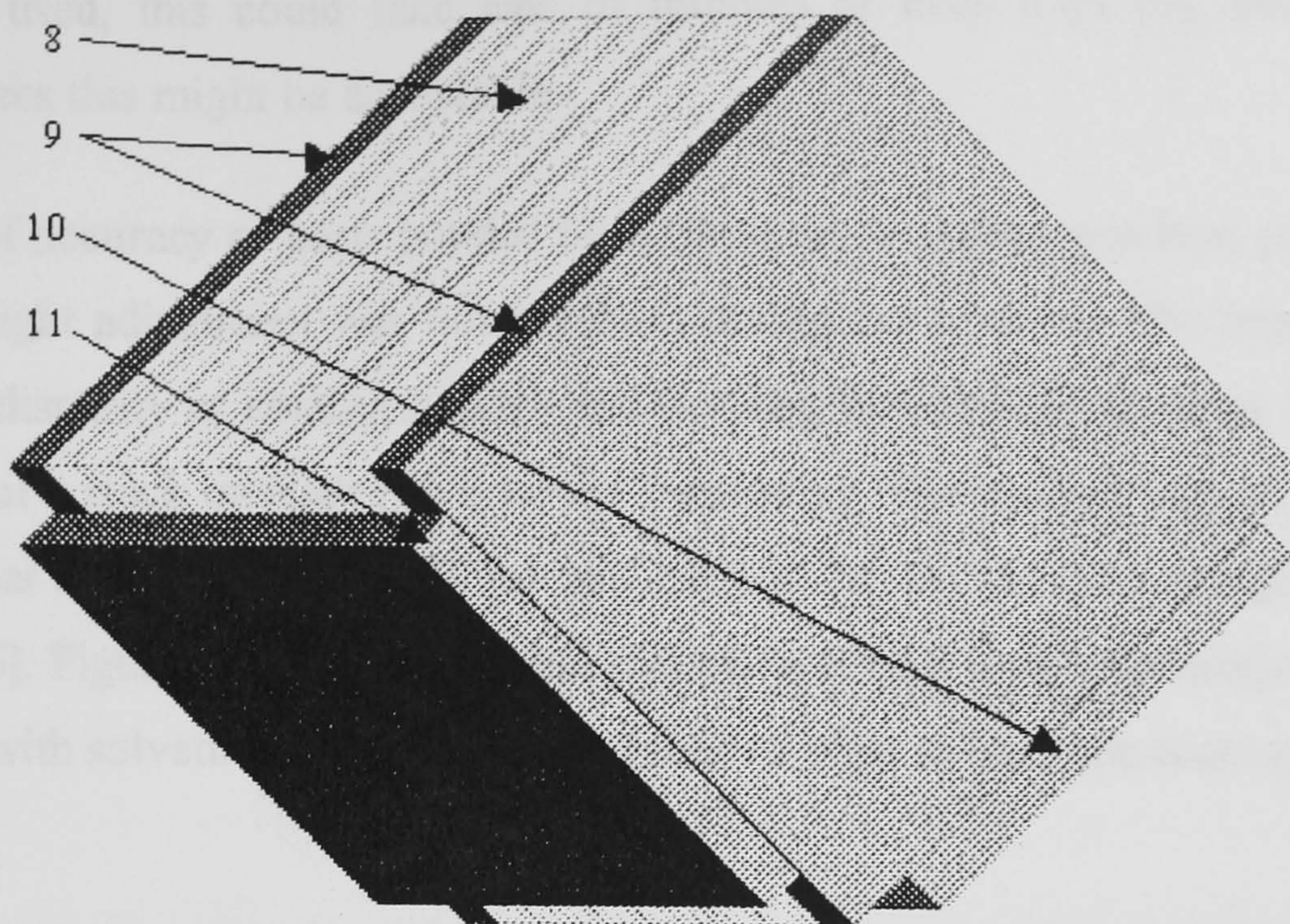


Figure 30: Parallel stack and registration with the aid of a paper jogger and clamping mechanism [6].

6.2.3. Bonding

It was found that if a clamped stack of registered coatings was left in an atmosphere containing a solvent vapour it caused the part coatings to bond together. This was achieved with coatings made of water-soluble resins such as Mowiol 4-88 and Aquazol (Poly (2-ethyl-2-oxazoline), and it is likely that the principle is applicable to other solvent and resin combinations. It tended to take to take around 12 hours to bond the coatings when there was average 62% relative humidity. It is possible that by increasing the humidity the time could be reduced, though it may be preferable to allow slow bonding, in order to limit the possibility of distortions occurring. The high level of work in progress that might be associated with this method of bonding may be acceptable, because expensive equipment would not be involved. It is even possible that the bonding could take place during transportation [6].

Infiltration of solvent was also examined as a bonding method and it was found that this would also bond clamped stacks of registered coatings into a part. It was difficult to control, because the coatings tended to distort when too much solvent was applied or when too much infiltration time was allowed. Time also had to be allowed for the solvent to evaporate, and dependent on the size and geometry of a part and the type

of solvent used, this could take tens of minutes or even days [6], but in some circumstances this might be acceptable.

The level of accuracy of parts bonded by infiltration or vapour was low, presumably because height adjustment was not involved during the bonding. The inaccuracy is caused by disparity in coating heights and bonding between the coatings and so, as the height of a stack increases so does the inaccuracy. The method may be sufficient for parts that are not very high or for applications that do not require high levels of accuracy [6]. Figure 31 shows a part that was made from a stack of coatings that were infiltrated with solvent which was then evaporated away to bond the coatings.



Figure 31: E2016 (methyl methacrylate / n butyl methacrylate) / Mowiol 4-88 coatings bonded together to form a 49 x 29 x 3 mm part [6].

It was found that a part could be divided into a number of relatively short stacks that could be bonded at the same time as using compression to adjust their heights. The resulting sections were then bonded with solvent infiltration. This proved to be a faster and more accurate way for assembling high parts than bonding all of the coatings together in a high stack. This is because of the adjustment of compression

and the fact that there was more area through which the solvent could penetrate and evaporate [6].

Parallel heat welding, selective heat and solvent welding and bonding methods were also conceptualised [6]. This indicated opportunities to produce developments that would meet nearly all the requirements to be found in solid free form manufacture.

6.2.4. Height Adjustment

It was decided that if the height adjustment needed were very small and it was to involve removing any irregularities on the surfaces of the coatings then abrasion was probably the only subtractive adjustment method that could achieve this. Figure 32 shows an arrangement for performing the abrasive adjustment which involves collating plates (119) and sheets (120) with a coating or coatings (121 and 122) attached, shims (123) that restrict the height of abrasion and a support (124) that holds an abrasive (125), to form a stack. The compression (126) of the stack presses the side of the support (124) containing the abrasive (125) onto the surface of the coatings (121 and 122). The compression (126) brings the surface of the support (124) without the abrasive into contact with the shims (123). This restricts the height of the subsequent abrasion. The plates (127) ensure that the pressure (126) is evenly distributed across the stack, and the support (124), with abrasive (125) on it, is then vibrated (128). This causes abrasion of the surface of the coating or coatings (121 and 122) down to the height that the restriction allows. It is preferable though not crucial, that the plates (127) sheets (120) and shims (123) be held together by pins or bars (129) during the vibration. This might be achieved by sliding the pins or bars (129) through holes in the materials. A number of these arrangements may be registered in a jogger so that a number of parts can be registered, bonded and height-adjusted in parallel and if necessary the function of the shims may be performed by another type of height control device (see Figure 32).

