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WMG
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THE UNIVERSITY OF WARWICK

Alternative Glazing For Automotive Vehicles

Engineering Doctorate Executive Summary

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Abstract

This document summarises the Alternative Glazing for Automotive Vehicles Research Programme. Having initially validated that a true engineering need existed for polymer glazing within Automotive OEM's, the programme has identified the technology constraints that are inhibiting widespread adoption of current (or 1st Generation) polymer glazing. The critical constraints are identified as poor weatherability, low scratch resistance and, for some applications, inadequate rigidity.

It was realised that no single polymer can satisfy the legislative and industrial performance requirements of polymer glazing so attention was turned towards utilising novel processing techniques to create hybrid structures of a high impact polycarbonate core with a chemical and UV resistant acrylic skin. Two separate approaches have been investigated within this programme and are intended to represent the 2nd and 3rd generations of polymer glazing.

The first approach utilises a thin film of acrylic that is moulded onto the outside of a polycarbonate substrate. It was found that the gate of the injection mould cavity must be of uniform cross section otherwise local shear heating can occur and melt the acrylic film. The injection gate must also be located entirely on one side of the mould cavity otherwise the film is punctured by the molten polycarbonate and free to float within the cavity. Any mixing of the two materials will lead to opaque components due the difference in the refractive indices. The film was found to improve the UV resistance of any component, acting as a protective buffer for the polycarbonate.

A new variety of hardcoat was applied to film-backed samples to impart abrasion resistance and samples were found to outperform commercially available alternatives under recognised laboratory conditions. The film-backed samples also exhibited excellent impact resistance when impacted upon the film-face. However, similar components failed at extremely low energy levels when impacted from the non-film face because flaws in the acrylic film caused cracks to be initiated when the film was placed into tension. The level of adhesion between the film and the polycarbonate has been found to be critical and if the failure mechanism could be guaranteed, then intruder resistant glazing that could be broken from the inside in an emergency becomes a possibility. Such a product would address the identified consumer concern of being trapped in a vehicle.

The second approach utilises simultaneous dual injection moulding (2K), which has previously only been used to manufacture coloured components. A successful feasibility study was undertaken to demonstrate the concept of producing transparent components via such a process. This showed that much greater control is required for transparent applications otherwise the skin and core materials mix and opaque components are produced. The generally accepted academic principles associated with the process have been shown to be too simplistic and cannot be relied upon to guarantee good results. The ratio of viscosities of the skin and core materials appear to be more dominant than previously thought and the relative injection speeds of the two materials has a direct influence upon interfacial mixing and haze generation. It was also found that haze could be avoided if the refractive indices of the skin and core material were matched to within ±0.002, but this is impractical.

A third area of research examined the feasibility of introducing structured glass fibres weaves into transparent components to improve rigidity. The study resulted in the construction of a transparent glass fibre pre-preg that could be moulded onto the outer surface of polycarbonate components. Flexural tests revealed that a single layer of glass fibre increased the flexural modulus of test samples by a factor of 3, whilst transparency and clarity were retained. Two patents have been filed as a direct result of this work.

In-depth analysis of the polymer glazing market has demonstrated that en-mass competition with conventional tempered glazing is a high-risk strategy because of the relatively high costs of manufacturing polymer components. The technology should be focussed at niche style-based applications that cannot be satisfied through current glass technology where a component premium could be charged. Both the film and 2K systems are shown to offer improved component performance at ongoing cost reduction compared to current polymer glazing, whilst a number of spin-off applications of lesser technical demand have also been identified for future exploitation.

Declaration

Unless otherwise acknowledged, the work contained within this document is entirely that of the author's and has not been submitted towards any other degree.

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Abbreviations & Terminology

2K – Simultaneous dual injection moulding.

ELV – End of Life Vehicle.

Exatec – A joint venture company owned by GE plastics and Bayer that is to develop and market polycarbonate automotive glazing.

Hardcoat – An organic and/or inorganic coating applied to polymer surfaces to improve scratch/abrasion resistance.

HIC – Head Impact Criteria, a measure of head injury sustained during an impact.

IPR – Intellectual Property Rights.

LCV – Lightweight Concept Vehicle.

Nanoparticulate – very tiny ceramic particles, smaller than the wavelength of light.

OEM – Original Equipment Manufacturer.

PC – Polycarbonate.

PMMA – Polymethylmethacrylate.

Recyclate – Recycled material of commercial value.

RI – Refractive Index.

RIM – Resin Injection Moulding.

Solar Control – Usually a coating that is applied to glazing that reflects or absorbs infra red energy, preventing the build up of heat within a vehicle.

Tp – Processing temperature.

UV – Ultra Violet light.

V – Injection speed.

Wetting – Occurs when intimate contact between fibre and polymer matrix is achieved.

1.0 The Alternative Glazing Research Programme – An Introduction

The alternative glazing project was established in 1997 and was intended to analyse the long-term evolution of polymeric glazing as an alternative to traditional automotive glasses due to changing consumer, legislatory and industrial demands. Where possible, new and novel technologies were to be proposed and developed that could provide solutions to problems identified within the investigation.

This document summarises the whole programme and discusses the key research activities undertaken, the methodologies adopted, the key findings obtained and how the programme evolved over time. This is achieved by relating the final programme back to the initial envisaged objectives to demonstrate where knowledge and novel solutions have been generated, illustrate how the research emphasis changed as new information emerged over the programme duration and bring the overall knowledge base up to date in order to close the research loop.

The initial objectives of the programmes can be summarised thus: -

- **Concept Validation** - establish that a true engineering demand existed for polymer glazing. Analyse the key drivers for that engineering demand.
- **Problem Analysis** - identify the technical constraints inhibiting widespread adoption.
- **Propose Solutions** - Construct a development programme to address as many constraints as possible.

1.0.1 The Structure of the Research Programme

As outlined above, the first phase of the programme was to investigate the numerous issues surrounding the idea of polymer glazing in order to confirm that a real engineering need existed and to understand what barriers were preventing en-mass adoption of polymers in glazing applications. Particular attention was paid to existing (or 1st generation) technology to establish a performance benchmark for future developments. This initial phase of activity is discussed in Chapter 2.

Having completed the Concept Validation and Problem Analysis stages, it was possible to structure a long-term research programme that addressed many of the issues. This is shown in Figure 1.1 and it can be seen that several generations of technology have been proposed in order to facilitate ongoing utilisation and dissemination of results to both industry and academia.

The considered benefit of this approach was that potential project sponsors would be able to recoup investments quickly, making the programme more attractive to industry, whilst further research programmes could be 'rolled-out' if findings provided a potentially new avenue of exploration away from the main programme.

It should be noted that it could never be the intention to fully complete the entire proposed programme as it would simply not be possible within the time scale of the Engineering Doctorate and the later generations of glazing approaches were intended to form future development programmes and subsequent products.

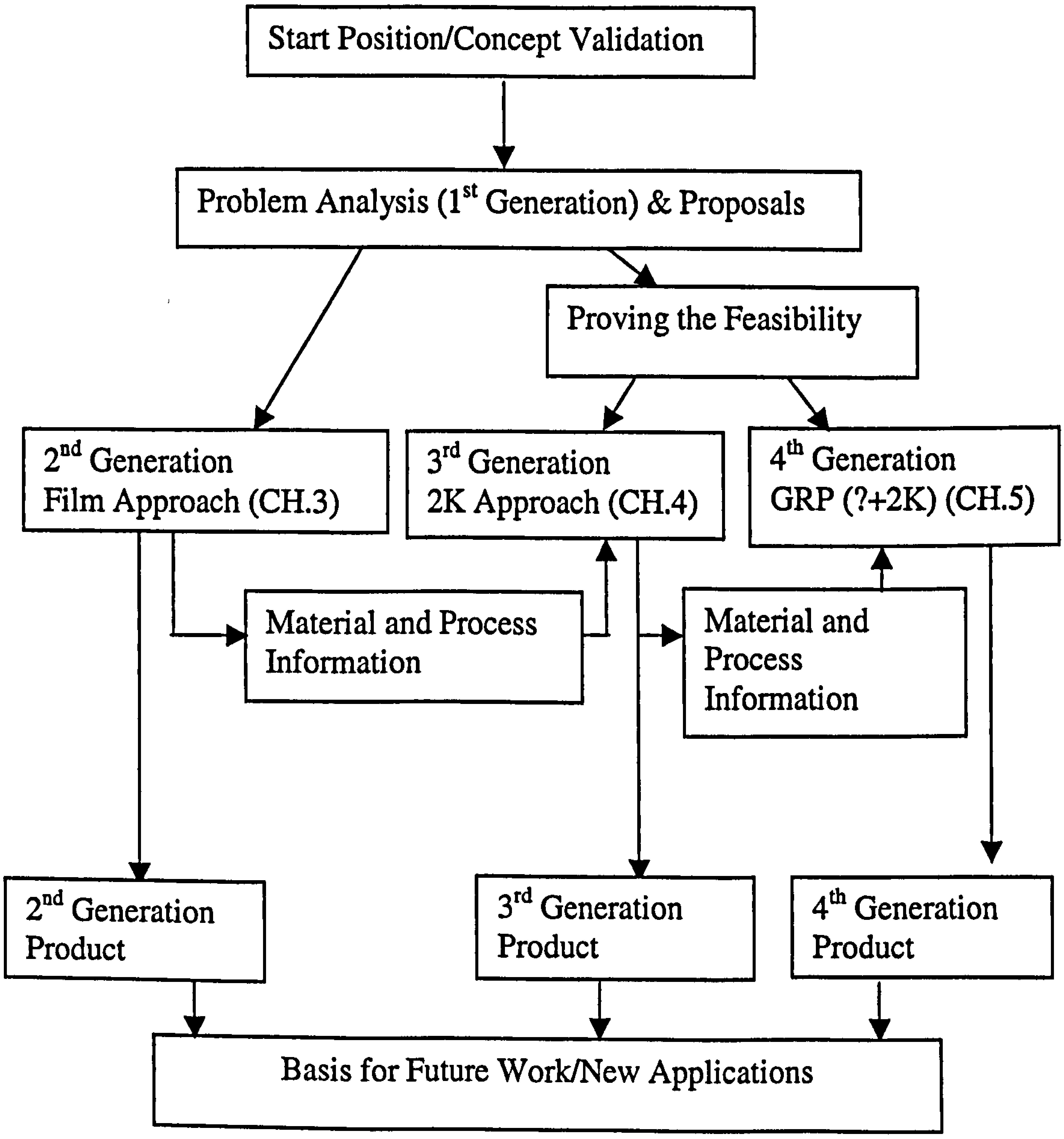


Figure 1.1: -The Proposed Research Programme

The findings of the Concept Validation and Problem Analysis stages showed that no single material would satisfy the legislative and industrial requirements for polymer glazing. Attention was turned towards utilising different materials and novel production processes to create hybrid systems without compromising the material properties as often happens when simply blending or compounding materials together. It was also found that any polymer component would need a suitable hardcoat applied to the outer surface to improve the scratch and abrasion resistance of any final component.

It was considered that the simplest way of combining materials was to utilise thin films that would impart excellent chemical and ultra violet (UV) light resistance to the high impact substrate. This approach would allow the production of test components that could be subjected to a wide variety of trials to establish the suitability of the materials being used. It was also thought that full-scale production pieces could be made via film moulding if appropriate resources became available and the approach would be the most suitable for delivering technology of commercial value within a reasonable time frame.

Whilst the film approach represented 2nd Generation technology and was the major focus of research within this programme, it was recognised that the use of film technology might incur a cost penalty because of the extra process stages associated with handling and storing.

A second recognised method of combining two different materials within a single system is via simultaneous injection moulding (or 2K moulding) which has been used previously within WMG for the production of coloured components. The key benefits of this process are that it removes all of the production stages associated with film handling and forming, thus reducing costs and lowering the potential for production error.

It was considered that a resin grade of the final film of the 2nd Generation could be used to produce similar 3rd Generation components, but at a lower cost, making the technology more attractive for mass application.

However 2K moulding has never been used for transparent applications and it was unclear whether it would be possible to produce components via this technology. A feasibility study was proposed to investigate whether it was a suitable process for the production of 3rd Generation components in the future.

Both the film and the 2K approach concentrated upon improving the long-term performance of polymer components by effectively providing a 'buffer' layer of chemical and UV resistant material between any applied hardcoat and the impact resistant polycarbonate. There are several distinct advantages of this approach over existing polymer glazing technology. The first is that in the event of the hardcoat being damaged, an effective protection mechanism remains in place. Secondly, the number of potential hardcoats available for application is increased as the need for UV resistance within the coating is removed. A further advantage of a laminate structure is that enhanced properties, such as solar control, can be imparted to the glazing in the future through the incorporation of different additives in the skin material alone.

The Problem Analysis stage also identified some issues with the stiffness of components, particularly for large, flat applications, which would not be addressed through the first two generations of technology proposed.

It is common to improve the stiffness of polymer components through the introduction of glass fibres. However this has always been limited to coloured components and has not been attempted for transparent applications.

The idea of introducing glass materials into a polymer matrix had been proposed before as a means of improving the scratch resistance of the material, but this was generally unsuccessful. (Manton, 1999)

Academic texts suggested that it was possible to retain transparency with glass fibres present in a polymer matrix, but nobody had attempted to develop this technology for industrial applications, mainly because of the timescales involved in production of samples. (Kirwan, 2001)

A second feasibility study was proposed to investigate the potential of introducing glass fibres into a polymer component as a means of increasing the stiffness for commercial applications. This area of activity was considered very much as 'blue skies' that would require a completely separate research programme to move towards a commercial stage. The purpose of the feasibility study was to provide physical evidence and understanding of the technology that could be used as a basis for future research.

It was hoped that a glass reinforced component would form 4th Generation glazing components, being the third system to be generated through this research programme, although this would not be achieved during the initial 4-year time-scale.

1.0.2 Contributions to the EngD Portfolio

For clarity, Table 1.1 overleaf summarises the link between the research areas of the EngD Programme, the portfolio submissions and the associated published papers. The two stand-alone documents that examine the 'business and financial aspects' of polymer glazing cannot be attributed to any single area of research activity as they draw together information that has been gathered throughout the entire programme. The Foresight Vehicle Application has been generated through the work performed during this programme and outlines the next phases of activity to be undertaken in collaboration with several industrial partners.

1.1 The History of Polymer Glazing and Some Early Examples

Glass has traditionally been the only material used for glazing within automotive applications. However during the early 1990's polymeric materials such as Polycarbonate (PC) and Acrylic began to be considered for glazing systems, along with glass–plastic hybrid components.

The original polycarbonate glazing technology was developed during the 1980's when polycarbonate and acrylic were first used as materials for headlight lenses in the US and Japan. Adoption of polymeric lenses in production vehicles began in Europe in 1994 and by the year 2000, 95% of all new vehicles were fitted with polymer lenses. Figure 1.2 shows some modern lens applications of polycarbonate. (Bayer, 1998)

The use of polymers in glazing applications is seen as a natural progression of the headlamp technology, which has given a degree of confidence to the automotive OEM's that the materials could feasibly be used as an alternative to glass.

The first Western European vehicle to be fitted with a polycarbonate glazing component was the Daimler Chrysler Smart Car in the late 1990's. The rear sixth-light was produced by Reitter & Schaffenacker of Holland, via a two-shot injection moulding process and subsequently coated with AS 4000 hardcoat from GE-Bayer Silicones to afford extra scratch resistance to the plastic. The component is shown in Figure 1.3.

EngD Research Area	Portfolio Submissions	Associated Publications
Start Position/Concept Validation Problem Analysis & Proposals	• **Alternative Glazing For Automotive Vehicles – An Overview** • **Defining The Product**	
1st Generation Film Approach	• **An Acrylic Film – Polycarbonate Hybrid Glazing System**	
2nd Generation 2K Approach	• **The Feasibility of Dual Injecting a Glazing Component** • **Foresight Vehicle Application – PABS2K**	• **American Society of Automotive Engineers, Dual Injection Moulding and Automotive Glazing, Technical Publication, 2000.** • **Institute of Materials, Interfacial instabilities in multimaterial co-injection mouldings - Part 1/Part 2, Plastics, Rubber and Composites, Jan 2001/TBC.** • **Institute of Materials, Co-injection moulding offers alternative solution for automotive glazing, Materials World, November 2000.**
3rd Generation GRP	• **Glass Reinforced Transparent Components – A Feasibility Study**	• **World Patent (WO000338), Improved Polymer Glazing.** • **UK Patent (GB2352249), Glass Reinforced Transparent Pre-Preg.** • **American Society of Automotive Engineers, Glass Reinforcing Transparent Polycarbonate Glazing, Technical Publication, 2001.**
Business & Financial	• **Analysing the Market Potential** • **Cost Predictions for Different Generations of Polymer Glazing**	

Table 1.1: - The EngD Portfolio Structure

In 1998, the world's two largest manufacturers of polycarbonate, GE Plastics and Bayer, formed a $40 million joint venture called 'Exatec', whose objective was to develop and market polycarbonate systems as an alternative to glass for mass automotive applications. Huge investments in research and development facilities, coupled with aggressive marketing, brought polycarbonate to the attention of automotive engineers who started to consider it as a possible material for future glazing applications. (PRW, 1998)

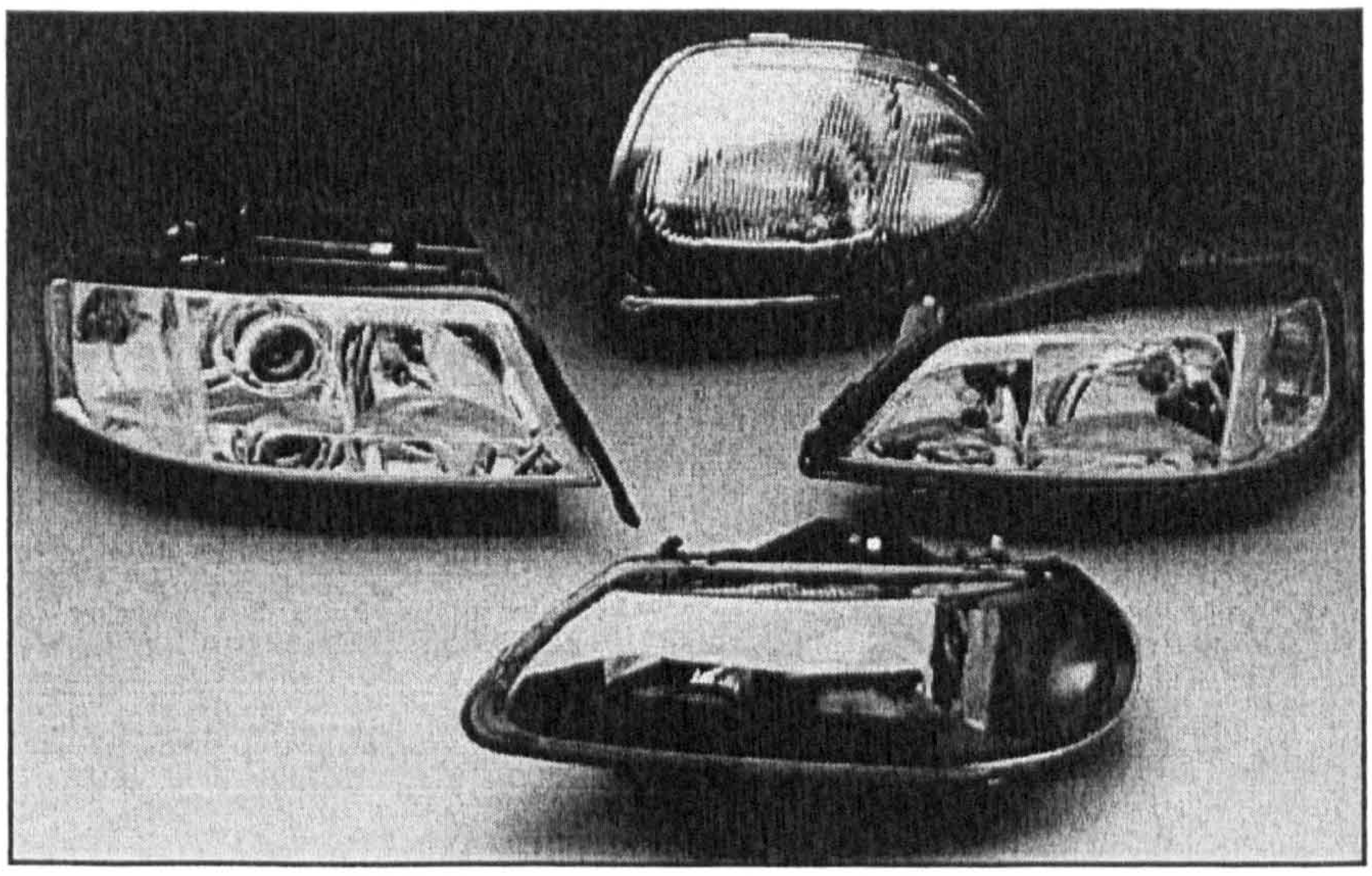


Figure 1.2: - Polycarbonate Headlamp Lenses

(Bayer, 1998)

However, to date, Exatec has failed to deliver any production components to the market place and the acceptance of polymer technology has been limited because of problems with scratch resistance and long-term weathering. Whilst a number of concept vehicles, such as the Fiat Ecobasic in Figure 1.4, demonstrate the possible uses of polymer glazing, no mass produced vehicle has yet adopted the technology.

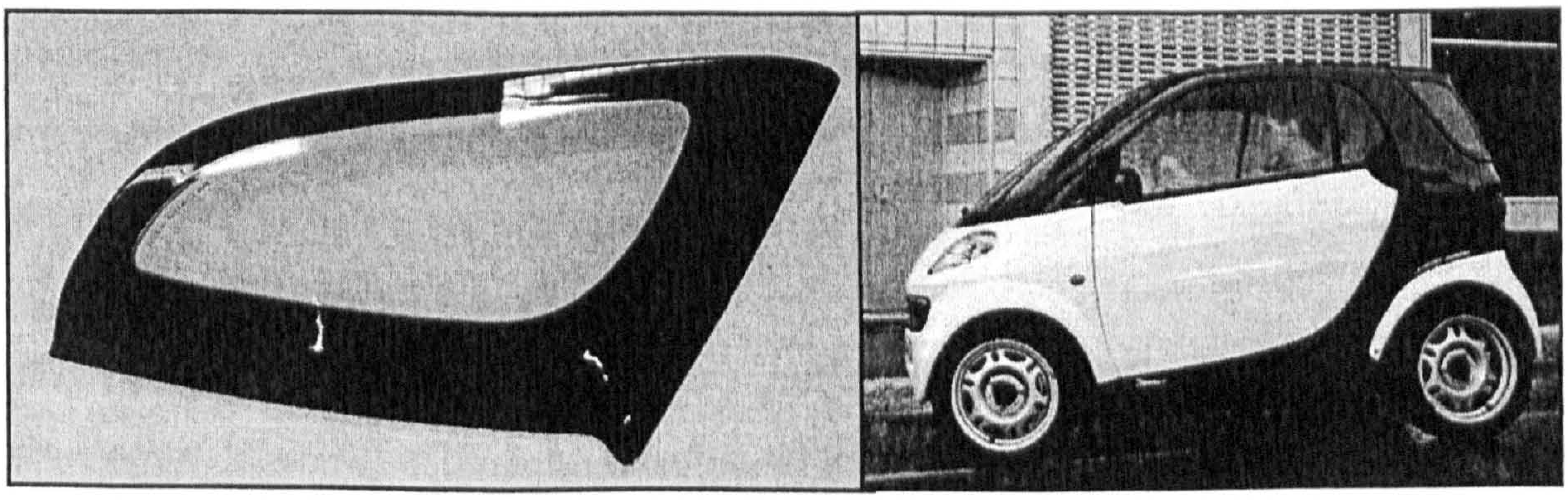


Figure 1.3: - The Smart Car Rear Sixth-Light

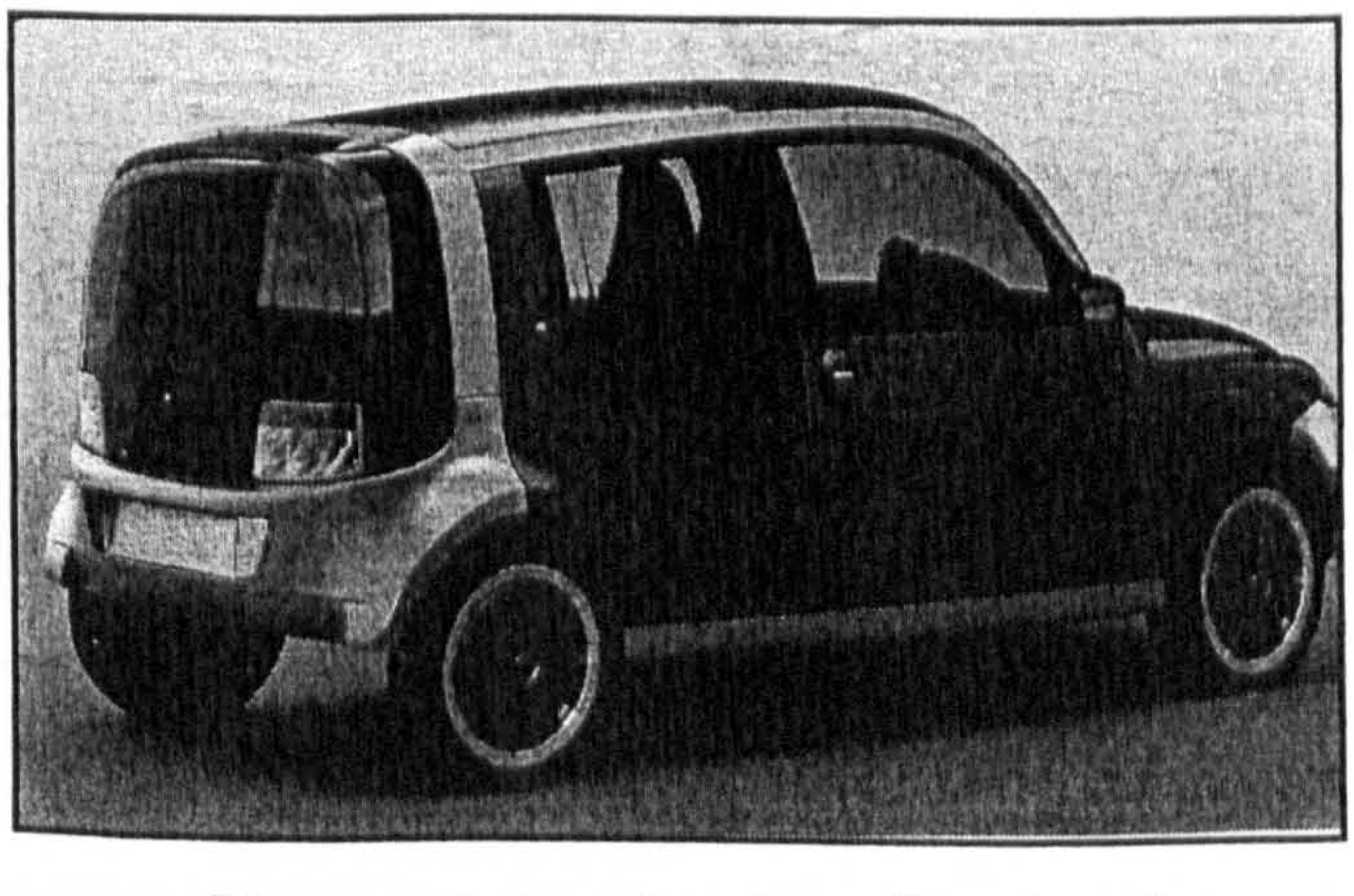


Figure 1.4: -The Fiat Ecobasic

2.0 Validating the Concept of Polymer Glazing

The first critical part of this development programme was to confirm that there was a true demand for polycarbonate glazing within the automotive OEM's and ensure that the apparent interest was not being created through aggressive marketing, with no real underlying requirement existing among the automotive engineering business units.

Several important theoretical benefits were identified as the key drivers for the engineering interest in polymeric glazing systems, namely: -

- Vehicle weight reduction
- Improved car security
- Increased styling flexibility
- Improved vehicle and occupant safety
- Recycling

2.0.1 Vehicle Weight Reduction

Every single car manufacture needs to reduce the weight of their production vehicles. There are major political and commercial drivers within Europe for the manufacture of reduced-weight vehicles, most of which can be attributed to environmental concerns about oil consumption and toxic emissions, which began in the early 1970's during the first energy crisis when fuel prices rose dramatically. (Grove et al., 1985)

Recent international legislation has also been aimed at reducing total fleet emissions for manufacturers of automotive vehicles, with heavy penalties for non-complying companies. (SAE, 2001) This has focussed attention upon reducing the weight of automotive components, as it has been shown that a saving of 10% in overall vehicle weight will result in an improvement in fuel efficiency of 6%. (Ridge, 1997)

Many motor manufacturers are also developing low pollution electric vehicles for urban use such as the Ford Th!nk and hybrid (i.e. they have a small petrol engine as well as an electric motor) vehicles such as the Toyota Prius for out-of-town driving.

The operational performance of such vehicles at present is limited and could be significantly improved if weight could be reduced.

Polymer glazing has the potential to deliver significant component weight reduction, simply because plastic components are approximately 50% lighter than glass equivalents, although 40% is a more realistic weight saving as polymer components will often have to be slightly thicker due to the reduced rigidity of the materials.

Given that the volume of glazing in a vehicle has increased as it has become an important styling element, as demonstrated by the roof glass in the new Mercedes C-class Coupe in Figure 2.1, it is clear that the introduction of weight reducing polymer technology could potentially bring significant benefits.

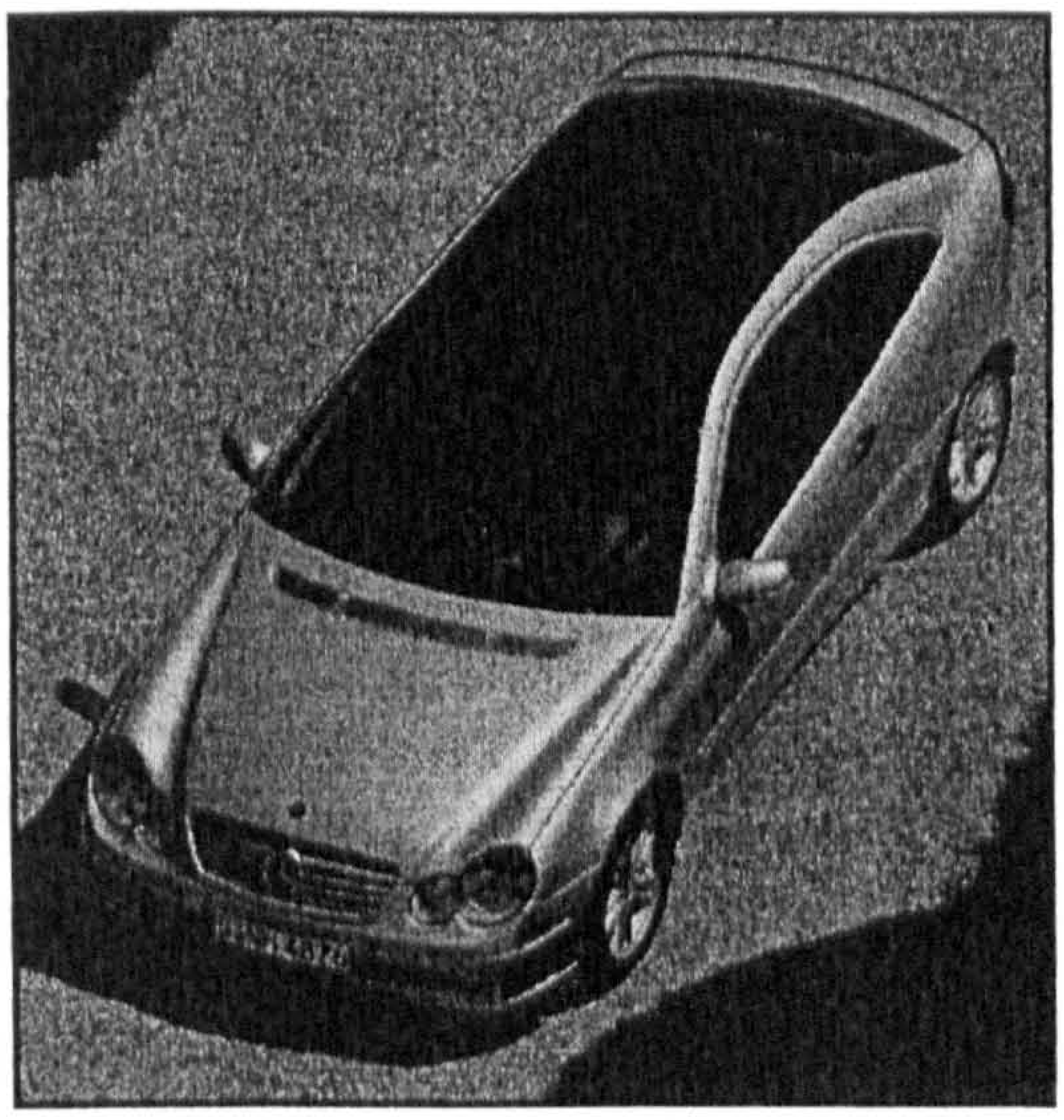


Figure 2.1: - Mercedes C-class Sports Coupe

2.0.2 Improved Car Security

Greater car security was identified as a consumer need that could be potentially satisfied through polymer glazing technology. Theft of items (i.e. smash and grab) remains the biggest problem with vehicle security with the latest British Crime Survey (Consumer Association, 2001) showing that over 60% of total car crime is theft *from* a vehicle, whilst theft *of* a vehicle represents only 13%.

The easiest way to enter a vehicle is by breaking a window, which has until recently been the 'weakest' point on the body. Side and rear windows have traditionally been made from toughened glass that shatters easily when impacted by a sharp object.

Glass manufacturers have advocated the use of laminated glazing (Kirwan, 1999) as a means of improving intruder resistance, but it tends to be thicker and heavier than normal tempered glass due to the number of layers it is constructed from. It has also been found during in-situ trials (Land Rover, 2000) that overall performance is heavily dependent upon the window remaining within the doorframe, otherwise the unit will simply collapse with the minimum of effort. This presents a problem as concept vehicle styling suggests that doorframes will not be acceptable in the future, with 'seamless' designs being desired (i.e. windows will meet outside of the B and C posts, giving the effect of one continuous piece of glazing).