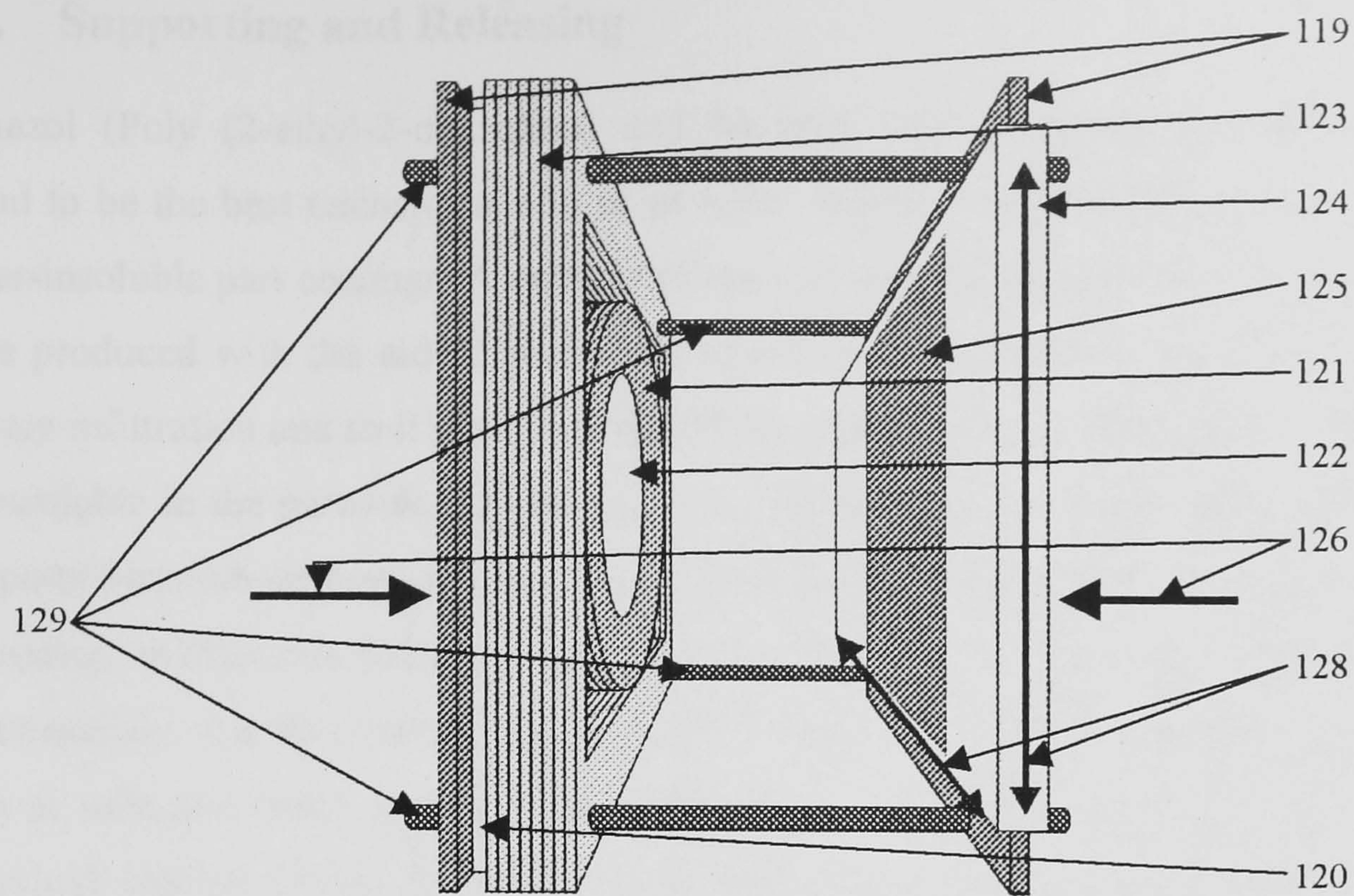


Figure 32: An arrangement for performing the abrasive height adjustment of coatings

6.3. Collating

Previous sections have mentioned the need for collation. It was decided to examine the speeds that could be achieved using various types of collators. This is important because collation may become a bottleneck in solid free form manufacture of parts. Industrial systems such as Setmasters' DuoMotion flat bed conveyor can collate over 6000 SRA2 sets per hour, fed from 16 to more than 100 stations [6]. CP Bourg's Modulen collators and A2 models can also exceed 6000 sets per hour, fed from 4 to more than 100 stations [6]. These systems are extremely robust and it is claimed that they are capable of collating paper, vinyl and even chipboard [6], so they would be more than capable of collating the coatings involved in this study.

Less expensive office collators such as Duplo's DC-Micro Collator are capable of producing 25 A4 sets per minute, fed from bins [6]. These types of systems are only designed to handle 64 to 80 gsm paper, so they would probably be unable to collate thick coatings.

6.4. Supporting and Releasing

Aquazol (Poly (2-ethyl-2-oxazoline) and Mowiol 4-88 (polyvinyl alcohol) were found to be the best resins to use in or as water-soluble support-coatings to support water-insoluble part coatings. A number of stacked and bonded parts 4 to 10mm high were produced with the aid of such support coatings. These parts were bonded by solvent infiltration and so it is recommended that in this instance the support coatings be insoluble in the particular solvent used. It was found that the best way to release the parts from the support coatings was to dissolve the coatings with a water jet, and depending on their size and geometry this could take from 10 minutes to an hour [6]. Consequently, it is recommended that in order to accelerate the releasing filler materials such as salts and resins such as gum Arabic [8] that are more soluble in water than polyvinyl alcohol (PVA) be examined as additions to or alternatives to the PVA support material. At 20 degrees centigrade, 100 grams of water will dissolve 145 grams of potassium iodine (KI) or 38 grams of potassium chloride (KCl). In contrast, during the study when trying to dissolve 20 grams of powdered Mowiol 4-88 (PVA) in 100 grams of water at 20 degrees centigrade without the aid of agitation, only part of the powder was dissolved and the rest formed sludge at the bottom of the water, even after four hours. This is probably because its long chain structure caused it to conglomerate, so the addition of salt which does not have such a structure, might substantially reduce the problem. Figure 33 shows a part that was made out of a stack of part and support coatings. Solvent was infiltrated into the stack and then allowed to evaporate and this bonded the part coatings. The support coatings were then dissolved away with a water jet, and this allowed the part to be released in around 10 minutes.