Because of the excellent impact properties of some plastics, polymer glazing has the potential to withstand substantial attack from a number of different objects and still inhibit entry to the vehicle.

2.0.3 Increased Styling Flexibility

Stylists are demanding greater curvature and more complex shapes from glazing components, as they become increasingly important aesthetic features of vehicle design.

Unfortunately glass is very difficult to form into complex shapes or severe curves as it tears and the residual stresses generated through the forming process can lead to unexpected and dangerous failure mechanisms. (NHTSA, 1996) This normally results in a compromise being made between what is wanted and what can be physically engineered.

The Smart rear window could not be made in glass because of the design of the top corner. However, through the injection moulding processes currently available, it is possible to create almost any shape of window in plastic, meaning that the needs of the stylist can be readily satisfied.

It is also possible to mould in auxiliary features such as fixings and mountings that would otherwise have to be installed by hand, hence reducing production costs and complexity. This is well illustrated by the Fiat Maero in Figure 2.2 which has a small aesthetic light beside the wing mirror incorporating the mounting fixture within the polycarbonate moulding. It has even been proposed that entire body units could be produced with clear polycarbonate acting as a window with coloured film providing the 'painted' area. (Exatec, 1999)

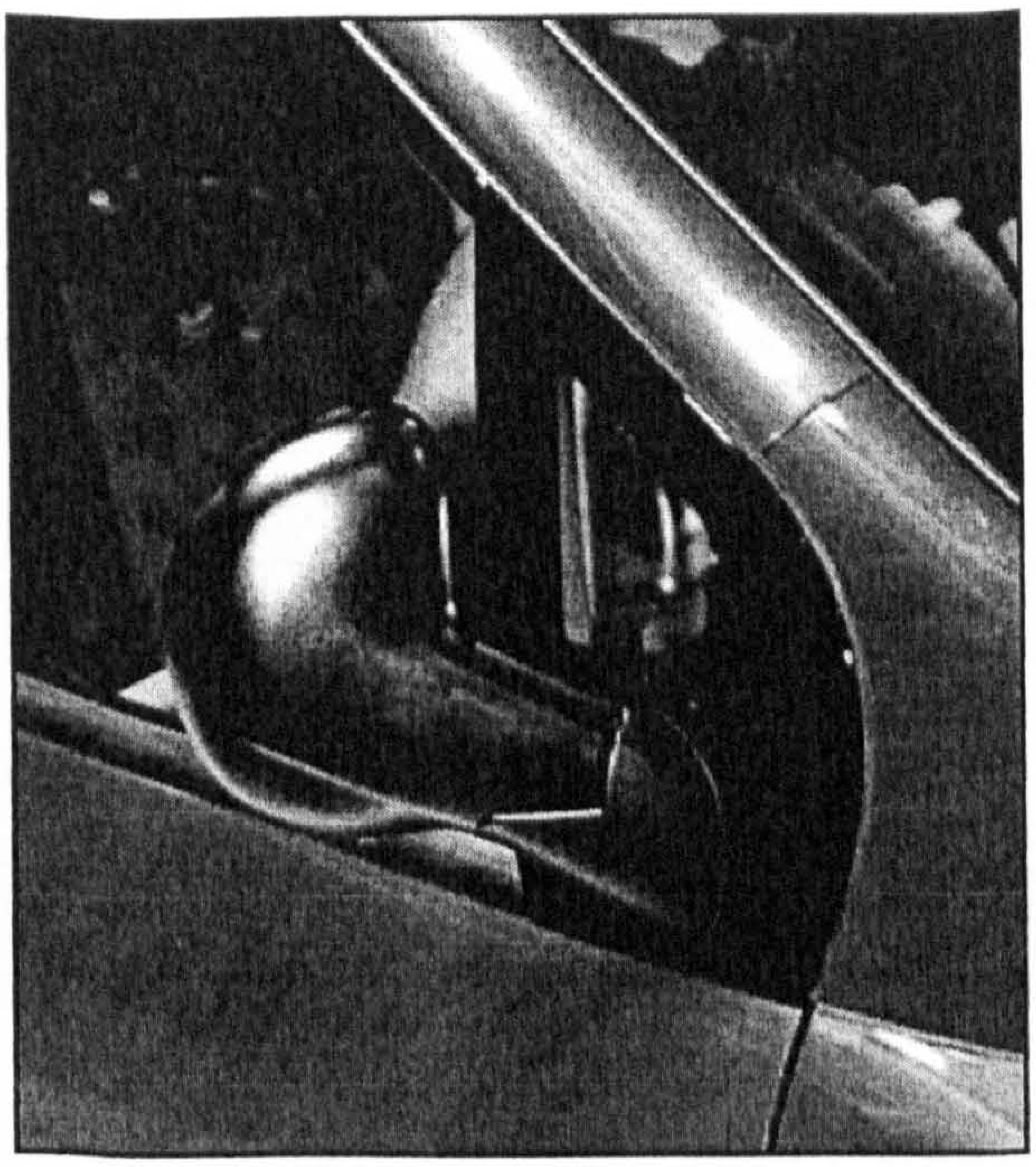


Figure 2.2: - The Fiat Maero Aesthetic Light Incorporating the Wing Mirror Mounting

2.0.4 Improved Vehicle and Occupant Safety

Polymer glazing could also improve the overall safety of vehicles compared to glass in areas such as occupant ejection, lacerations, head-screen impacts and stability.

Driver/passenger ejection has always been considered a dangerous result of an accident.(Patrick, August 1996) Any unbelted occupants can be thrown through a window and they are then vulnerable to potentially fatal injuries from road side objects or the vehicle itself in a roll-over situation.

Over the period 1990 – 1995 when restraint usage increased from 23% to 68%, the level of side-ejection incidents was relatively constant (NHTSA, 1996) suggesting that seat belts do not necessarily prevent ejection through side windows.

An alternative approach to occupant retention in the event of an accident could help save a great number of lives and polymer glazing systems have been shown to provide excellent occupant retention because of their ability to deform upon impact, without being destroyed as shown in Figure 2.3. (Exatec, 1999)

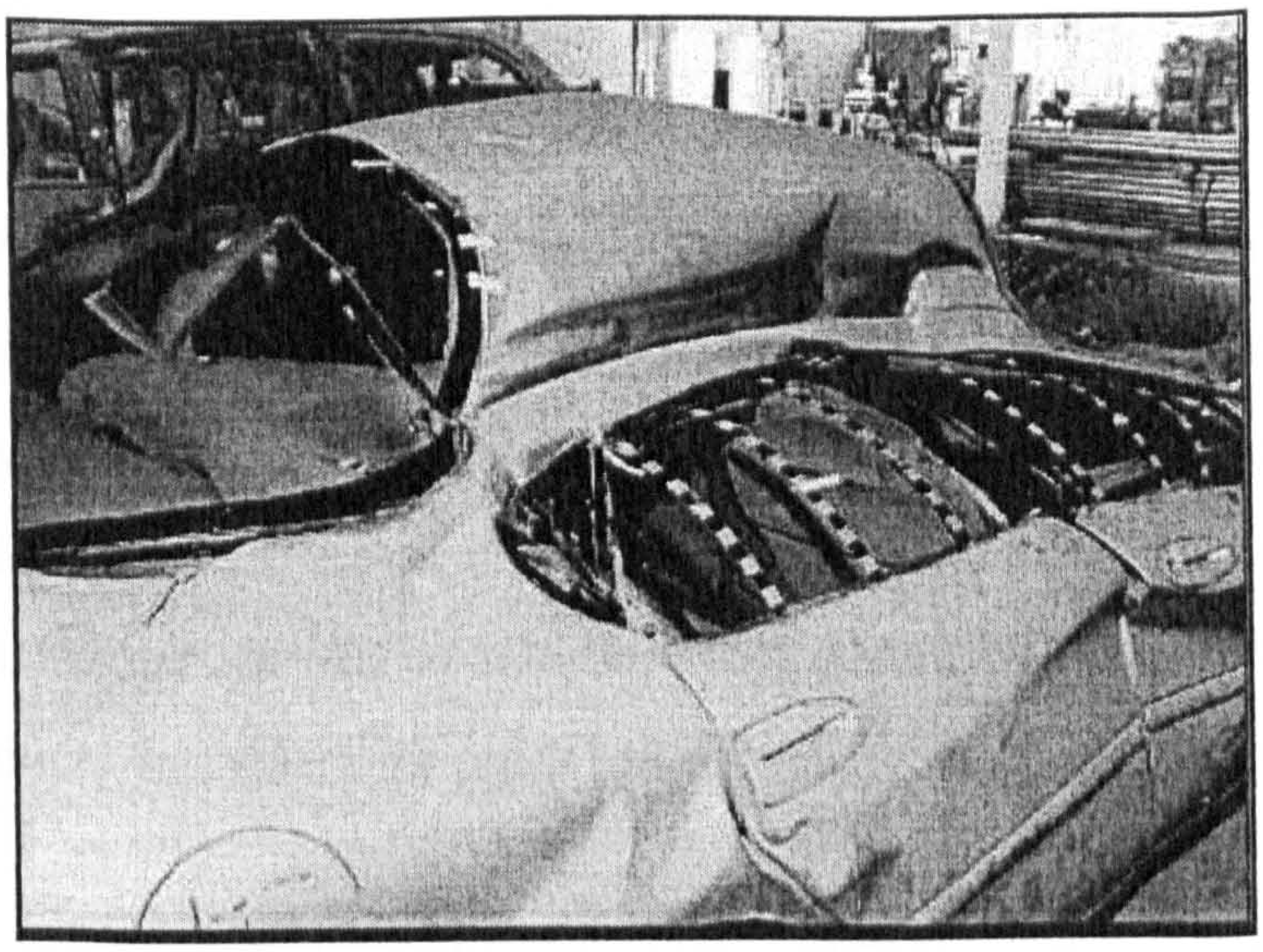


Figure 2.3: - Crash Tested Vehicle Fitted with Polycarbonate Windows

Polymers also present an opportunity to reduce impact injuries in less severe accidents due to their more ductile nature. Glass will behave in one of two ways during an impact with an occupant; either acting as a rigid stop which results in high head impact (HIC) levels (Patrick, 1996) and severe neck and cranial trauma, or shattering, causing lacerations, cuts and increasing the likelihood of occupant ejection.

Tests carried out upon polymer glazing units and bi-laminate components (constructed from an outer sheet of glass and an inner sheet of plastic) have shown that the polymer deforms during a collision, absorbing energy and dissipating it away from the impact point, resulting in much lower levels of trauma and injury. (NHTSA, 1996) Because polymers are ductile, there is also a much lower risk of flying debris causing cuts and lacerations.

A final area of vehicle safety that could be improved through polymer glazing technology is road handling and stability. Any reduction in the weight of vehicle glazing through the use of polymers will help to lower the centre of gravity, thus improving handling and helping to reduce rollover occurrence.

This is particularly important when the ongoing trend of body weight reduction is coupled with the increased area of glazing in modern vehicles, which results in heavy glass at the top serving to raise the centre of gravity and make the vehicle less safe.

2.0.5 Recycling

Within the Commission of the European Council document 'Proposal for a Directive of the European Parliament and of the Council on End of Life Vehicles' (ELV), targets are set regarding the recyclability of whole vehicles. By Jan 2005, type approval will only be given to new vehicles if re-use and recycling of materials can be shown to be possible with more than 85% of the vehicle weight. In order to satisfy these requirements, materials will have to be selected which can be readily recycled into valuable products (recyclate) in order to support the economic feasibility of recovery.

This presents a major problem for the automotive OEM's as there appears to be no immediate solution to recycling ELV glass components because of the wide variation in their nature. (CARE, 1999) Glass technology has changed so dramatically over the last 10 to 15 years with the introduction of several different bonding techniques and materials, numerous interlayers in laminated glazing and different metal oxide coatings applied for solar control properties, meaning that no single recycling methodology can be adopted.

It should be noted that ELV's may not all be of a similar age, depending upon the nature of their final failure (i.e. a 15 year old worn-out vehicle may be processed alongside a 2 year old crashed vehicle), and glass recycling is only normally cost effective when the scrap is very closely controlled as mixtures of different glasses and the presence of contaminants will result in poor quality recyclate.

The cost of new glass is also relatively low and the labour costs alone of retrieval of components from a vehicle will probably be greater than the value of even excellent quality recyclate, meaning the whole exercise is not economically viable.

In order to satisfy the ELV requirements, there is an increasing need for economically recyclable glazing systems. A cost-effective method of recycling polycarbonate has already been demonstrated for music CD's where 750,000 surplus discs a week are recycled. This equates to 10 tonnes of polycarbonate, which is then sold on for re-use, either for new discs, or other applications such as headlight lenses. (Hague, 2001)

2.0.6 The Changing Engineering Environment

At the outset of the programme, it was thought that a reduction in component weight and increased vehicle security would be the greatest attributes of polymer glazing, with the remainder of the list satisfying minor needs.

However as the programme progressed in conjunction with several automotive engineers and companies, an overall mind-set evolved such that styling flexibility became the most desirable capability of the technology, with recycling of increasing importance as the ELV Directive approaches realisation.

This shift in requirement can be mainly explained by emerging glass technologies that allowed substantial decreases in component thickness (and therefore weight) to be achieved and enhanced intruder resistance through laminated glazing which became more readily available within the marketplace.

Table 2.1 summarises how engineering needs have changed during this programme and how polymer technology could potentially satisfy those needs. The financial implications of these changes in emphasis are discussed further in Chapter 7 and elsewhere within the portfolio. (Kirwan, October 2001)

Engineering Need	Benefits Acquired Through Polymer Technology	Original Ranking of Importance	Final Ranking of Importance
Vehicle Weight Reduction	50% weight saving compared to glass. Improved fuel efficiency – lower emissions.	1	2
Car Security	Inherent intruder resistance. Thinner/lighter than laminated security glazing.	2	4
Styling Flexibility	Almost total design freedom. Can mould in auxiliary fixtures/mountings - reduced complexity and costs.	3	1
Vehicle and Occupant Safety	Potential to retain occupants in most severe accidents. Lower HIC levels generated during impact - reduced head and neck trauma. Very low risk of flying debris. Can lower centre of gravity/improve handling of a vehicle.	4	5
Recycling	Can be reground and reused if separation of different polymer types can be achieved economically. Cost effective recycling route for polycarbonate has already been proven.	5	3

Table 2.1: - Summary of Engineering Needs and Potential Benefits of Polymer Glazing

2.1 Problem Analysis – Identifying the Technology Constraints

It was found that several technology issues existed that inhibited the widespread adoption of polymer glazing and these were classed as either 'critical' or 'desirable'.

Critical technologies were defined as being 'must-have' capabilities essential to the acceptance of polymer glazing and if they were not addressed then polymer glazing could not even enter the market place.

Desirable technologies were identified as 'nice-to-have' features and were generally auxiliary functions readily available for glass. It was considered that these were 'order winners' and the more that could be made available to polymer glazing, the more competitive the technology would become for any given application.

Two constantly critical constraints were identified; component scratch resistance and long-term weatherability. A third critical issue was also noted as being component stiffness, although this was highly dependent upon the required component shape.

Several desirable capabilities were found to be prevalent for polymer glazing including solar control, anti-fogging, thermal stability and hydrophobic (anti-frosting) capabilities and these have all been discussed elsewhere within the portfolio (Kirwan, 1999) and are summarised in Table 2.2.

Desirable Technology	Function
Solar Control	Minimises build of heat inside a vehicle due to sunlight through absorption or reflectance of infrared light from the solar spectrum.
Anti-fogging	Prevents moisture droplets forming on inner surface of window – no need for demisting.
Thermal Stability	Polymers have much higher coefficients of thermal expansion compared to metals. Several potential problems if polymer glazing is exposed to elevated temperatures including: - • Significant distortion of component when directly bonded to metallic body - adhesive also subjected to high stress. • If installed in body recess, will expand until constrained and then distort. • Refractive Index is related to material density – may exhibit significant change with temperature.
Anti-frosting	Prevents ice from forming on the outer surface of a window – no need for scraping.

Table 2.2: - Summary of Desirable Technologies

Whilst many of the identified issues were technical, it was also found that psychological hurdles existed as well. The perception of feeling trapped inside a vehicle fitted with 'indestructible' glazing was very real and has also been noted elsewhere. (RSC, 2001; RIQ, 1996) It was also found that plastics are still misconceived as being cheap or inferior when compared to more traditional materials. The public is very much aware of glass and how it looks, feels and behaves, and more importantly glass is expected to be the glazing material within a vehicle. From the outset it was obvious that any potential polymer glazing would have to appear to be glass to the untrained eye if that mindset was to be overcome.

2.1.1 Critical Technology - Scratch Resistance

The single biggest and most apparent problem with polymers is their very low scratch resistance when compared to glass. (Kirwan, 1999; January 2001) and even minor contacts with sharp edges or abrasive materials can lead to damage on the polymer surface. Any glazing that becomes easily damaged would have to be replaced by the manufacturer who would have to meet the associated costs and, more importantly, poor quality could deter consumers from future purchases of a particular vehicle brand.

The most common way of improving scratch resistance is to apply a thin (4 - 12μm) silicone hardcoat (Kirwan, December 2001) which can be either organic or inorganic.

Inorganic coatings are based upon silicone chemistry and are thermally cured at around 130°C. These offer the highest performance of abrasion resistance and are applied at a thickness of around 5 –7μm. (GE-Bayer Silicones, 2000)

Organic coatings are based upon silicone modified polyol/acrylate materials and are UV curable, thus offering much reduced process times but unfortunately are not as durable (weatherable) as inorganic coatings and have to be applied in a greater thickness of about 12μm.

The Smart car window was coated with a commercially available inorganic coating and generally performed well in the urban environment that the car was designed for. However there were (undocumented) reports of damage from tree branches and bushes when the vehicle was used in the open countryside.

There remains a general feeling among automotive engineers that the current commercially available hardcoats are still not good enough to withstand everyday use in anything but the most sympathetic climate.

More recent attention has turned towards the application of exotic materials, such as metal oxides, onto polymer surfaces through plasma deposition. (Wang et al, 1994; Benmalek,

1997) Exatec have adopted this approach in conjunction with the more traditional liquid hardcoat, which is used as an interlayer as shown in Figure 2.4. (Exatec, 2001) The exact material deposited is not publicly known, but performance values released by the company report that the combination works very well. (Orth et al., 2000)

However, whilst this system has been available since the creation of Exatec, no components have ever made their way into production vehicles and there are no apparent plans for any in the near future.

One reason for this may be that plasma deposition is an incredibly expensive coating operation because of the high oven costs, low coating speed and the small batch sizes that can be processed at any one time. (Browall et al., 1997; Harbison, 1993) When this is considered against the unit price of traditional glass components, the high plasma coating costs could far outweigh the benefits that using polymer technology would bring.

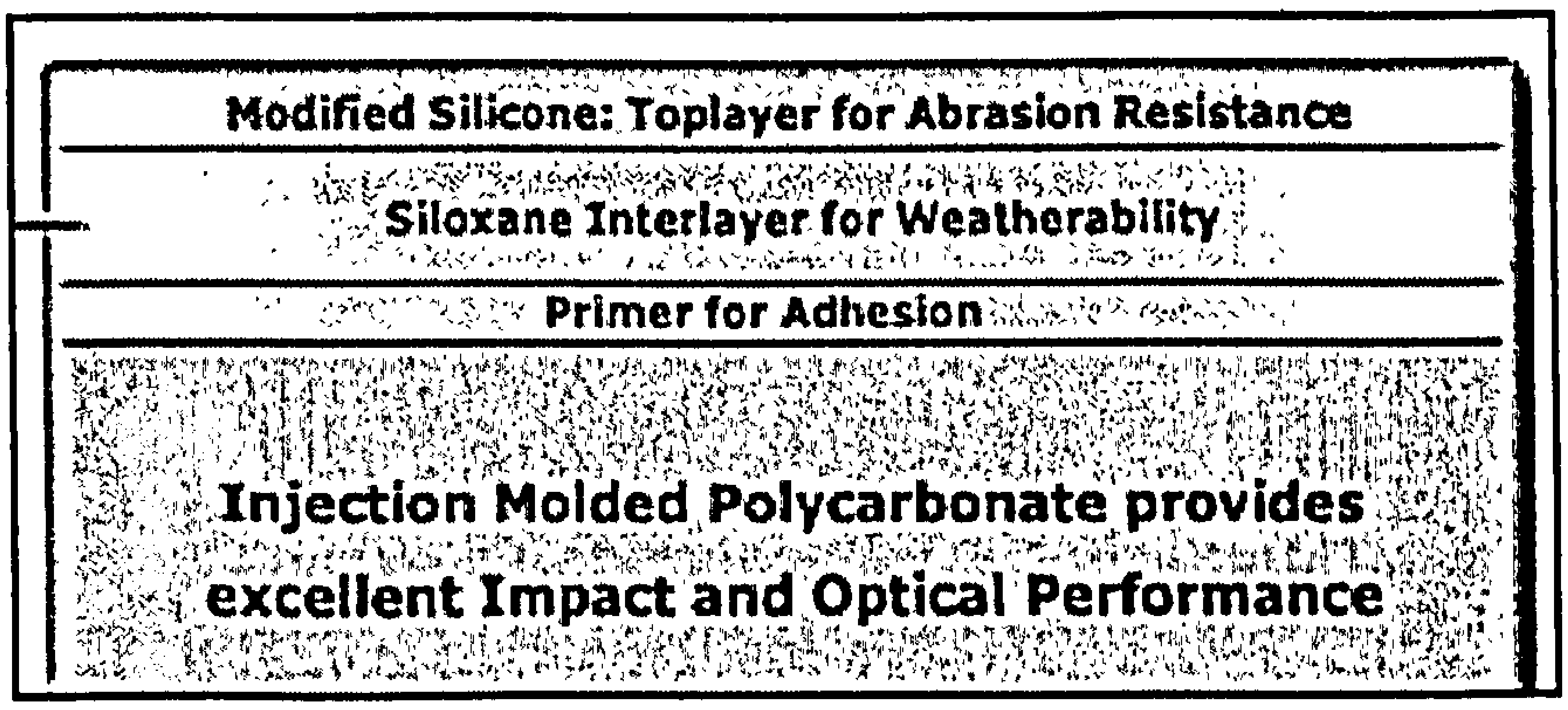


Figure 2.4: - Exatec's Plasma Deposition Coating Solution

Research has recently focussed upon ceramic nanotechnology for use within solution based hardcoats. (Kirwan, December 2001) TWI have developed 'Vitresyn', an organic-inorganic hybrid composite coating (TWI, 2001) which can be tailored to behave in a certain manner by altering the inorganic loading and this has been found to be the most effective hardcoat available.

A substantial amount of work was carried out by TWI to develop the coating for use within this programme and this is discussed in Chapter 3 in the context of the development of an acrylic film-polycarbonate hybrid glazing system.

2.1.2 Critical Technology - Long-term Weatherability

The second critical issue identified was long-term weatherability. At present polycarbonate is the most desirable material for use within a glazing system because of its inherently high impact resistance but it is particularly vulnerable to degradation when exposed to even mild chemicals, as found in many cleaning solutions, and UV light, which is of course present in sunlight. (Maxwell, 1994)

Most automotive OEM's require exterior components to withstand 5 years Florida and Arizona exposure with minimal degradation. (Kirwan, December 2001) The only recognised way to increase long-term weathering resistance is via the hardcoat, which normally has a UV resistant primer layer.

Unfortunately, as discussed previously, the hardcoat technology is at present not good enough to reach the standards required for automotive glazing applications. Given that the coatings are only about 10µ thick, any damage beyond mild abrasion, i.e. a scratch or stonechip, will reveal the vulnerable polycarbonate substrate, which can then degrade as it is exposed to the environment. This can in turn lead to a loss in both optical and mechanical properties meaning that the glazing unit would have to be replaced.

2.1.3 Critical Technology - Component Stiffness

A third critical concern exists over the stiffness of polymer because of the inherent flexibility of the material. This can cause problems with large or flat applications where rigidity cannot be designed in through curvature. In order to improve the stiffness of any polymer component, it would normally be necessary to increase the thickness and therefore the weight, which reduces one of the benefits of the technology.

A component that flexes would clearly not be aesthetically acceptable and there is empirical evidence from Land Rover's LCV 2 vehicle (Kirwan, January 2001) that flexure of the polymer substrate can lead to cracking and failure of any applied hardcoat. If a moving side window were made from polymeric materials, then flexure caused by closing of doors could lead to premature failure.

It has been shown that a half-open polycarbonate window of similar dimensions to glass cannot be closed whilst the vehicle is moving due to the distortion caused by the pressure differential between the inside and the outside of the vehicle. It has also been reported that the vacuum caused by the airstream over a moving vehicle is strong enough to pull polycarbonate glazing out of its running channel. (Orth et al., 2000)

A secondary effect of poor rigidity is noise attenuation. Vibrations in the vehicle body can be transmitted to the glazing and if the component is not rigid then it can resonate like a drum and cause considerable discomfort in the passenger compartment.

The level of noise transmission associated with a polymer component of comparable thickness to glass will also be higher for slow moving vehicles. According to the law of masses, noise transmission in the frequency range up to 1000Hz correlates with the mass or wall thickness, i.e. given the same dimensions, polymers will transmit more noise because of their lower density compared to glass. It has however been shown that polycarbonate will behave more effectively above 2000Hz as shown in Figure 2.5 which is the range for wind noise over a moving vehicle and the range at which the human ear is more sensitive. (Orth, February 2000)

No satisfactory solution has yet emerged for addressing the issue of rigidity. Traditionally a frame would have been used for free-standing glass components, but this is no longer permissible due to styling demands of seamless vehicles. One proposed solution involves gas-injecting a 'frame' around the outer extremity of a polycarbonate window and results in a stiffness equivalent to glass, however the long lead-time on component development and alterations to the door system render this method impractical. (Orth et al., 2000)

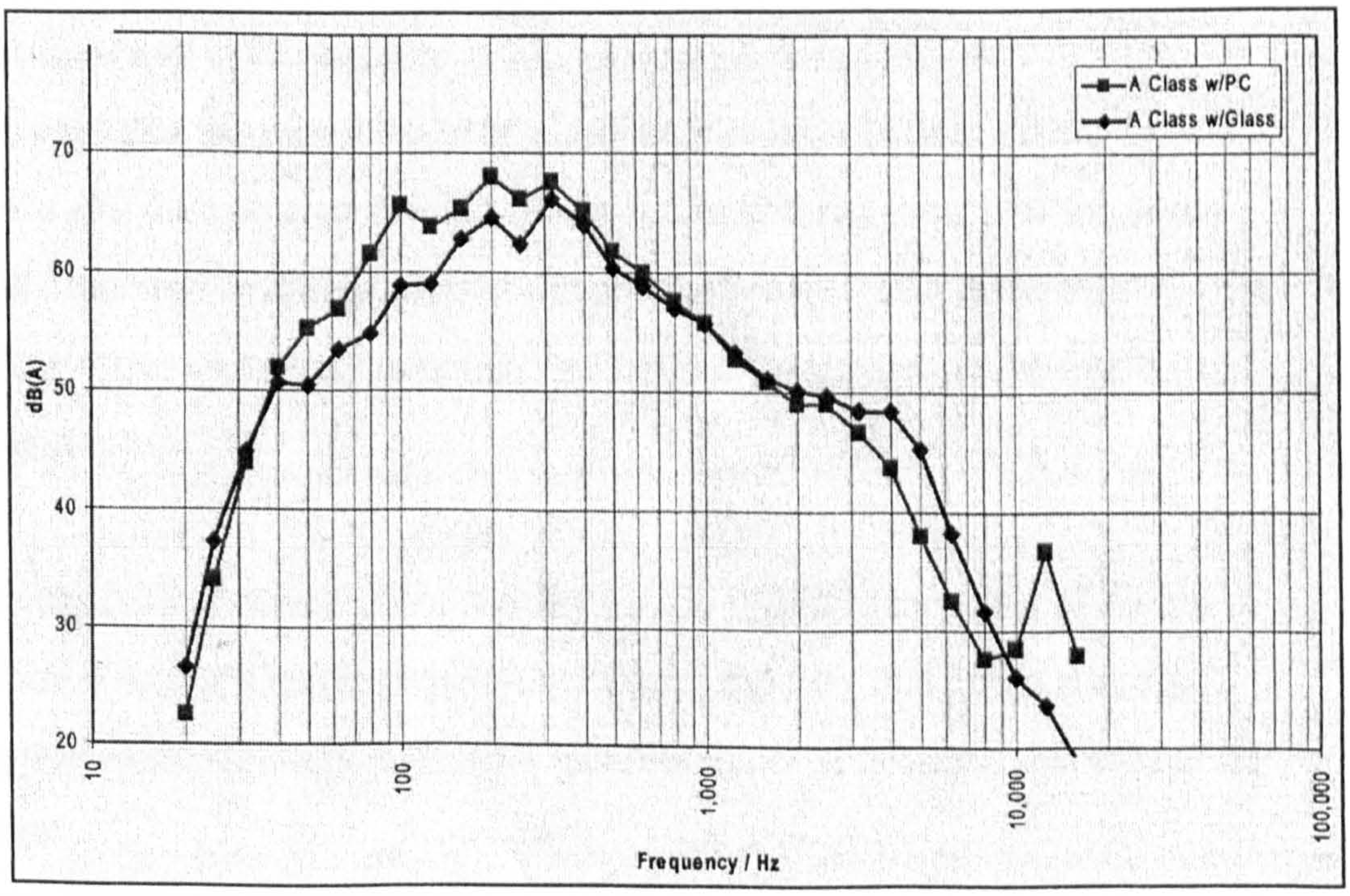


Figure 2.5: -Noise Transmission of Different Glazing Materials

(Orth , February 2000)

2.2 Proposed Solutions to Technical Constraints

Upon completion of the Problem Analysis stage, it was possible to identify where research activities should be focussed given the competencies available to the programme. The realisation of the critical technology constraints meant that effort could be focussed upon those areas in order to bring the concept of polymer glazing nearer to reality through the programme outlined in Chapter 1.

It was not possible to physically undertake development of any form of coating system as the resources and skills were simply not available. This meant that addressing the constraints of solar control, scratch resistant and anti-fog/frost coatings was beyond the scope of the programme. A decision was taken to keep a watching brief over these different areas of coating development and to assist other parties if possible to gain access to any new emerging technology.

The issue of long-term weatherabilty has been linked to the development of more resilient hardcoats, which still does not appear to be happening as rapidly as required. It was decided that a major focus of this programme would be the development of alternative approaches that combine polycarbonate with acrylic, which has much superior chemical and UV resistance. (Kirwan, December 2001; February 2002)

It was proposed that the introduction of a thin acrylic layer between the polycarbonate and the hardcoat would act as a buffer and any breach of the outer surface would not lead to degradation of the polycarbonate. Two different manufacturing approaches were adopted, and further discussion can be found in Chapters 3 and 4.

The remaining critical constraint of rigidity can be linked to the issue of thermal stability. No real solution has become evident from industry that could address thermal expansion in polymers, as it is an inherent material property that cannot be readily altered.

It was suggested at the outset of this programme that attention should be focussed upon the use of a frame that would allow expansion into the recess area around the component. (Dow, 1998) This was quickly dismissed, as it was quite apparent that the use of frames around glazing would not be acceptable to automotive stylists.

The polymer component on the Smart car is directly bonded to the vehicle, but incorporates a foam gasket between the adhesive and the polymer to allow expansion of the window without transmitting stress to the adhesive. This appears to work very well for fixed components, however there is a security issue as the window can theoretically be levered out of position if the foam gasket fails.

However it has been recognised elsewhere (Rosato, 1997) that the inclusion of glass fibres within a polymer matrix improves both the rigidity and the thermal stability because the fibres do not expand and 'hold' the polymer in place.

It is common to reinforce polymeric components with glass fibres, but this is not easily performed with transparent applications, as the component will turn opaque due to light refraction within the different substrates.

It was proposed (and later demonstrated) within this programme that it is possible to introduce substantial glass fibre reinforcement into a transparent polymer whilst retaining optical quality, if certain conditions are satisfied. This approach has the potential to address both rigidity and thermal stability and as such represents a very important engineering capability of significant business value.

Two patents have subsequently been filed on this technology (GB2352249 & GB2338675) and further discussion can be found in Chapter 5 and elsewhere within the portfolio. (Kirwan, April 2002)

3.0 An Acrylic Film – Polycarbonate Hybrid Glazing System

A technical assessment of the candidate materials that could be used for glazing applications showed that no individual material could satisfy all of the performance requirements with the best theoretical solution being a combination of polycarbonate (PC) and acrylic. (Kirwan, Jan 2001)

It was considered that the easiest way to combine such materials would be to back-inject PC onto a thin film of acrylic as it would allow the quick manufacture of samples that could be used for validating material selection and examining critical properties such as impact resistance and weatherability. The different techniques for in-mould laminating films onto components are readily understood and widely used in many different areas, providing a wealth of process information that could be easily utilised. (Nastas, 1994; Ellison, 1993; Matsco et al., 1996, Griffin, 1996)

The key reason for incorporating an acrylic film into a glazing system was to enhance the long-term weathering resistance of a component. Pure polycarbonate glazing systems rely upon all weathering and chemical resistance to be provided by the applied hardcoat. This limits the number of coatings that can be used and if the coating is breached then the vulnerable substrate is able to rapidly degrade.

Acrylic is characterised by 'crystal clear transparency...unexcelled weatherability, outstanding surface hardness, good chemical resistance... and a useful combination of stiffness, density and moderate toughness'. (Ulrich, 1993) Toughness can be further increased through the addition of rubber modifiers. (Ram, 1997)

Acrylic has previously been used, in the form of a lacquer, to protect polycarbonate from chemical and UV degradation, in applications such as tail lamps and side lenses. (Carlisle, 1987)

This part of the programme used a film made from a proprietary acrylic resin, which was chosen because of its good UV blocking capability and it did not affect component ductility, unlike PMMA film, which was found to greatly reduce the overall impact strength. (Dow, 1998) Due to confidentiality agreements, it is not possible to describe this film in any more detail.

The main objective of this part of the programme was to investigate the film application process and assess its suitability for the production of 2nd Generation glazing components.