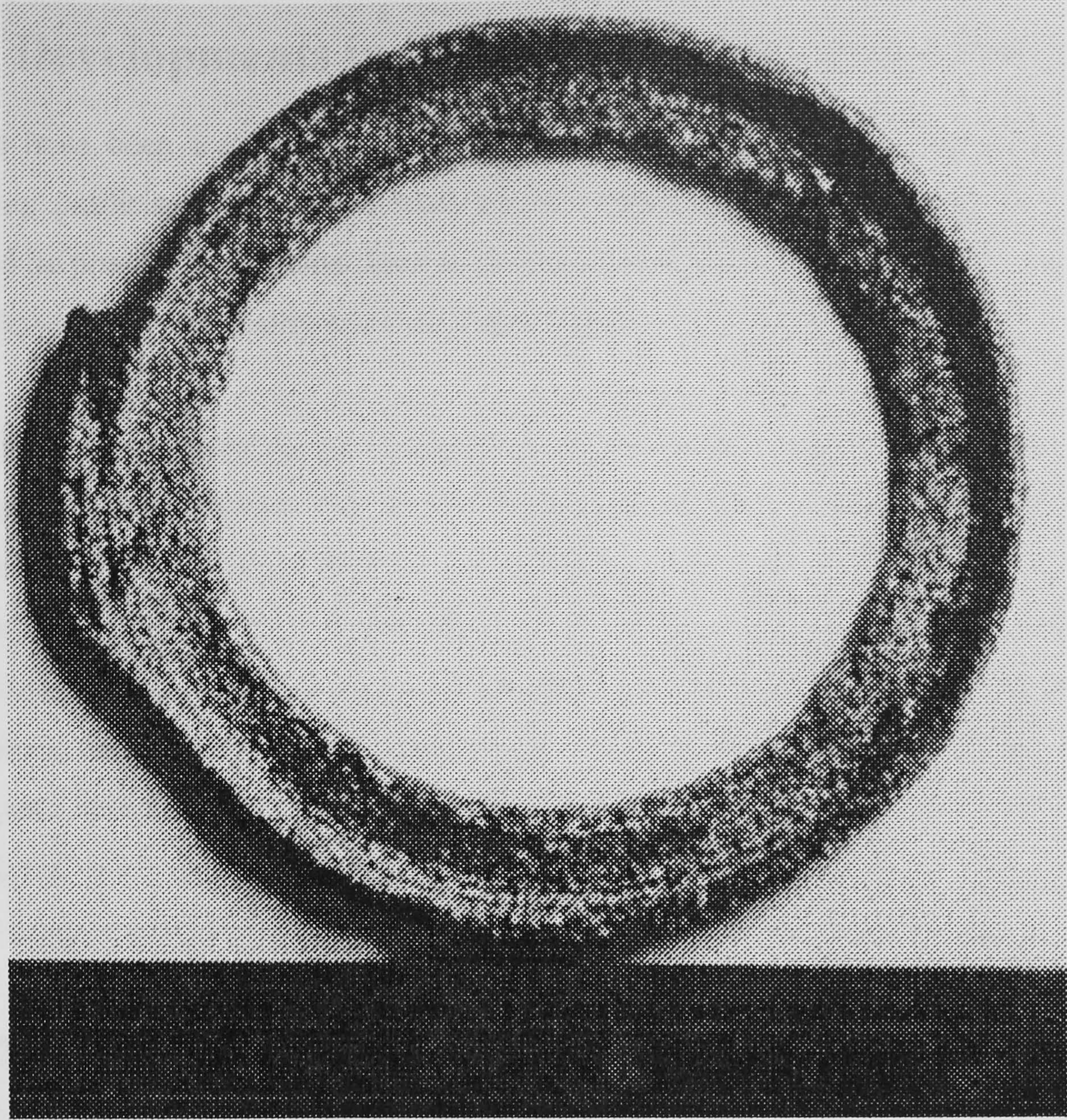


Figure 33: A 52 x 50 mm 4mm high (or thick) polyethylene, molochite and E2016 (methyl methacrylate / n butyl methacrylate) part that was released from an Aquazol (Poly (2-ethyl-2-oxazoline) water soluble support structure by washing [6].

7. Developments in SFF Manufacture and Printing

There have been a number of developments in the field of SFF manufacture and printing publicised near to the study's completion date and it was decided that it would be prudent to examine these to define the implications and the effect that they may have on the originality and future development of the study's inventions.

The SFF developments do not duplicate or invalidate the technology invented during the study (see sections 7.1 to 7.1.8), though Japanese patent JP2001308126, concerned with printing solder on circuit boards, does infringe one embodiment of patent GB9927127.2, PCT GB00/04359 filed during the study. The priority date for this study's patent is before that of patent JP2001308126, which gives an opportunity to inform the Japanese patent examiner that patent JP2001308126 is invalid. The company that filed the patent may then wish to licence the study's patent. This, combined with extensive searches of various international patents, involved in the final stage of applying for grants substantiates the newness of the technology.

On the basis of this companies were offered information that confirms the novelty of the technology, which hopefully will encourage the confidence necessary for commercialising the technology.

7.1. Solid Free Form Developments

The diversity of developments in the field of SFF manufacture corroborates the assessment made in section 2.1.1 that the future SFF market is likely to be more fragmented than in the past, and confirms the novelty of SFF thermography. The most innovative developments are described in the following sections.

7.1.1. Additive/Subtractive Material Processing for Mesoscopic Parts

Mesosopic additive/subtractive material processing (Meso A/SMP) integrates silicon processing, hot pressing, casting and traditional machining methods and is used to produce parts that are between macroscopic and microscopic in size (mm to micron) [20]. The production of this type of part seems to be the focus for

development of Meso A/SMP and is aimed at niche markets such as those needed to manufacture Micro-Electro-Mechanical Systems (MEMS).

7.1.2. Sand Painter

The Sand Painter is an automated version of the traditional Native American techniques that allow sand painting art to be produced [21]. This project is at an early stage, and it is almost certainly the case that substantial investment and development will be needed to speed the system up to the production rates that have been demonstrated with SFF thermography. In addition the system does not have a method for retaining the powder, and if it were speeded up there might be issues about controlling the powders so that they stayed where they had been deposited.

7.1.3. Contour Crafting

Contour Crafting is a system that involves the use of trowelling to create smooth surfaces on parts [22], and as such it may be added to SFF thermography and other SFF systems' processing to enhance the surface quality of the part produced.

7.1.4. Ice Part Fabrication

Rapid Freeze Prototyping involves jet printing water and freezing the printed water to form a part [23]. Water is almost certainly the least expensive build material that has ever been used in SFF manufacture. However, because ice melts relatively easily it is likely that this system could only be used to produce patterns for moulding or water-based confectionery items. In addition, if it were used to produce patterns, the pattern's temperature and high water content might dictate the need to develop specialised mould techniques.

7.1.5. Fast Ink Jet Based Process

A fast ink jet based process that involves printing thin shells that define the surface geometry of a part and rapidly applying build material into areas that form and support the part has been developed by I. Ederer, H. Seitz and A. Welisch. This process builds a thin shell layer and then molten build wax is deposited inside and around the layer by a roller. A smoothing and planing device is then used to level the wax and to reveal the shell so that the subsequent layer may be printed onto it [24].