The deliverables from this project were: -

- Transparent test pieces that exhibited excellent adhesion between film and substrate layers.
- Test data to show how the application of the film to the polycarbonate substrate affected critical parameters in polymer glazing such as long-term weatherability and component impact resistance.
- Information and understanding of the production process and how different system variables affected the quality of components.
- Scratch resistance benchmark data of components coated with different commercially available hardcoats.

The film development programme was split into several stages of activity to address each of the required deliverables in turn, namely: -

- Process & tooling development
- Benchmarking of available hardcoats
- Accelerated Weather testing
- Impact testing

Detailed discussion of the entire development programme can be found in the relevant portfolio submission. (Kirwan, December 2001)

3.1 Process & Tooling Development

The film employed for all of the trials in this development programme was a 'blown' grade that did not exhibit a high enough standard of optical quality. As such, a 'cast' variety would be needed for any final application. The film also needed to be cut slightly smaller than the mould cavity to allow for thermal expansion when back injected with molten polycarbonate, suggesting that a final solution would require the film to be pre-formed, particularly for more complex shapes.

Initial trials revealed that 100μm film was the thinnest gauge of acrylic film that could be back injected onto because of the temperature difference between the melting point of the film ($T_m = 240°C$) and the processing temperature range of the polycarbonate ($T_p = 280 - 320°C$).

The processing conditions of the polycarbonate needed to be such that the resin temperature and injection speed (V) were kept as low as possible, typically Tp = 270°C and V = 25mms^{-1}. (The reduction in polycarbonate processing temperature was possible because the acrylic film acted as an insulator and reduced the rate of cooling of the injected polymer, meaning that full mould packing was still achieved.) This minimised the risk of the acrylic film melting and reduced the shear stress generated over the film by the flow of polycarbonate, which can lead to melt fracture in the acrylic layer, as shown in Figure 3.1, and the subsequent component hazing that is seen in Figure 3.2.

However it was found that simply optimising the process conditions was not sufficient to prevent hazing. The gating arrangement of the moulding tool was also found to be critical in obtaining haze free samples.

The runner and gating arrangement must be designed so that the polycarbonate can flow under, and not through, the film as it enters the cavity. If the polycarbonate does flow through the film then mixing of molten acrylic and polycarbonate will occur, causing significant haze within the component due to a mismatch in the refractive indices of the two materials. If the materials are kept in discreet layers then hazing does not occur.

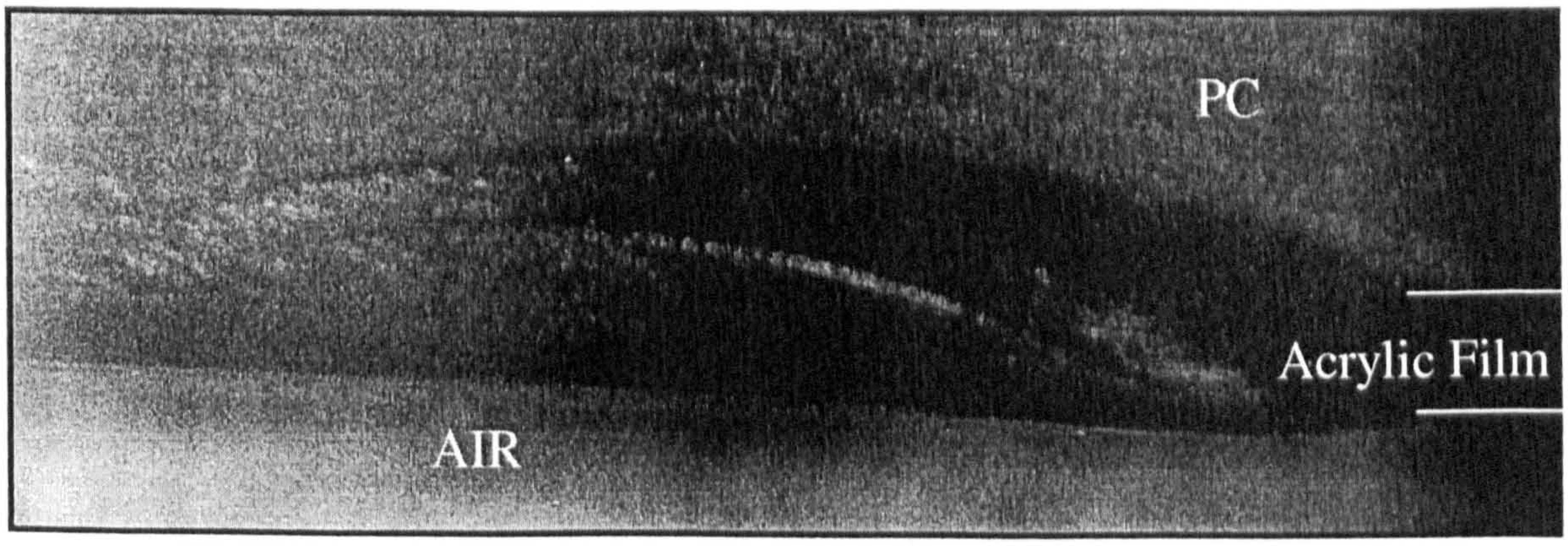


Figure 3.1: - Cross-Section Through A Hazy Sample Showing Flow Instability Between the Acrylic Film and PC Substrate

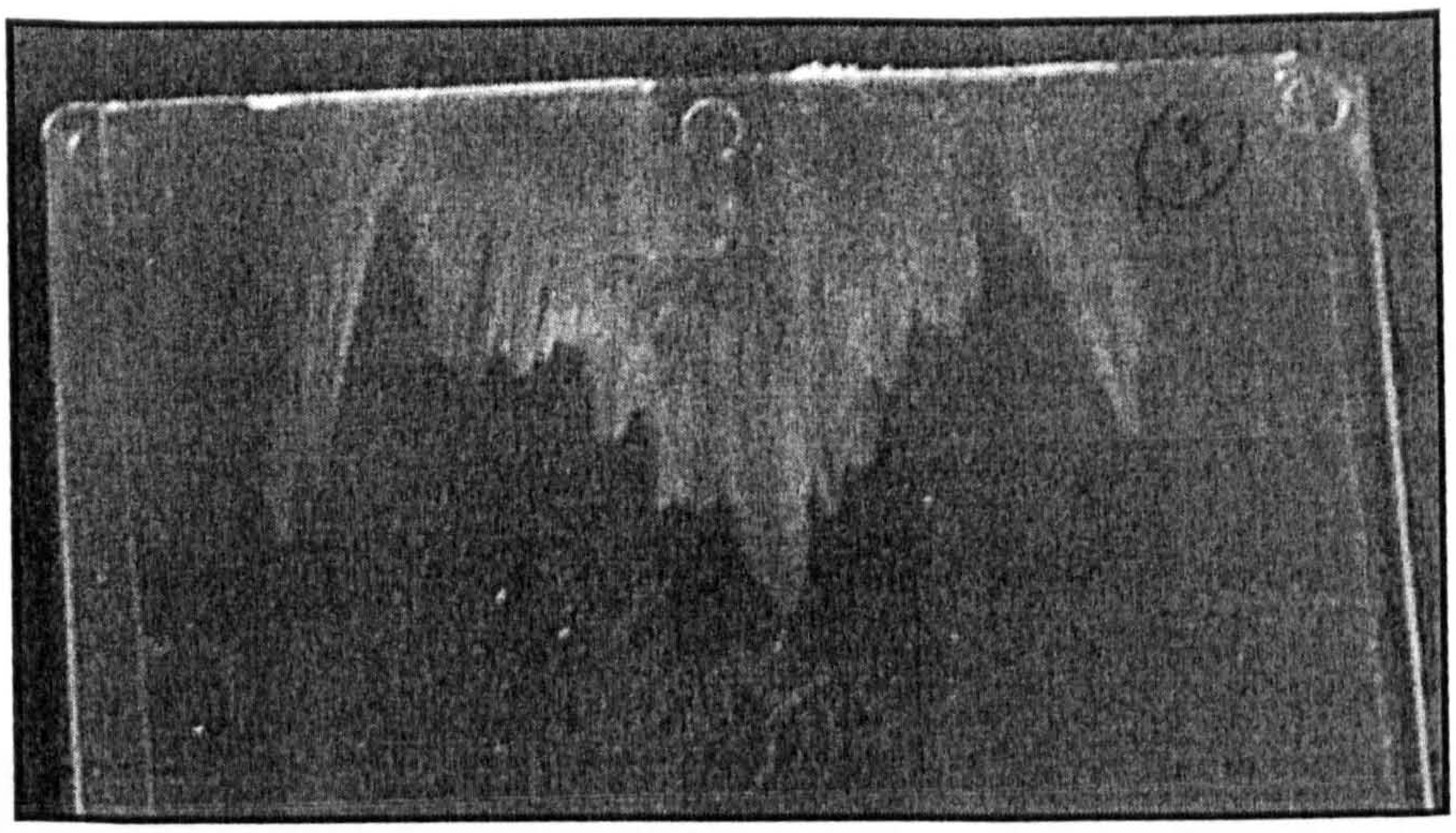


Figure 3.2: - Melting of the Acrylic Film Causing Hazing in the Sample

The original design of the injection gate was rather complicated, containing very thin sections as shown in Figure 3.3. In these regions, a constriction in material flow lead to localised increases in melt temperature due to the increased work on the polymer required to maintain a constant flow rate.

The material shear heated within the thinner section of the gate to a temperature high enough to melt the acrylic film. The speed of the material flow in this area would also have increased because of the constant volume flow conditions imposed by the injection machine.

The combination of increased temperature and flow speed induced film-melt fracture because the shear stress over the surface of the film in this area became greater than the film-melt strength.

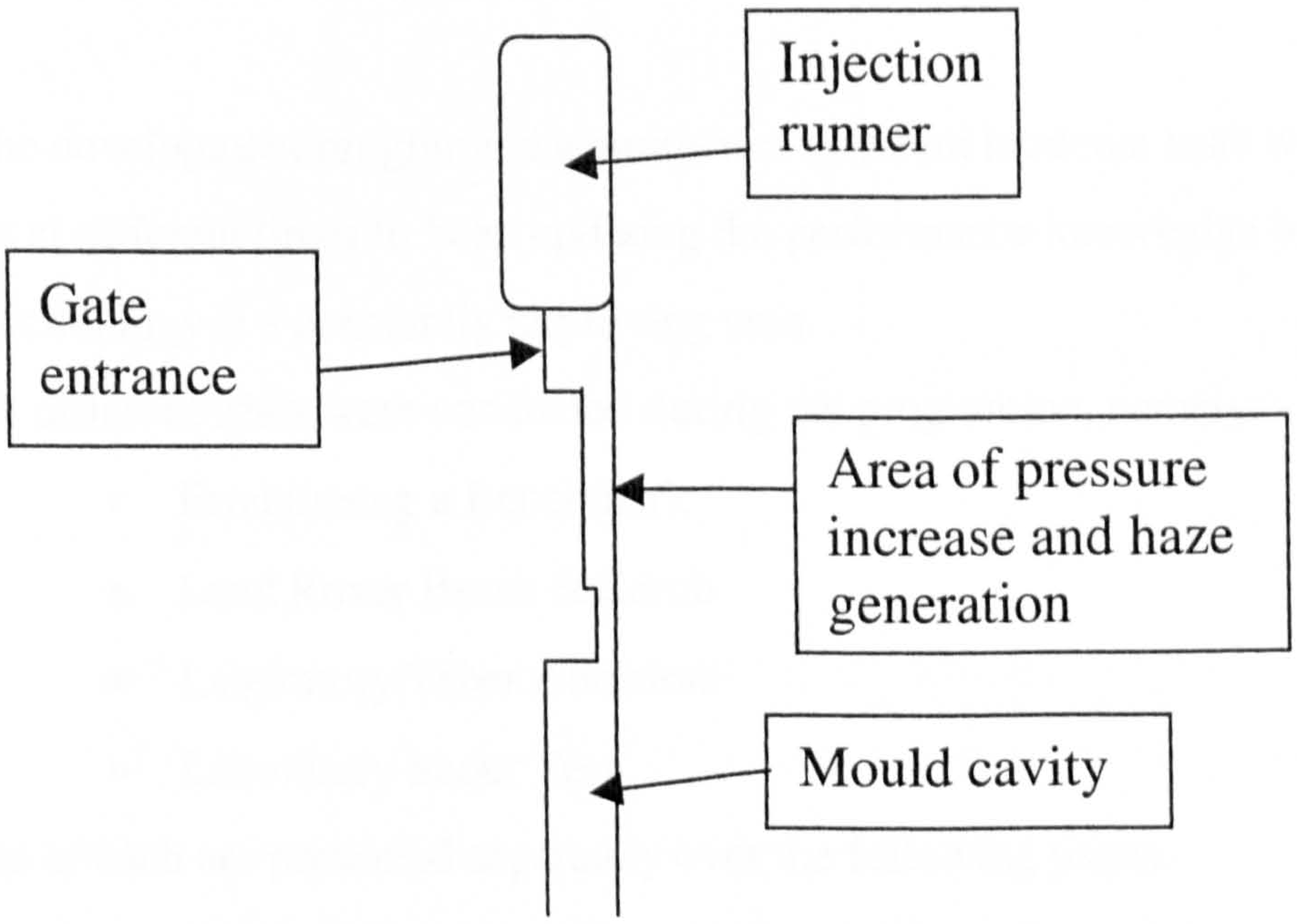


Figure 3.3: - The Initial Tool Gating Arrangement

It was hypothesised, and later demonstrated, that this problem could be removed by designing a gate of constant cross section to minimise any pressure differential and subsequent heat generation.

A new tool, based upon a Land Rover Alpine light, was constructed in-house employing this principle and all subsequent test components made via this tool exhibited no film-melt fracture or hazing as shown in Figure 3.4.

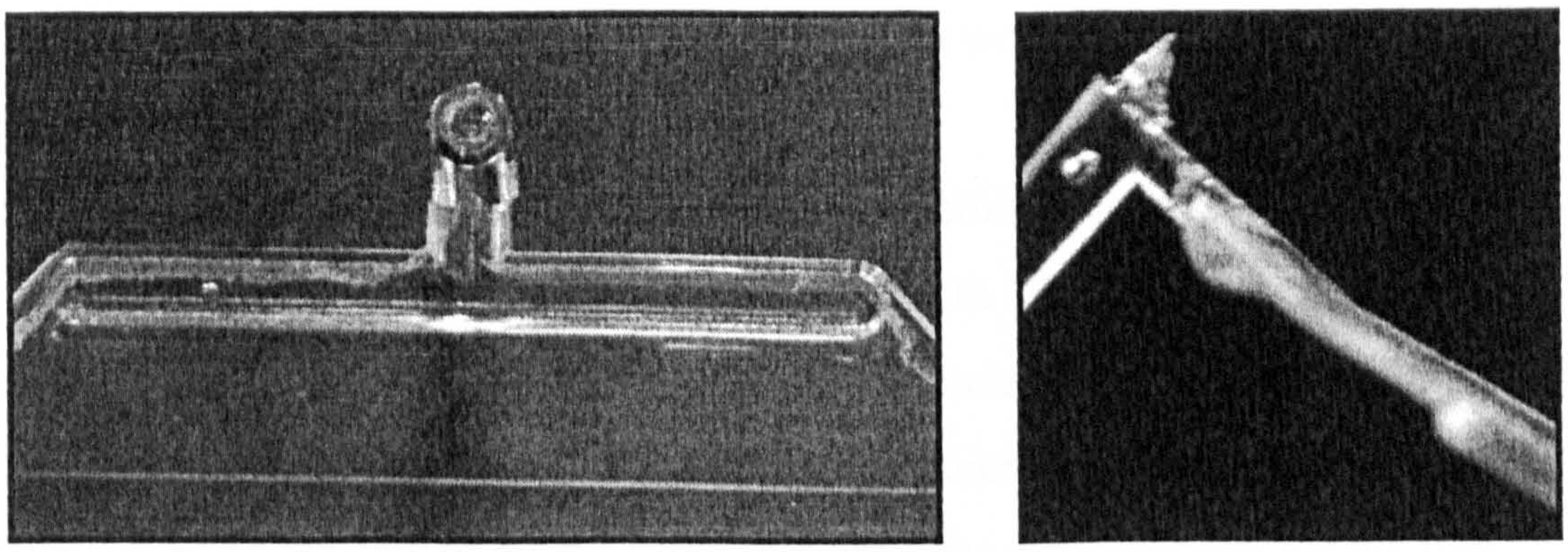


Figure 3.4: - The New Alpine Light Component Showing the Constant Cross Sectional Gate and No Haze

3.2 Benchmarking Available Hardcoats

It is commonly accepted that any polymer used for a glazing application will require the addition of a hardcoat, the principles of which have been discussed in Section 2.1.1.

During the development programme a number of different hardcoat tests were carried out at different times to keep updating the performance knowledge base as hardcoat technology is a constantly improving area.

In total, 4 different trials were conducted during the programme, namely: -

- Establishing a Benchmark
- Land Rover Brush & Scrub
- Laboratory Taber Abrasion
- Laboratory Scour Test

The results of each are presented separately over the following pages.