The main limitations of this process are that the support material needs to be manually removed and this may be impossible if the part has inclusions.

7.1.6. Objet

Objet Geometries Ltd introduced its Quadra machine in March 2000. The machine is based on the jet printing of UV curable polymer [17] and so, as with the SLA machines, it is limited to using one class of material.

7.1.7. Controlled Metal Build Up

Albrecht Roders GmbH & Co KG has commercialised a system called Controlled Metal Buildup (CMB). This system involves selective steel wire laser cladding to deposit material and the milling of each clad layer to ensure the accuracy of the build [17]. The system is orientated towards making tools rather than finished products, and so it is unlikely that it will be used for mass-production applications.

7.1.8. Solidimension

Solidimension is developing a machine that laminates thin layers of plastic to form a part. The machine uses a knife mounted on an X-Y plotter to cut the layers from a roll of plastic and solvent welding is used to bond them together [17]. The main limitation of this system is the speed at which the X-Y plotter can move the knife and so even with extremely simple part geometries it is unlikely to be able to compete with the production rates of SFF thermography.

7.2. Printing Developments

The developments made in printing are primarily concerned with increasing the flexibility, speed, materials and/or resolution of printing [25 to 30]. It is likely that many of these developments could be used to support and enhance the technology invented during the study, and it is recommended that the developments be assessed for use. They may have implications which might allow the development of the flexibility, speed, materials and/or resolution of SFF thermography to be relatively rapid, because it uses off-the-shelf printing technology.

8. Commercial Exploitation

The study has been technically successful in terms of showing that the speed of manufacture necessary for mass-production can be met (see sections 6.2.2 and 6.2.3) but it is not yet known whether the resolution, accuracy and material properties of the products will meet the precise specifications of the end users of mass produced parts. This could impact on the commercial success of SFF thermography, and might limit it to being used in a low-value niche market. Foundations for commercialization are being laid and this will remove these uncertainties and define the potential for commercial success more clearly.

8.1. Plan

A company called “Rapid Manufacturing Systems Limited” (incorporation number: 4491437) has been formed and the company has submitted a SMART application for funding for an eight-month project to define the feasibility of commercialising SFF Thermography and a number of other SFF processes. The suitability for commercialisation will be defined by the degree of customer interest and commitment, and the technical capabilities in meeting their specifications. The most suitable process will be commercialised in the year after the project and it is anticipated that licence and share options would be offered for sale during the project so that the foundations are laid for this.

Following completion of the project, further commercialisation would involve developing products of the process for licensee-defined applications in different market sectors and encouraging the licensees to set up their own production facilities to sell the products into their sectors. At the same time the company would be promoting the processes by selling the products in sectors that had not been licensed. At this point it would be prudent to sell the products in a number of different sectors affected by different economic climates, because this would spread and thus limit the commercial risk to the company.

In order to encourage licensing and to generate further revenue, it might be useful to sell equipment and consumables for the process. Initially, it would almost certainly

be less risky to do this on a re-sale basis, because suppliers already exist, and the capital cost in manufacturing either consumables or equipment would be relatively high. Re-badging of equipment and consumables will be considered since it would assert and advertise the company's position in the market and a number of suppliers have indicated that they are willing to re-badge and install equipment free of charge in return for 60% of the sale price of the equipment. Anti trust laws may impede the effectiveness with which revenue can be derived from the sale of consumables, because an end user has the right to buy consumables from any supplier that they may wish to, and they might do this because they can obtain less expensive materials from other suppliers than the company. The only recourse would be to claim that a process's equipment warranty would be invalidated if another supplier's consumables were used. Even so, this might be contested and so it would probably be best to supply consumables in cartridges necessary for the operation of the process's equipment. This would allow the cartridges to be patented, so that if another supplier wished to supply consumables they would have to negotiate the rights to manufacture the cartridges. If necessary, the cartridges might be designed so that they could only be used once, to prevent them from being refilled with other materials.

8.2. Markets

The SFF market has been in existence since 1988 and has expanded rapidly. In the year 2000 the market for products and services was worth \$601.1 million and in 2001 and 2002 it is projected to be worth \$620 and \$680 million respectively [17]. 1320 SFF systems or process units were sold in 2000, and in 2001 and 2002 the growth of these sales is projected to be 6.4% and 12.5% respectively. In 2000, 3,004,006 parts were produced by the 6,755 systems installed worldwide.

Companies using solid free form manufacture are spread across most manufacturing industries [17]. Figure 34 shows a breakdown of the various market sectors by industry and institution. This indicates that greatest demand for the process may be found in the consumer products and motor vehicle sectors, so to generate high volume demand rapidly the company may initially market the process in these sectors [17].

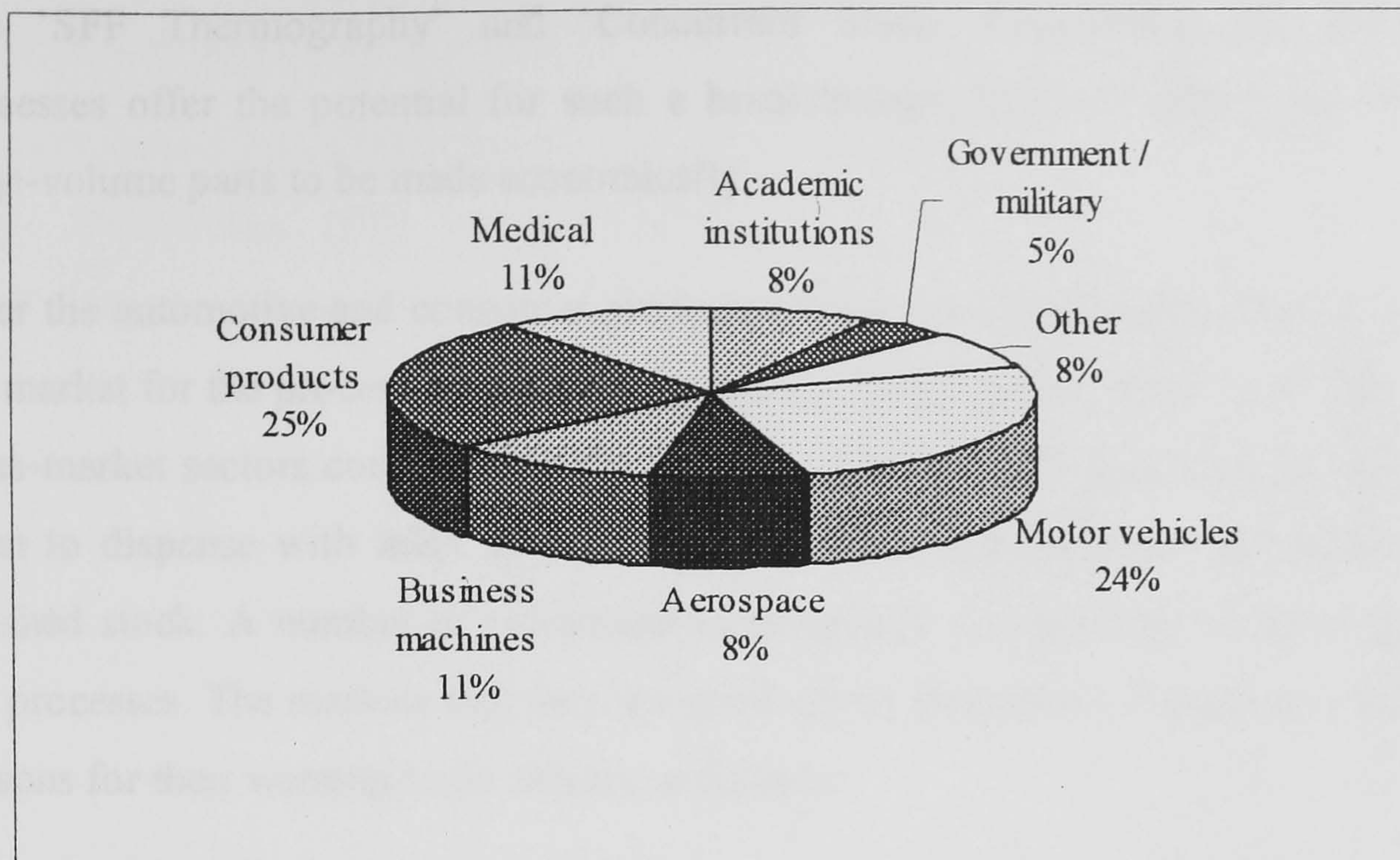


Figure 34: Market sectors for SFF manufacture in 2000 [17].

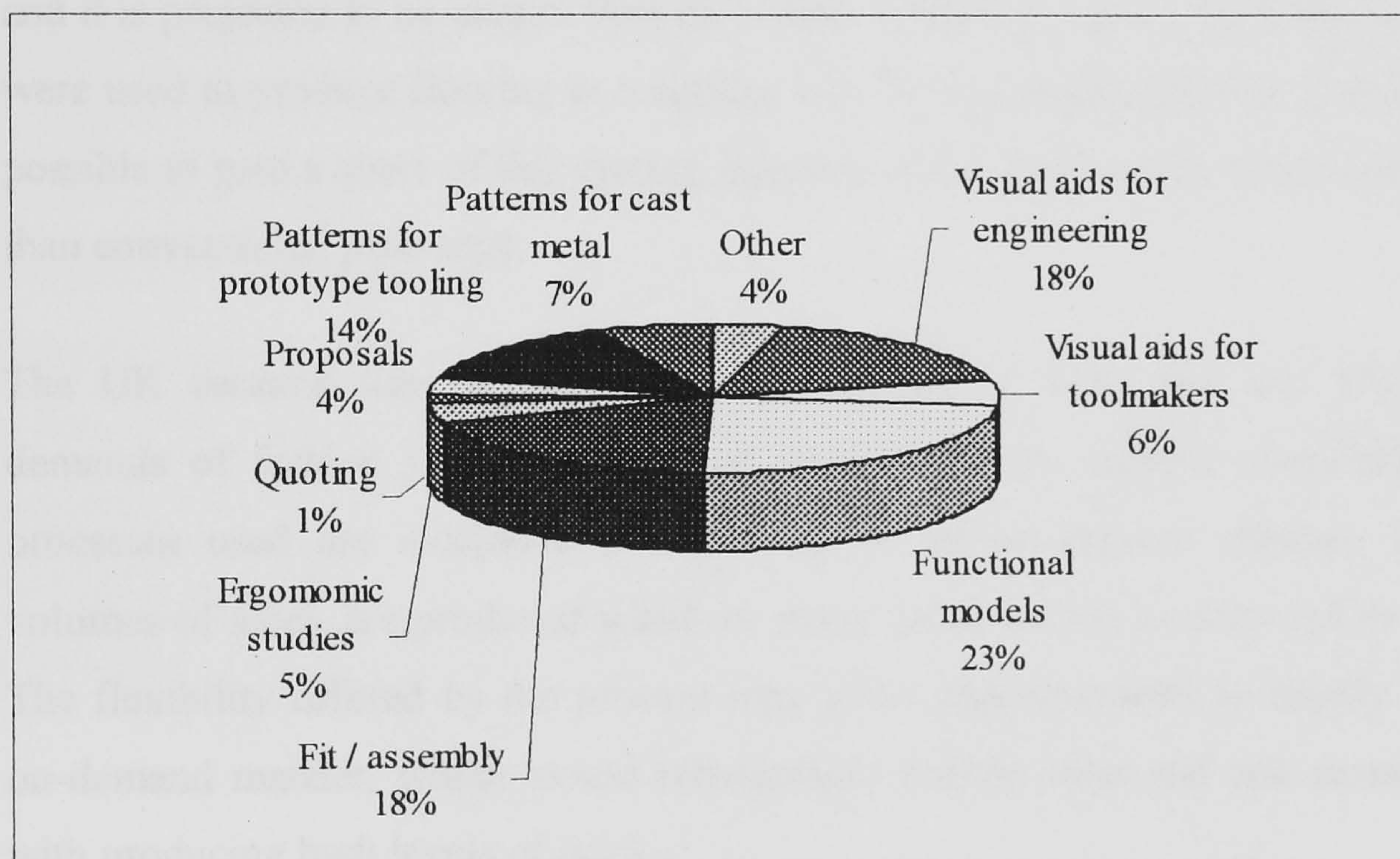


Figure 35: The applications for SFF parts in 2000 [17].

Figure 35 indicates how parts made by SFF systems are being used [17]. Nearly all of these applications involve the manufacture of one-off parts. It is very seldom that an SFF system will make more than a hundred duplicate parts, because in these situations it is more economic to use mass-production processes such as silicone and injection moulding. It is generally accepted that doubling of the size of a market every two or three years only happens when there is mass-market appeal. Given that the industry has entered adolescence, it is unlikely that this will occur until there is a technical breakthrough in the ratio of price to performance in system technology [17].

The 'SFF Thermography' and 'Concurrent Stack, Registering and Bonding' processes offer the potential for such a breakthrough, that will allow one-off and large-volume parts to be made economically.

After the automotive and consumer products sectors have been established as part of the market for the processes, it may be possible to look further a field. It is likely that mass-market sectors could benefit from the flexibility of SFF manufacture, allowing them to dispense with most of the need for tooling and inventory associated with finished stock. A number of companies have already said that they want to licence the processes. The markets that they are involved in, their market values and possible reasons for their wanting to do this are as follows:

- The UK commercial floorcoverings market was worth over £1.7 billion in 1998 and it is projected to be greater than £2 billion in 2004 [13 and 15]. If the process were used to produce flooring in a similar way to on-demand printing it might be possible to gain a share of this market, because of the need to carry less inventory than conventional processes.
- The UK ceramic tiles market was worth £329m in 1999 [13 and 14]. The demands of fashion tend to drive this market and the current manufacturing processes used are incapable of supplying in an on-demand manner. Large volumes of stock are produced which in many cases cannot be recycled or sold. The flexibility offered by the process may allow manufacturers to supply in an on-demand manner, which would substantially reduce costs and risk associated with producing high levels of stock.
- The UK printed circuit board (PCB) market was valued at £2.145 billion in 2000 with an annual sales growth of just over £1 billion compared to the previous year [18]. The process might allow this market to reduce manufacturing costs and lead times substantially, because current processes such as flat bed screen printing are relatively slow and costly. There would almost certainly be problems with achieving the tolerances needed for PCBs and so commercialisation of the technology seems unlikely in the near future.