3.2.1 Establishing a Benchmark

An original project partner stipulated that any final polymer glazing system would have to be coated with a variation of a commercially available coating from SDC Coatings in the US- their subsidiary company. Some primary benchmark trials were therefore conducted to examine SDC's Crystalcoat MP100 coating and the intention was to establish the performance of the SDC MP100 + acrylic film system as a standard against which coating refinements could be measured. There was also an interest in whether the inclusion of the acrylic film would improve or detract from the overall hardcoat performance.

Two sets of polycarbonate samples were manufactured, one set with acrylic film present and one without. Both sets were coated with MP100 by SDC. Both sets of samples were tested using a conventional taber abrader and a summary of the results is presented in Table 3.1, along with the manufacturers published performance for MP100 applied directly to plain acrylic that provides a comparison for the film performance.

It was found that the hardcoat performed as per the manufacturers data sheets when applied to plain PC, but when applied to the acrylic-backed samples, the abrasion resistance of the coating increased dramatically suggesting that the film was significantly influencing the overall performance.

Coating Identity	Substrate	Primer Required	Abrasion Damage♦/Cycles
CrystalCoat MP100	**Acrylic**	**No**	**7% / 500 ***
CrystalCoat MP100	**Polycarbonate**	**Yes**	**5%/500**
CrystalCoat MP100	**Acrylic Film**	**No**	**4% / 1000**

♦ Abrasion damage is measured as a loss in transparency (ΔHaze) and measured as per ASTM test method D1003.

* Manufacturers Published Data

Table 3.1: - Results of Initial Taber Abrasion Trials

It has previously been found that head impact damage is vastly reduced when bi-laminate screens were impacted by headforms as compared to traditional tri-laminate glazing. The thin, soft rubberised polymer layer that was applied directly to the hard, rigid glass transferred the energy associated with head impact away from the impact point, reducing any resultant damaging forces. (NHTSA, 1995)

It has also been shown that the level of protection afforded to a coated component is a function of the level of adhesion to the substrate and stress dissipation. (Awad et al., 1997) Abrasion damage is caused when a load over an area exceeds the hardness of the material it is applied to. Hardcoats cannot deform and they are extremely rigid, in effect behaving like very thin sheets of glass so they have no 'cushioning' characteristics.

In this instance, the presence of the comparatively thick, soft rubberised acrylic film directly underneath the hardcoat, suggests that the applied load was being transferred through the hardcoat and then dissipated away from the contact point. Hence the improvement in abrasion resistance.

However it has been recognised that coatings performance will vary under different laboratory examinations, meaning that ones that perform well in one type of trial may perform very badly in another and vice-versa. (Awad et al., 1997; Browall, 1993) It was also felt that laboratory trials did not reflect in-situ conditions that any coating would be exposed to.

It was decided that the 'real-life' Land Rover Brush & Scrub test was needed to further evaluate the improved performance of the SDC - film system and benchmark it against other hardcoats available at the time.

3.2.2 Land Rover Brush & Scrub Trials

In order to provide more evidence of the improved performance of the SDC coating, which was the preferred solution, a practical trial was arranged at Gaydon in March 2000 to assess 'in-situ' performance of the developed system and alternative commercially available solutions.

The trial involves installing the test components onto a Land Rover Discovery and then driving the vehicle through a woodland area without any paths. The scrub must overhang the bodywork by a minimum of 12 inches and the vehicle is driven forward 5 times through a section and then reversed once. This is repeated for the opposite side.

The vehicle is then returned to the wash area and subjected to a high powered jet-wash all over to remove dirt and debris. Test components are then removed and their performance evaluated.

The components subjected to the test are listed in Table 3.2. The test pieces were bonded to the rear quarter window on each side of the vehicle as shown in Figure 3.5, to ensure that any branches being dragged across the surface had reached a steady horizontal motion rather than having a 'shock' impact on the leading plaque.

Sample	Component Identifier	Film Present	Hardcoat	Manufacturer
1	SDC	Acrylic	MP100	SDC
2	SHC 3000	None	SHC 3000	GE-Bayer Silicones
3	PC	None	None	N/A
4	Autoflex	PC	Proprietary	Autotype
5	EMS	None	Proprietary	EMS

Table 3.2: - Brush & Scrub Trial Components

The final ranking of the tested samples for both sides of the vehicle was the same despite the obviously different test conditions that each side was subjected to. The samples that faired worse were the base PC, followed closely by the coated EMS nylon sample, both of which were severely damaged. The SDC-acrylic film solution had virtually no damage at all and was the best performing set of samples. Appendix A contains a series of photographs of all of the samples after they had been removed from the vehicle.

Figure 3.5: -Brush & Scrub Samples In-situ Before Trial

3.2.3 A New Generation of Hardcoat

Unfortunately the collaboration with SDC and its parent company ceased shortly after the primary benchmarking trials had been conducted. However the new nanotechnology based coating 'Vitresyn' from TWI, discussed in Section 2.1.1, became available to the programme soon after.

Independent testing of this system by the Paint Research Agency indicated that the hardcoat was far more effective than any commercially available alternative. (TWI, 2001)

It was necessary to benchmark this new coating against the existing SDC-film system to see if it faired as well. It was not possible to repeat the Brush & Scrub test because of the huge cost involved, so investigation took place under laboratory conditions.

3.2.4 Laboratory Taber Abrasion Testing

A series of laboratory taber abrasion tests (Kirwan, Jan 2001) were performed at Gaydon and Table 3.3 outlines the exact construction of all of the samples tested.

The wheels of the taber abrader were loaded to 500g and refaced between each trial by running a fresh re-facing disk on the turntable for 50 cycles.

The samples were located in position, locked down to avoid slippage during rotation and the turntable was operated at 65 rpm for a series of 250 cycles for each component. Depending upon the damage present, some samples were subjected to a further series of 250 cycles as shown in Table 3.3.

Sample	Component Identifier	Film Present	Hardcoat	Manufacturer	No. of Taber Cycles
1	SDC	Acrylic	MP100	SDC	500
2	SHC 3000	None	SHC 3000	GE-Bayer Silicones	250
3	PC	None	None	N/A	250
4	Autoflex	PC	Proprietary	Autotype	500
5	Vitf	Acrylic	Vitresyn	TWI	500
6	Vit	None	Vitresyn	TWI	500
7	AS4000	None	AS4000	GE-Bayer Silicones	500

Table 3.3: - Construction of Taber Samples

Abrasion damage is measured as a loss of transparency, i.e. the more opaque a sample becomes the less well the hardcoat has performed. This can be quantified as a value of Δhaze, which is the difference between the background haze and the haze in the testing area; greater values indicate more surface damage.

An attempt was made to quantify the values of the haze damage on each of the samples by sending them for optical measurement at an independent company.

Unfortunately the results appeared to be highly erroneous and time pressures did not allow any retesting to be performed. As such the data could not be used for any scientific analysis and it was necessary to rely upon the human eye when evaluating the samples, photographs of which can be found in Appendix A.

The Vitresyn hardcoat did outperform all of the other coatings tested, with the presence of the acrylic film appearing to enhance the performance further. However the evidence of improvement is only visible on the bottom half of the plaque as the coating on the top half suffered from poor adhesion, delaminating early in the test cycle and this resulted in greater damage in that area.

3.2.5 Laboratory Scour Testing

A second series of laboratory abrasion trials was conducted using a piece of in-house equipment developed many years ago by Rover Group. The same specimen formats, described in Table 3.3, were used and the intention was to confirm the ranking of the hardcoat performances, but under different test conditions.

A weighted arm was translated horizontally across the test specimens at a speed of 1 full cycle per second, causing an abrasive action upon the surface through a small piece of Scotchbrite ^{TM} between the component and fulcrum of the arm as shown in Figure 3.6. The arm transferred a force of 16N to the surface of the test piece and each sample was exposed to 50 sweeps.

The construction of the scour arm meant that the full mass acted as a point load on the component surface with maximum damage inflicted in that area. However, the Scotchbrite squares also caused an abrasive effect away from the point load and it was necessary to consider the loss of transparency and the width of the abrasion track when ranking the samples in order of performance. Again, the independent haze measurement results were not reliable and could not be used.

The scour test results agreed with the previous taber results and photographs of the tested samples can be found in Appendix A. Again the Vitresyn samples, and in particular the acrylic film backed sample, performed to the highest standard and hardly showed any damage after the 50 scour cycles which significantly damaged other components. There was also no sign of delamination in any component.

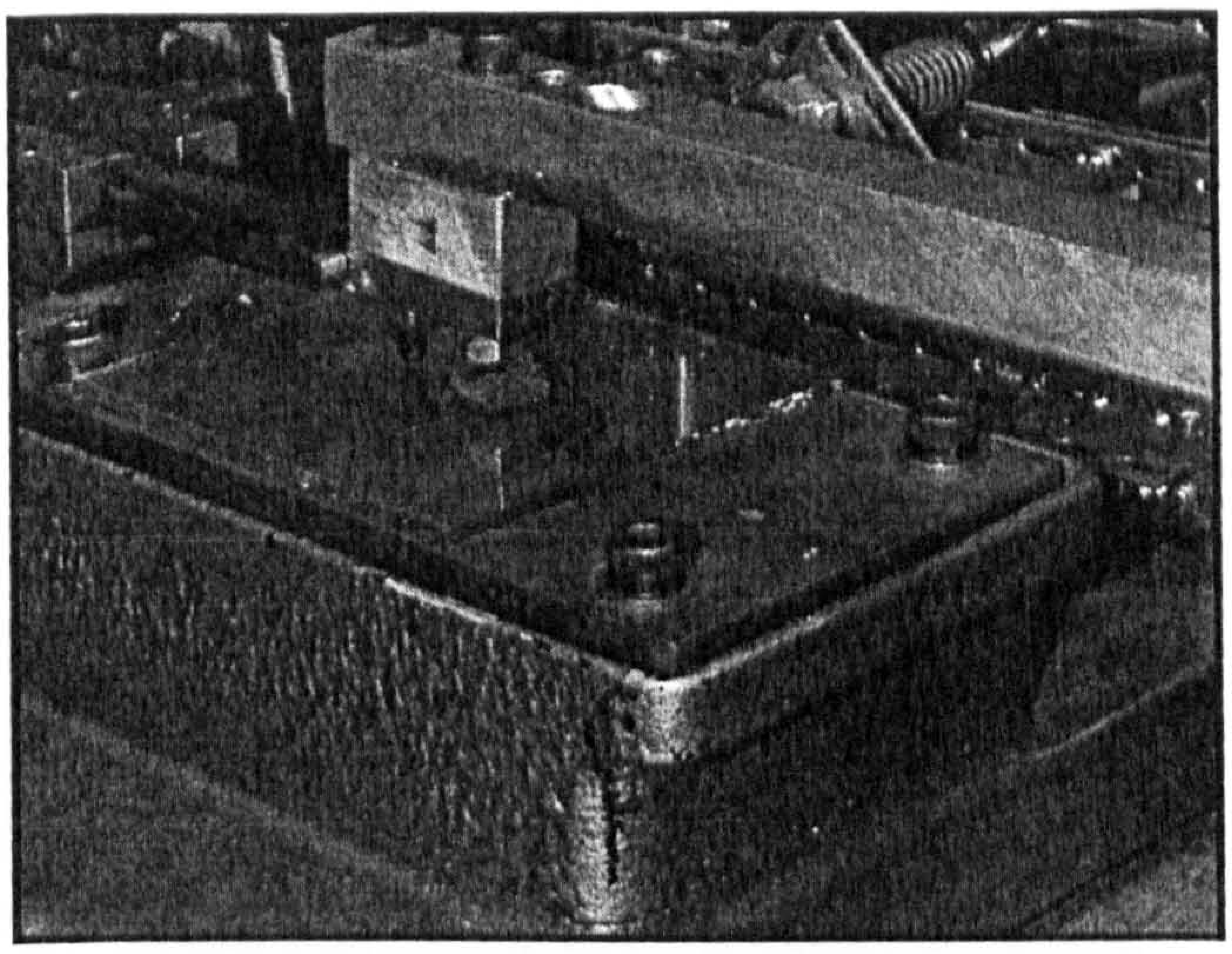


Figure 3.6: - The Laboratory Scour Test Machine

3.2.6 Investigating Coating Adhesion

As mentioned previously, the level of protection afforded to a coated component is a function of the level of adhesion to the substrate and stress dissipation. (Awad et al., 1997) The level of adhesion between different material layers is also an important consideration because not only will it affect the aesthetic quality of any final component, but also influence other properties such as impact resistance and long-term weathering.

During early trials with Vitresyn, it was found that the coating would crack near the edge of the film-backed test plaques and the level of adhesion in these areas was very low with the coating being easily removed by hand.

The problem was identified as the surface tension of the coating, which was cracking upon being cured. The coating chemistry was slightly modified and subsequent plaques that were coated did not exhibit surface cracking. (Kirwan, December 2001) However the problems observed with Vitresyn in the taber trials meant that it was necessary to reassess the level of adhesion achieved between the acrylic film and the Vitresyn hardcoat. The level of adhesion between the acrylic film and the polycarbonate substrate was also investigated and was satisfactory. (Kirwan, December 2001)

The adhesion test procedure adopted was taken from a Rover Engineering Standard and the basic test consists of scribing a 10 x 10 grid of 2mm squares and then applying a strip of pressure sensitive tape that is then pulled sharply back across the sample as shown in Figure 3.7. The adhesion of the coating is measured in terms of the number of squares removed, i.e. 5 squares removed equates to 95% adhesion.

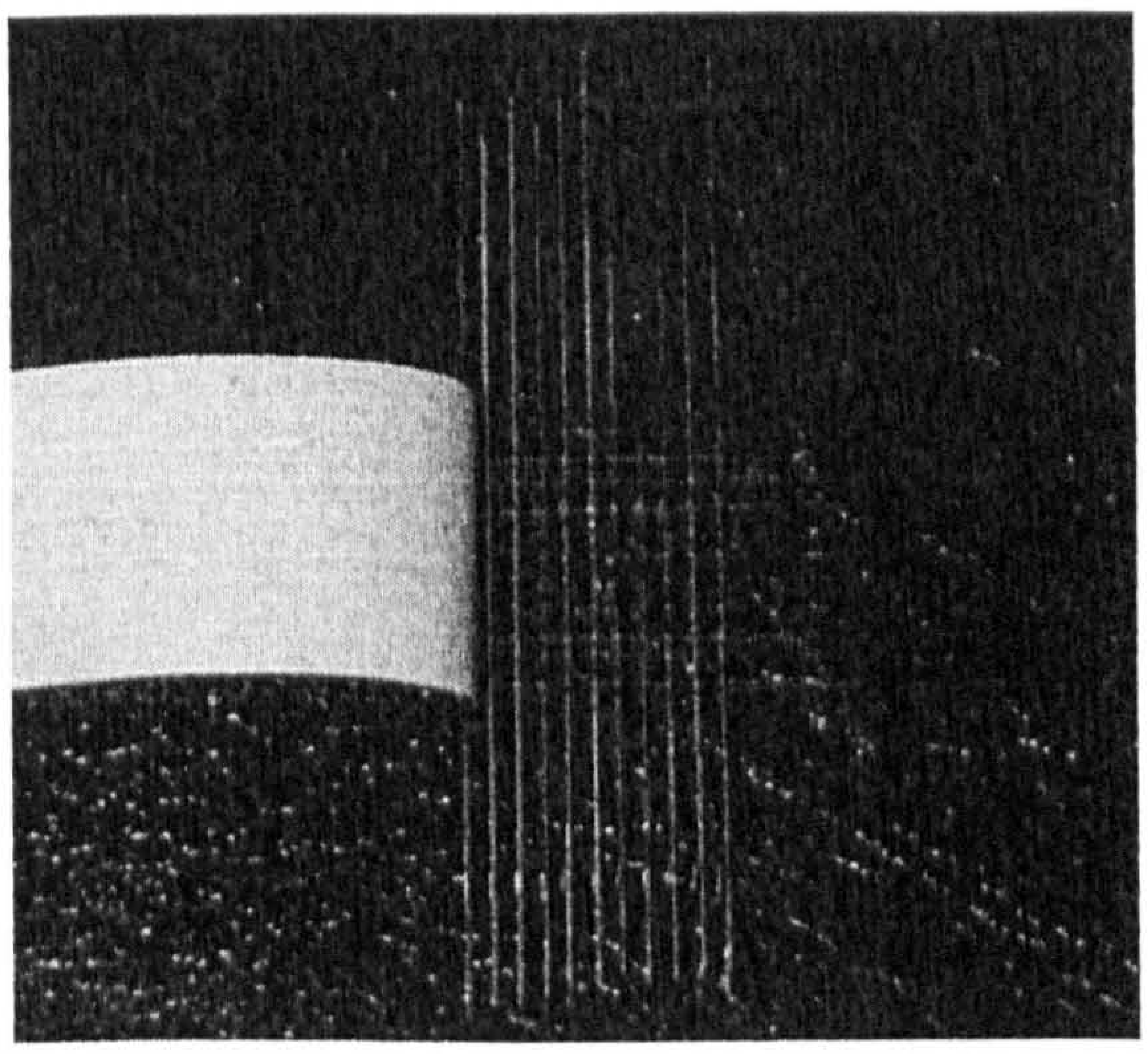


Figure 3.7: - The Coating Adhesion Test

Two different sets of test plaques were used to assess adhesion. The first set were acrylic-backed PC hardcoated with the modified Vitresyn and the second set were commercially available coated polycarbonate (Bayer Makrolon coated with AS4000) that provided a suitable benchmark. Table 3.4 shows the results of the adhesion tests.