8.3. Competition

In 2000 around 3,004,006 models and prototype parts were produced by the 6,755 Rapid Prototyping (RP) systems installed worldwide [17]. This indicates the capabilities of the potential competition. On average, each system produced 445 models and prototype parts. These production rates are almost certainly insufficient for mass production, and the competition appears to be at a great disadvantage in competing with the rates of the ‘SFF Thermography’ and ‘Concurrent Stacking, Registering and Bonding’ processes and in satisfying high-volume demands.

Table 6 shows the number of systems sold between 1988 and 2000 by the company’s main competitors [17]. The majority of these are based in the USA and these companies tend to dominate the market. 3D systems has recently bought DTM. This has further secured their position as market leader in terms of the number of systems sold. There is little competition from Japan because Japanese companies tend to limit themselves to selling in their home market. This may be in part due to the possibility of problems with patent infringement and it may also be because they wish to reserve the benefits of their technology for their home market. Kira is an exception to this but they have only sold a relatively small number of systems. EOS is the only major competitor in Europe. Their systems are highly specialised and are priced at \$300,000 to \$650,000 [17]. The ‘SFF Thermography’ and ‘Concurrent Stacking, Registering and Bonding’ processes priced a hundred times less than this would compete well.

Country	Company	Technology	1998	1999	2000
USA	3D Systems	SL. Jetting	224	303	387
	Stratsys	FDM	262	293	297
	Solidshape	Jetting	110	129	127
	DTM	Sintering	65	73	77
	Helisys	Lamination	50	36	5
	Z Corp	Jetting	48	105	170
Japan	NTT Data CMET	SL	24	27	35
	Sony/D-MEC	SL	23	21	26
	Kira	Lamination	18	24	20
Germany	EOS	Sintering	39	42	51

Table 6: The systems sold between 1998 and 2000 by the company’s main competitors [17].

Table 7 shows the revenues generated from 3D printer sales for 3D Systems and Z Corp [17]. This indicates that Z Corp's rapid increase in revenue may allow it to become the market leader in terms of revenue. This is partly due to the technology in Z Corp's systems being less costly than that used in 3D Systems's hot melt jetting systems. The hot melt jetting systems (thermojet) price is \$50,000 and the 3DP jetting systems is \$49,000 for the Z400 and \$67,500 for the Z406 [17]. In 1999 and 2000 3D systems sold 148 and 160 SLA systems respectively ranging in price from \$149,000 to \$800,000 [17] and this combined with 3D Systems purchase of DTM might ensure that 3D Systems continues to be the market revenue leader. Z Corp's rapid increase in revenue does however emphasise the advantages that Rapid Manufacturing Systems Ltd may derive from the extremely low cost of the technology involved in its processes and the substantially lower ratio of cost to price which can be achieved.

Company	Technology	1999		2000		%Change in revenue
		Systems sold	Revenue	Systems sold	Revenue	
3D Systems	Hot melt jetting	155	\$5,157,000	227	\$6,520,000	26
Z Corp	3DP jetting	105	\$5,526,000	170	\$8,643,000	56

Table 7: Revenues generated from 3D printer sales excluding service, consumables and other revenues [17].

8.3.1. Strengths and Weaknesses

The strengths of the 'SFF Thermography' and 'Concurrent Stack, Registering and Bonding' processes are their speed, price and range of materials. The weakness is that the processes are new and so the resolution, accuracy and material properties of their products are undefined and end user confidence needs to be generated. Even so, the price and speed of the processes are so advantageous that even if the resolution, accuracy and material properties were not as good as some of the other SFF manufacturing systems it may still be possible to compete. To compete on price existing RP system manufacturers such as 3D Systems, Stratasys and Sanders Design International would have to drop the price of their systems by around 87% and the

price for consumables by around 85%, which is highly unlikely because such companies need to maintain high prices to pay for the development costs of their specialized systems and consumables. Table 8 shows a qualitative assessment of the advantages and disadvantages of the processes in relation to competing systems. This indicates that as long as the resolution and accuracy of the products made by the processes are roughly comparable to the averages in the industry it is likely that they could compete because of their high speed and low price. £6,000 pounds would be the lowest price that the processes could be sold for, which is substantially lower than the price of the main competing systems (see Table 7). Studies have shown that, dependent on the geometry of the products and the particular process used, the process may be between 158 and 790 times faster than an SLA5000, which is one of the fastest competing systems (see section 3). This ensures that the processes would be almost unbeatable in terms of productivity to price ratio (see sections 2.1 and 2.2).

	Systems	SL	Hot- melt jetting	FDM	Lamin -ation	Sintering	3DP
Processes	Strengths	Speed, materials, price,	Speed, materials, price,	Speed, price,	Speed, price,	Speed, price,	Speed, materials, price,
	Weaknesses	Resolution, Accuracy	Resolution, Accuracy	N/A			

Table 8: The strengths and weaknesses of the processes in comparison to the commercial systems.

8.4. Displacement of UK and Overseas Technologies

Initially the process will augment existing manufacturing capability, because its flexibility allows products to be manufactured in way similar to demand printing, which dispenses with the need for tooling and lead times associated with conventional manufacturing processes such as injection, rim and rotational molding, die cutting, punch pressing and etching. This would allow manufacturing industries to satisfy the demands for low-volume products, which previously it has been too costly to satisfy or which have resulted in losses. Initially this might for example take the form of manufacturing replacement parts or products, or producing limited numbers of products to evaluate their saleability. In time the advantage of the process

in reducing the need for holding stock might encourage end users to replace processes such as injection, rim and rotational molding, die cutting, punch pressing and etching. In 2000 around 44% of the market for SFF manufacture was in the North America, 25% in Europe and 29% in Asia/Pacific (see Figure 36) [17]. This indicates that initially there is sufficient market in Europe for the company to obtain revenue from licensing, equipment and consumable resale to fund its development. The products might also be exported to the USA and Asia/Pacific to obtain further revenue for the company and licensees. Consequently, the manufacturing capability of Europe would be augmented and the capability of the rest of the international community displaced.