Test Plaque	Hardcoat Present	Film Failure (No. of squares)	Hardcoat Failure (No. of squares)
1	**Vitresyn**	**0**	**5.5**
2	**Vitresyn**	**0**	**0**
3	**Vitresyn**	**0**	**60**
4	**Vitresyn**	**0**	**90**
5	**Vitresyn**	**0**	**70**
6	**AS4000**	**N/A**	**0**
7	**AS4000**	**N/A**	**0**
8	**AS4000**	**N/A**	**0**
9	**AS4000**	**N/A**	**0**
10	**AS4000**	**N/A**	**0**

Table 3.4: - Results of Coating Adhesion Tests

The level of adhesion exhibited by the Vitresyn samples varied enormously even though they were produced at the same time. In comparison, the commercially coated polycarbonate exhibited total adhesion for all samples.

Clearly, although it is possible to achieve total adhesion, the manufacturers of Vitresyn (TWI) must identify and address the coating and process issues that are stopping the reproducibility of the coating adhesion. This must obviously be done before the coating can be used on a commercial component and is being undertaken at present.

3.3 Weather Testing

Exposure to the natural environment causes damage to most polymers over a period of time. The sun's powerful ultraviolet (UV) rays combined with the effects of heat and moisture can degrade polymers and the rate at which this damage occurs can vary greatly between materials. (Kirwan, December 2001)

There are two predominant real life tests used for evaluating the long-term performance of polymer components for automotive applications, namely Florida Weathering and Arizona Desert Weathering. Unfortunately both of these test require five years of exposure time, making them totally impractical for research programmes such as this.

However it is possible to gauge the performance of materials through accelerated weather machines that can simulate environmental conditions at greatly increased intensity. (Kirwan, December 2001)

There is no simple formula that can be applied to obtain real-life equivalent results and accelerated data must be thought of as comparative, not absolute. The data obtained provides a reliable indication of the rankings of performance of different materials or systems.

The weathering trials performed in this programme were intended to provide an indication of what the overall system weathering performance was. Much more data and testing will still be required using the final system to satisfy legislative and OEM requirements, but this is extremely costly and can only be carried out much later in the development cycle.

3.3.1 Assessing the Effect of the Acrylic Film

An initial project partner provided some colour coded PC to be back-injected onto the acrylic film so that an assessment could be made concerning the effectiveness of the acrylic as a UV blocking mechanism to afford protection to the PC.

The PC had been matched to the standard US glazing 'Galaxsee', but unfortunately the colour had been developed for 4mm PC plaques and the only available trial tool was 3mm thick. In practical terms, this meant that the samples were lighter than they should have been. However it was considered that they would exhibit the same weather degradation.

It was also subsequently realised that an error had occurred during the processing of the colour coded PC. Spectral analysis revealed that no UV stabilisers (PDL, 1994) had been included in the resin. The spectral data is presented in Table 3.5 and shows that a relatively high level of UV light was passing through the component before the accelerated weather testing began.

	3 mm PC	4mm Galaxsee
UV Trans	5.7%	2.8%
Visible	19.7%	16.9%
AM2 Solar	32.1%	14.7%
A* (ill C)	-4.0	-4.1
B* (ill C)	+3.0	+2.3

Table 3.5: - Colour and Transmission Data for Colour Coded PC Compared to Galaxsee Glass

The UV transmission value presented in Table 3.5 is the average transmission level measured between the wavelengths of 280 to 380 ηm. However stabilised PC at only 2mm component thickness has a transmission rate of about 5% at 380ηm, reducing to virtually nothing at about 360 ηm, which makes the average transmission rate much lower than 5.7% meaning that the exclusion of stabilisers in the test PC can be confirmed. (Bayer, 2001)

A detailed laboratory-based weathering test was performed at Gaydon using a Xenon Arc accelerated weather test unit. For completeness this trial used every combination of stabilised and unstabilised PC, with and without acrylic film. Unfortunately it was not possible to get a stabilised version of the colour coded PC, so normal clear grade had to be used.

No hardcoats were applied to the components because it was the performance of the film that was being investigated. In order to maximise the number of potential hardcoats that could be used with this 'building-block' system, it was important that the film provided the main UV blocking mechanism for two key reasons.

Firstly, because some hardcoats (including, at the time of writing, Vitresyn) are UV transparent and have no blocking capabilities at all. Secondly, as discussed previously, commercially available hardcoats with UV blocking capabilities are so thin that they can easily be breached by a single stone-chip, allowing subsequent degradation of the polymer matrix. In this situation, the film is intended to act as a protective buffer so that UV protection would be maintained.

Table 3.6 describes the different components used in the trial. One component of each format was placed in the weather chamber and the bottom half of each was masked off so that it was not exposed to any UV light, thus providing a constant zero hour baseline to assess subsequent degradation against.

Each component was exposed to 2000 hours of UV light in shifts of 500 hours. At the end of each shift, a slice would be taken from each component for records and the remainder returned to the weather chamber.

Sample Number	Polycarbonate Grade	Acrylic Film
1,2	Unstabilised Colour Coded	No
3,4	Unstabilised Colour Coded	Yes
5,6	Stabilised Transparent	No
7,8	Stabilised Transparent	Yes

Table 3.6: - Details of Samples Used In Second Accelerated Weather Test

In order to define the artificial light sources used in appearance evaluation, a standard set of 'illuminants' has been established. For measuring the visible colour changes (L*, a*, b*) exhibited by the samples in this trial, illuminant C was used which represents average daylight from the total sky.(Hunter et al, 1987) Delta E is defined as the square root of the sum of the squares of the differences in L*, a* and b* for the two colours. (Kuehni, 1997)

It has been found that if a component does not exhibit a change in Yellowness Index (An internationally accepted measure of material discoloration as a result of long-term exposure to irradiation, e.g. International standards DIN 6167, ASTM E313) of more than 8 units after 4000 hours exposure then it would almost certainly survive 5 years Florida testing. (Pilkington, 2000)

The trials confirmed the UV blocking effect of the film material. Figure 3.8 shows the effect of laminating the acrylic film onto unstabilised polycarbonate. The monolithic unstabilised polycarbonate is shown in the left hand frame and it can be seen that the material degrades substantially even over the first 500 hours, whilst the laminated component shown in the right hand frame shows very little colour shift over 2000 hours. Table 3.7 quantifies the degradation of the samples over time.

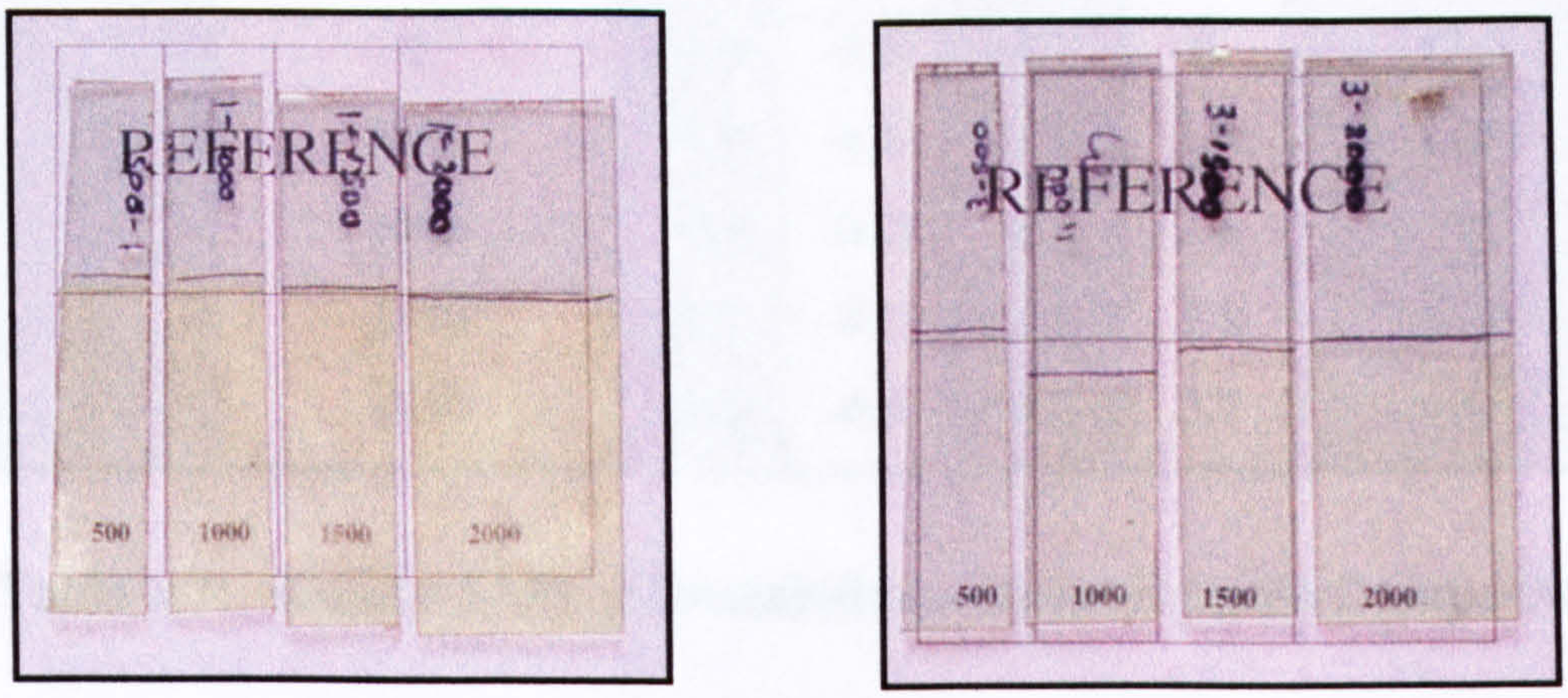


Figure 3.8: - Accelerated Weathering Results for Unstabilised Polycarbonate

It can be seen that the unlaminated component's appearance changed dramatically during the trial with the colour pigments in the PC breaking down and the samples becoming clearer and lighter. (L^* is a lightness factor and a positive movement in a^* means that a material is moving away from green colour towards red).

Figure 3.9 illustrates the improvement in performance of the laminated sample and projects the change in Yellow Index forward by 2000 hours based upon the historic behaviour of the sample. The sample is forecast to exhibit slightly less than 8 units change over 4000 hours and so would be likely to survive 5 years Florida weathering.

The stabilised polycarbonate samples were also subjected to the same test, although an error early in the trial resulted in the laminated sample needing to be replaced.

The second laminated clear sample (No.9), was taken from the same laminated plaque as sample 7 to ensure everything remained constant and the experiment was repeated. Unfortunately because of the size of the second component, it was not possible to take four samples, so it was decided that three would be taken at 500, 1250 and 2000 hours respectively.

Sample	Hours Exposure	ΔL	Δa^*	Δb^*	ΔE	Yellow Index
1	**0**	**91.5**	**-3.7**	**+3.2**	**0**	**+3.3**
	500	**-0.1**	**-2.0**	**+6.5**	**6.9**	**+14.0**
	1000	**-0.3**	**-3.0**	**+10.9**	**11.3**	**+21.0**
	1500	**-0.3**	**-3.2**	**+12.0**	**12.5**	**+24.0**
	2000	**-0.4**	**-3.3**	**+13.0**	**13.5**	**+28.0**
3	**0**	**91.8**	**-3.7**	**+3.2**	**0**	**+3.3**
	500	**-0.1**	**-0.2**	**+1.0**	**1.5**	**+4.8**
	1000	**+0.3**	**-0.5**	**+2.5**	**2.6**	**+7.2**
	1500	**+0.2**	**-0.7**	**+3.0**	**3.1**	**+8.4**
	2000	**-0.2**	**-0.9**	**+3.5**	**3.7**	**+9.5**

Table 3.7: - Colour Shift of Unstabilised Polycarbonate Components

Figure 3.10 displays the performance of the stabilised components and the damage is quantified in Table 3.8.

The final level of damage exhibited by the laminated stabilised sample was again less than the unlaminated equivalent. However the level of degradation has rapidly accelerated after 1250 hours, suggesting that whilst the film initially affords extra protection to the polycarbonate, its effectiveness diminishes with time.

Any UV radiation passing through the film would be dealt with by UV stabilisers within the PC, but there is a limited amount of stabiliser that can be incorporated into a resin and when these have been exhausted (the stabiliser is sacrificial) the PC is able to degrade.

The film was never intended to be 100% UV blocking, but more a shield that would remove a large quantity of the UV that any component would be exposed to. This has been shown to be successful with the overall effect being that a real component would have a much longer life. In order to extend this life further then a thicker acrylic film (e.g. 150μm or 200μm) may be required to impart sufficient UV resistance to clear polymeric windows.

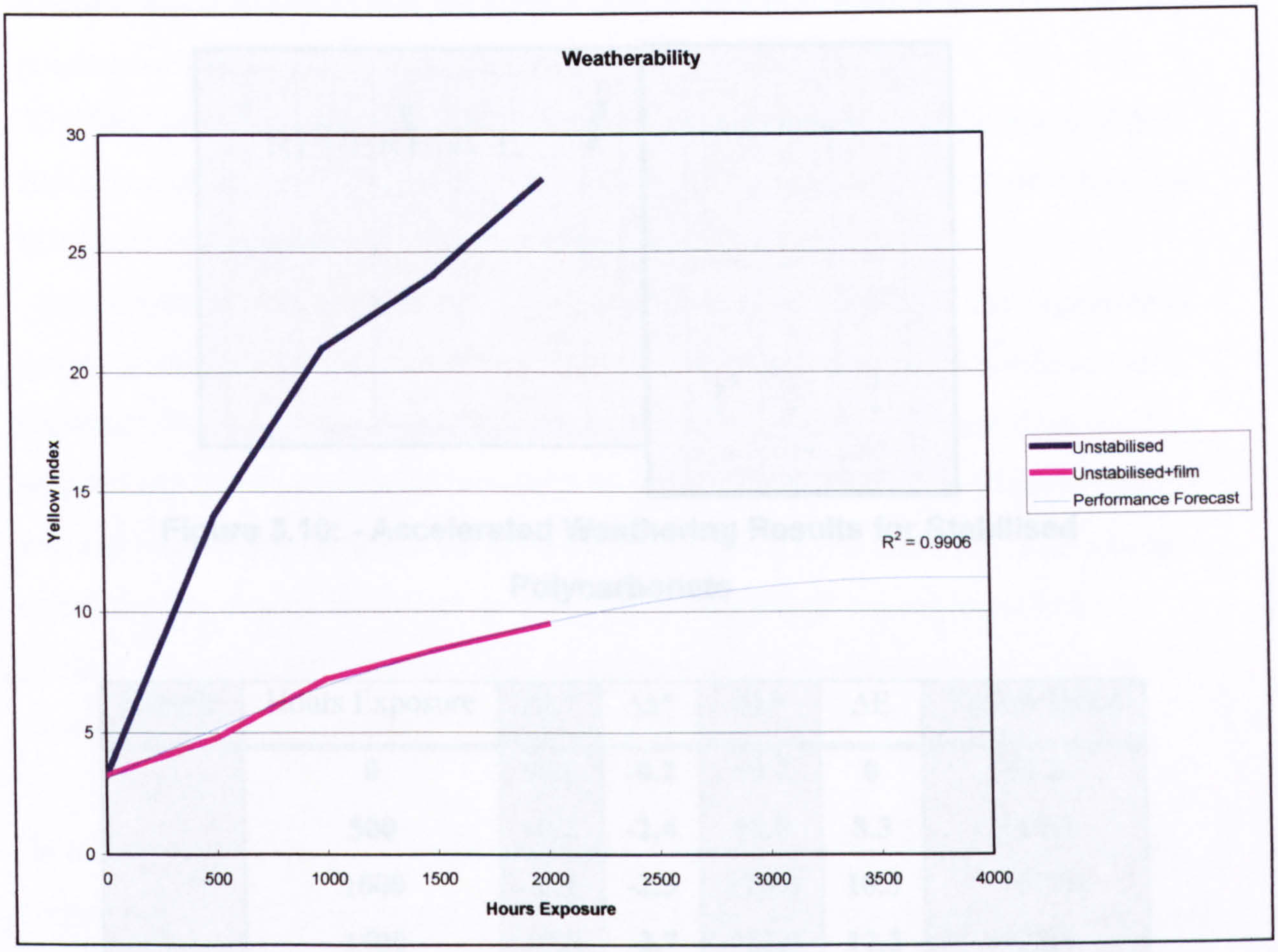


Figure 3.9: - Improvement in UV Resistance Afforded by the Acrylic Film

The difference in degradation between the two types of polycarbonate revealed that another important factor in component durability was the colour of the samples. Even though the tinted polycarbonate had no UV stabilisers added to it, the laminated sample out-performed the equivalent stabilised component. This is because the pigments in the tinted sample masked the onset of yellowing due to degradation, i.e. although more degradation is likely to have physically occurred in the tinted sample the component appear visually to have performed better.

The test plaques in this trial were only 3mm thick instead of 4mm and therefore lighter in colour than they should have been. Any visible colour change due to UV degradation in 4mm-tinted polycarbonate would be even less than that seen in this trial, supporting the evidence that this system would survive 5 years Florida testing as demanded by automotive OEM's.