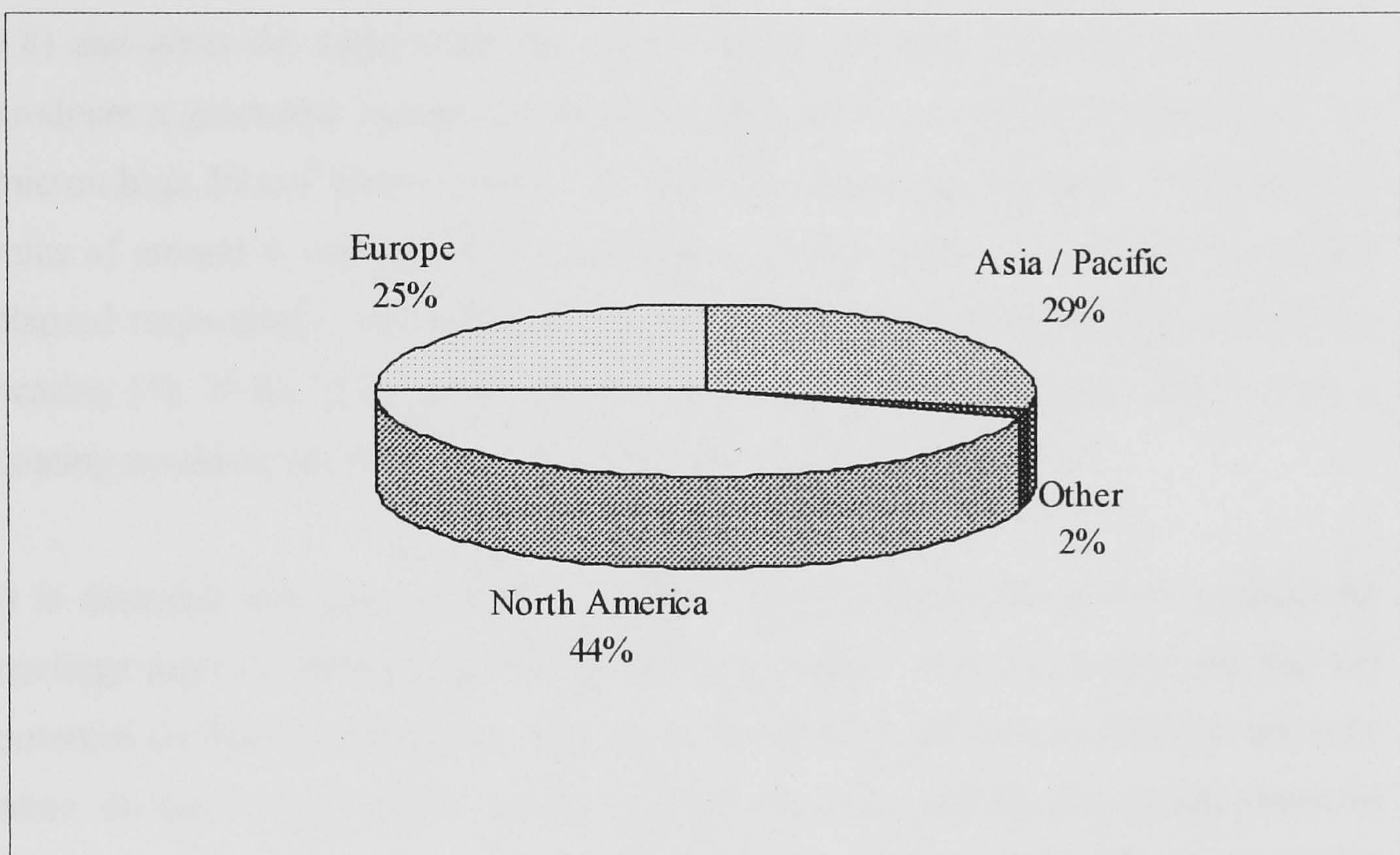


Figure 36: Estimates of installations SFF systems by region. This accounts for 6,251 of the 5,755 systems sold between 1988 and 2000 [17].

9. Conclusions

The main objective of the four-year study, to develop a prototype solid free form manufacturing (SFF) system capable of being used for mass production as well as for rapid prototyping, has been met. The outcome is several patented inventions. Searches have confirmed their novelty and revealed no significant competitors (see section 9.1). Recommendations have been made for future development that will allow production systems to be produced and refined (see section 9.2).

It is recommended that the system use concurrent thermal processing of coatings in a stack (see section 5.3). This will allow time for such things as annealing (see section 5.8) and gives the opportunity for recycling the heat used in the processing. This produces a geometric increase in the processing rates and it was calculated that 500 micron high 20 cm² Mowiol 4-88 (polyvinyl alcohol) coatings could be produced at rates of around 4, 107 and 752 coatings per second after 1, 24 and 168 hours had elapsed respectively. This assumes that 6kW of un-recycled power are used for the heating [5]. If the same power were used conventionally, around 0.23 of such a coating would be processed every second (see section 5.3).

It is desirable that devices similar to paper joggers should be used to register the coatings prior to their being bonded together, because it is less costly and has the potential for being substantially faster than consecutive lamination, which is the only other alternative (see section 6.2.2). This would be a radically new development in the field of SFF manufacture and would allow the registering and bonding of coatings to be performed separately, which may reduce the annealing problems (see section 5.8) associated with welding laminations together consecutively.

The need for peeling the coatings away from their substrates was assessed. It was found that, dependent on the materials used, it was possible to make 1.5 mm high parts by over-printing and re-thermographing the coatings. Consequently, as long as the parts are around 1.5 mm high, there may be no need to resort to peeling off coatings and stacking and bonding to form them (see section 6.1).

The use of parallel registering necessitated the invention of bonding methods that would allow all the coatings in a stack to be bonded in parallel, because otherwise consecutive lamination would have to be used, and the speed advantage of the parallel registering would be lost (see section 6.2.3). In theory this would allow a stack to be bonded in the time that it takes to bond a single coating, and so this would be substantially faster than any of the methods presently used for bonding SFF layers. If extremely accurate parts were required, it was judged that subtractive height adjustment would have to be involved, and so a method for performing this in parallel has been devised (see section 6.2.3) [6]. This might allow the system to compete with the accuracy of existing systems.

Commercial collating capabilities were assessed and it was decided that there were no significant problems with meeting any of the collation needs for forming parts (see section 6.3).

It was necessary to thermograph a water-soluble resin around the most delicate coatings, so that the resin supported the coatings when they were peeled off the substrates (see section 5.5). This is a new use of support, because at present SFF systems only use support to underpin the overhanging sections of parts. PVA was found to be the most suitable support material, because its water solubility allowed it to be washed away from the bonded part coatings in a stack so that the bonded parts were released from their support.

The system is new and it is difficult to predict whether it will be commercially successful, but the foundations for commercialisation are being laid, and will define the potential for commercial success more clearly (see section 1). The main strengths of the system compared to competing systems are its potentially high productivity to price ratio (see section 2.1 and 2.2) and high speed (see section 8.3.1.). In addition, it shares in the inherent flexibility of SFF systems, allowing products to be manufactured in way similar to on-demand printing, using a wide range of materials (see section 8.4). This combination suggests that manufacturers may find it attractive to use the system initially to augment their existing mass-production processes. In

time the system may displace these processes, because of its cost advantages the reduction of lead times and the reduced need for carrying stock (see section 8.4).

9.1. Level of Innovation and Competition

Present SFF systems are too slow for mass production (see section 2.1) [17 and 31 to 38]. The study's experiments and calculations have shown that SFF Thermography will be fast enough and will be able to use a wider range of materials (see sections 6.2.2 and 6.2.3). It is flexible in use, and because it is based on a new use of existing equipment its price is likely to be substantially lower than that of current systems (see section 2.1 and chapter 1).

SFF thermography is innovatory on an international scale and in an area ripe for rapid expansion. One academic referee for an EPSRC funding proposal described some of the processes as "world beating" [39 and 40]. The intellectual property rights to the apparatus and methods involved in SFF thermography are protected by patent GB9927127.2, PCT GB00/04359 that is near to being granted in the USA and various European countries. The University of Warwick has assigned this patent to me and it has had three official searches. Subsequently I have filed six patents pending on certain other processes which have had seven searches and which secure the IPR for future development. Further details have to be withheld, since they might jeopardise future commercialisation by Rapid Manufacturing Systems Limited (incorporation number: 4491437), a company formed for this purpose. The assigned patent and the six patents pending are being used in a SMART application for funding for a project to define the feasibility of commercialising the inventions [41]. The SFF Thermography patent is as follows:

- GB9927127.2, PCT GB00/04359 "A Method of Manufacturing an Item and Apparatus for Manufacturing an Item" [42].

Many innovative materials and processes have been developed during the study, including the following:

- Non-drying ink formulae, which are printed onto a conductive, non-stick substrate such as PTFE coated carbon filled glass fibre belting that does not attract powder excessively thus ensuring good definition of the subsequent coatings (see chapter 3 to section 3.1.2).
- Thermopolymer, thermoset, metal or ceramic powders which are dusted onto the printed ink, with any powder that does not adhere to the ink being vacuumed or shaken off and recycled (see chapter 1).
- Interleaving of powder-coated substrates with conductive plates in a stack, in a way new to SFF manufacture and thermography. This allows heat to be conducted into the stack rapidly and evenly so that the powder coatings melt or sinter into a solid form (see sections 5.3.1, 5.3.3 and 6.3).
- Using the above interleaving technique, concurrent annealing may be performed to remove stress in the coatings without adding significantly to the processing time (see sections 5.3.1, 5.3.3 and 5.8).
- A ground-breaking development whereby the plates are then used to conduct heat evenly and concurrently away from the annealed coatings, so that they rapidly cool to room temperature without stress building up in them, while the heat is recycled to another stack that needs to be heated. This offers the potential for high levels of efficiency in energy utilisation and significantly decreases the maximum power required (see sections 5.3 and 5.3.3).
- Provision for repeated printing, dusting and processing to produce higher or more uniform coatings. So far this has allowed 1.5 mm high coatings to be made, which have uses as low-relief parts (see section 6.1).
- An original method for producing high parts, where extreme accuracy is not required, by concurrently peeling coatings from their substrates and then stacking, registering and bonding them in a device similar to a paper jogger, with a clamping mechanism. This bonding, and any subsequently mentioned

bonding, may involve solvents, glues or thermal welding. This innovative method allows a part to be formed in the same time that a conventional SFF system would take to form a single layer (see chapter 6). It is recommended that to allow this a novel two-dimensional support method be used, which involves surrounding each part coating with a support containing edge features (lay edges) that are the male or female counterpart of a registration feature within the jogger.

- Provision of a novel method for bonding the coatings in parallel that may involve the use of solvent or glue infiltration or thermal welding.
- The production of high-accuracy parts by collation of coated substrates with plates before stacking, registering and bonding in a paper jogger or similar device, so that the coatings can be bonded in register onto the plates. This allows the substrates to be peeled off each of the bonded coatings at the same time. Concurrent subtractive height adjustment may then be used to ensure that the coatings have accurate heights. The process may be repeated as required to build highly accurate parts. This concurrent method will ensure considerable time-saving over conventional SFF adjustment methods, which are performed consecutively (see section 6.2.4).

Thermographic processing allows parts to be made rapidly from a broad range of materials supplied in the form of fine or coarse powders. This may have the benefit of allowing the build rates to be increased by using coarser powder with the additional benefit of reducing materials costs since, generally, less processing is needed to produce these powders. This may even allow parts to be made so that their surfaces are made with fine powders and the inside with coarse powder, and this would almost certainly be another major innovation because none of the commercial or researched systems allow this.

The novel systems developed during this study, as described in the submissions, have the potential to be much faster than existing processes (between 158 and 790 times faster than an SLA 5000), they can use a wide range of materials including

thermopolymers, thermosets, metals, ceramics and glass, and they have the potential to be relatively inexpensive (around £6000 compared with £327,300 for an SLA 5000) (see chapter 2).

9.2. Future Work

Impact and non-impact jet printers may be used in the system and to a large extent the particular printer used will depend on the customer's requirements (see section 3). For example, an impact printer may be used if a customer needs to produce large volumes of parts, and a jet printer if the need is to produce one-off, small volumes or multi-colour parts (see section 3). In the latter case this will almost certainly necessitate the development of inks suitable for colouring the part coatings, and this would be feasible as long as the range of coating materials were limited and existing ink technology that is currently used to colour the material were used. Even so, the cost of this development should not be underestimated, and since the majority of SFF parts are mono-colour, further research would be needed to define a market that would justify this type of development. The PVA and other water soluble coating materials are an exception to this is since it was found that their hydrophilic properties allow high coatings to be formed on conventional colour jet printer inks which they absorb and retain in a similar way to the PVA coatings on jet printer paper. However, since inks developed in the study were found to be sufficient for producing mono-colour parts, it is recommended that such parts be commercialised prior to coloured parts, since further research such as defining the UV resistance and longevity of the colour parts will almost certainly be needed before they could be sold (see section 3.1.1 and 3.1.2). It is recommended that development of inks suitable for colouring different coating materials such as polymers be undertaken, because this will extend the capabilities of the system and allow end users to use the colour printing facilities involved in the system.

Conductive PTFE coated glass fibre substrates were identified as the most suitable substrates to use in SFF thermography, because of their low coefficient of friction (which allows coating to be peeled off it easily), high operating temperatures (that allow it to be used in a broad range of thermographic thermal processing) and low background powder problems (that ensure the high definition of the coatings) (see

section 4.3). Nevertheless, it is recommended that the availability of similar and smoother substrates be investigated, because these may allow parts and coatings to be made with higher resolution and accuracy than at present.

The long chain structure of the PVA support coatings tended to mean that it took a long time to dissolve them away and release a part from them. Depending on the geometry of a part, the time involved in releasing it may have a great impact on the commercial viability of SFF thermography, and so further research concerning speeding up the releasing is of crucial importance. This may involve the examination of other materials instead of PVA (see section 6.4).

Annealing schedules for each coating material used must be defined with respect to the concurrent thermal processing of coatings in a stack, because this will broaden the range of usable materials and increase the speed of the system (see section 5.8).

The capabilities of the system with respect to meeting specific commercial specifications must be defined.

Detailed plans for production systems must be drafted.

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