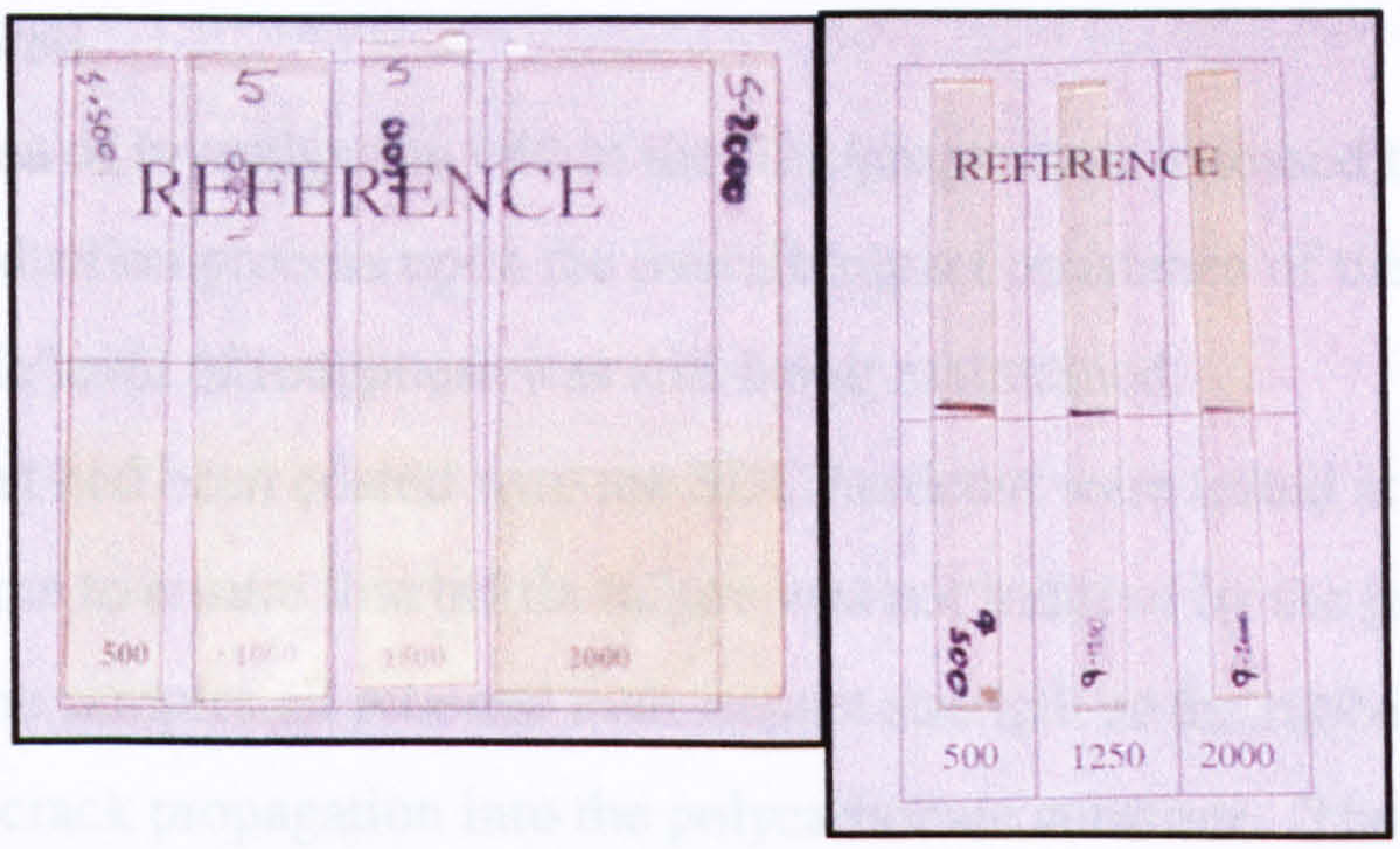


Figure 3.10: - Accelerated Weathering Results for Stabilised Polycarbonate

Sample	Hours Exposure	ΔL*	Δa*	Δb*	ΔE	Yellow Index
5	**0**	**95.6**	**-0.2**	**+0.7**	**0**	**+1.2**
	500	**-0.2**	**-2.4**	**+8.0**	**8.3**	**+14.0**
	1000	**-0.4**	**-2.5**	**+10.0**	**10.3**	**+17.0**
	1500	**-0.6**	**-2.7**	**+12.0**	**12.2**	**+20.4**
	2000	**-0.8**	**-3.0**	**+12.8**	**13.0**	**+22.0**
9	**0**	**95.8**	**-0.2**	**+0.8**	**0**	**+1.3**
	500	**-0.1**	**-1.0**	**+2.0**	**2.2**	**+4.5**
	1250	**-0.3**	**-1.4**	**+3.8**	**4.0**	**+7.6**
	2000	**-0.5**	**-2.4**	**+8.0**	**8.3**	**+14.4**

Table 3.8: - Colour Shift of Stabilised Polycarbonate Components

3.4 Impact Testing

Polycarbonate is known to possess excellent impact properties but is a notch sensitive polymer and when a crack is initiated it is able to propagate rapidly through the material. If the film used had been a normal PMMA film, rather than the highly rubberised acrylic selected, then the impact resistance of the overall system would have been relatively low. If components are not moulded correctly then internal stresses can be generated that can significantly reduce the impact strength of the polymer as well.

The final area of investigation within the film programme assessed the effect of the film and production process upon the overall impact resistance of the system to ensure that a suitable level of toughness was still being maintained.

Samples that had been coated with the SDC hardcoat were tested at the beginning of the programme to ensure that brittle failure was not induced by the presence of the hardcoat. The samples all retained their impact strength as the rubberised acrylic film stopped any crack propagation into the polycarbonate substrate. The Vitresyn coating was not tested due to constriction upon the supply of samples, but there is no reason to believe that similar behaviour would not be exhibited. However it would be prudent to impact test samples coated with Vitresyn at some point in the future to ensure the expected behaviour is exhibited in reality.

In order to assess the quality of the mouldings produced, several impact tests were carried out on both laminated and unlaminated plaques using a Pneumatic Dart Impact machine equipped with a 12.5mm radius hemispherical impact dart in accordance with ASTM D3763-99. (ASTM,1999)

The samples were impacted from a height of 40 mm at a speed of $4ms^{-1}$ with the dart falling onto the film face of the sample if it was present. A computer logged several types of data for post-test analysis but the only data of initial interest was the total energy absorbed by the component before failure along with observations of the manner of failure, i.e. brittle or ductile.

A graphical representation of the output data for both laminated and unlaminated PC is shown in Figure 3.11. There was no hardcoat present on any of the samples and all of the unlaminated components showed excellent impact resistance, absorbing between 72 and 86 J (average 80J) of energy before failure, which is similar to intruder resistant glazing. (Kirwan, Jan 2001)

There was also a high level of reproducibility between the samples indicating that the moulding process was consistently good.

The laminated samples also showed a high level of repeatability, but their impact strength tended to be slightly lower, being between 57 and 72J of energy with an average of 66J which is still on a par with intruder resistant glazing.

This reduction can be attributed to the reduced impact strength of the acrylic film compared to the polycarbonate as a crack initiated in the film due to the impact from the dart will travel through the interface with the polycarbonate leading to failure.

However, despite this reduction in impact strength due to the film, the components all still exhibited a higher level of impact resistance than required by legislation and were of a similar level to intruder resistant glazing, despite being only 3mm thick (any final component is envisaged to be at least 4mm thick to maintain rigidity).

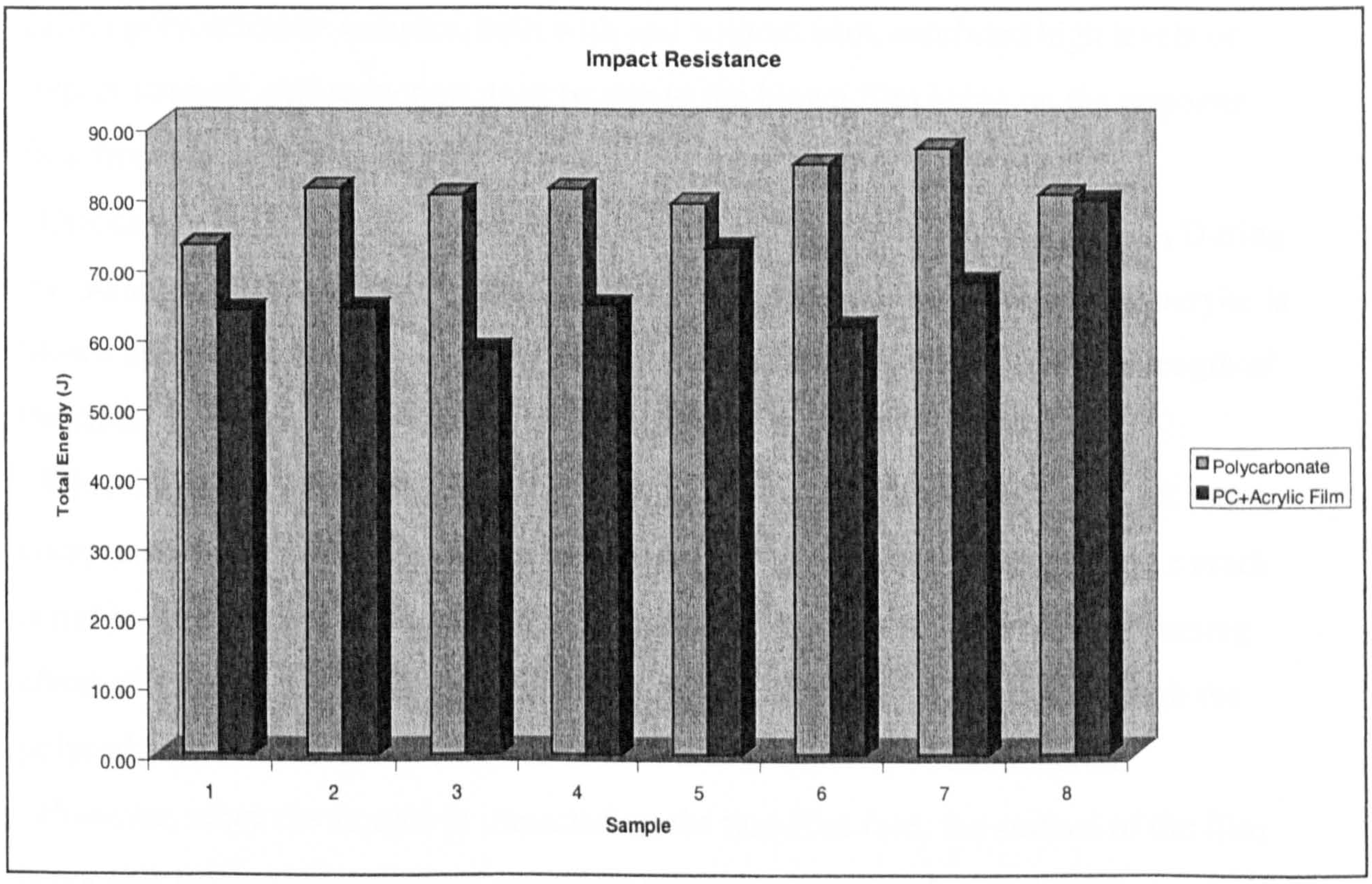


Figure 3.11: Impact Resistance of Polycarbonate and Acrylic Backed Polycarbonate

Another key issue of these trials was the nature of component failure. It is highly desirable that all glazing components fail in a ductile manner as it means that they would probably maintain their integrity even after a severe impact and assist in the retention of unbelted occupants within a vehicle.

All of the components from these trials exhibited ductile failure at a high energy level meaning they appear to be suitable for glazing applications. However, when samples were placed upside down in the impact testing machine (i.e. impact was on the non-laminated face), quite different impact behaviour was observed.

3.4.1 Inducing Brittle Failure

It was found that if the test plaques were placed film-face down in the impact-testing machine then they would fail quite dramatically, in a very brittle manner and at very low levels of energy absorption. A set of 8 components was impact tested and Figure 3.12 compares the impact resistance of these samples to identical samples impacted from the film-face.

In seven cases the samples failed at extremely low energy levels. Given that the earlier polycarbonate samples, both with and without film, exhibited high levels of impact strength, this reduction must be due to the blown film being on the opposite face from the impact point.

Cracks will be initiated at a flaw in the surface of the blown film. (Xia et al, 2000) During the manufacture of the film, a series of flaws will be generated as the molten acrylic is blown up and freezes. This leads to a fine series of hesitation flaws over the length of the film.

When impacting the film face, the surface of the highly rubberised film is put into a compressive state by the impacting head, any flaws are effectively closed and a crack is not initiated until a medium-to-high energy level is reached due to the cushioning effect of the compressed rubber molecules. This crack then propagates through the polycarbonate with relative ease due to the notch sensitivity of the material.

However, when the sample is impacted on the non-film face, the surface of the film is put into tension upon impact, any flaws present open up and a crack becomes initiated at a very low energy level, travelling backwards through the sample. This behaviour has also been noted in glass structures where 'star cracking' initiates on the surface opposite the impact head when the surface stresses exceed the tensile strength of the glass. (Grant et al., 1999)

In simple terms, the film 'tears' easily in tension and the crack then propagates rapidly through the sample, causing brittle failure. Figure 3.13(a) shows the breakage pattern of one of these components compared to the ductile failure exhibited when impacted face-up shown in Figure 3.13(b).

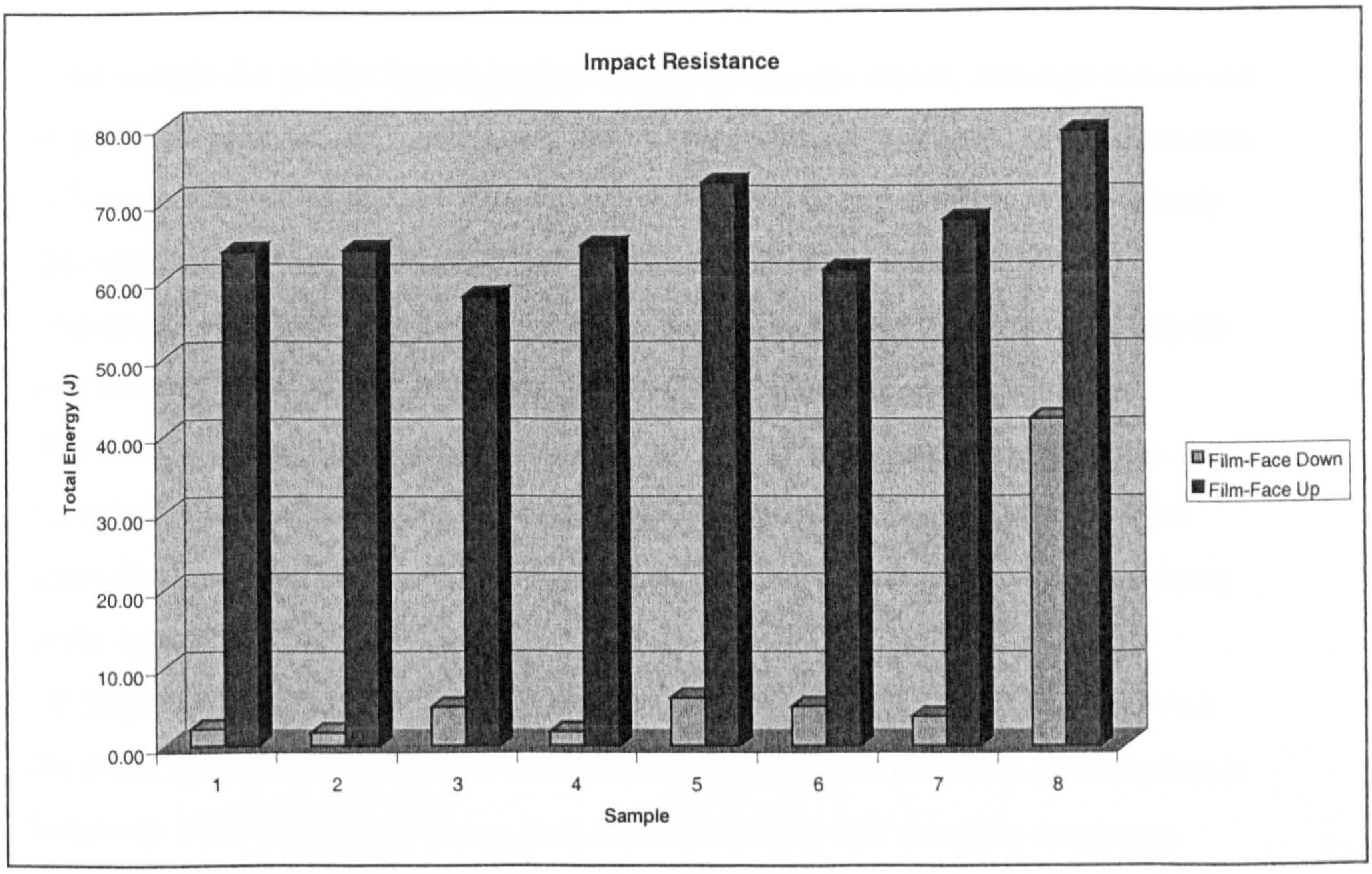
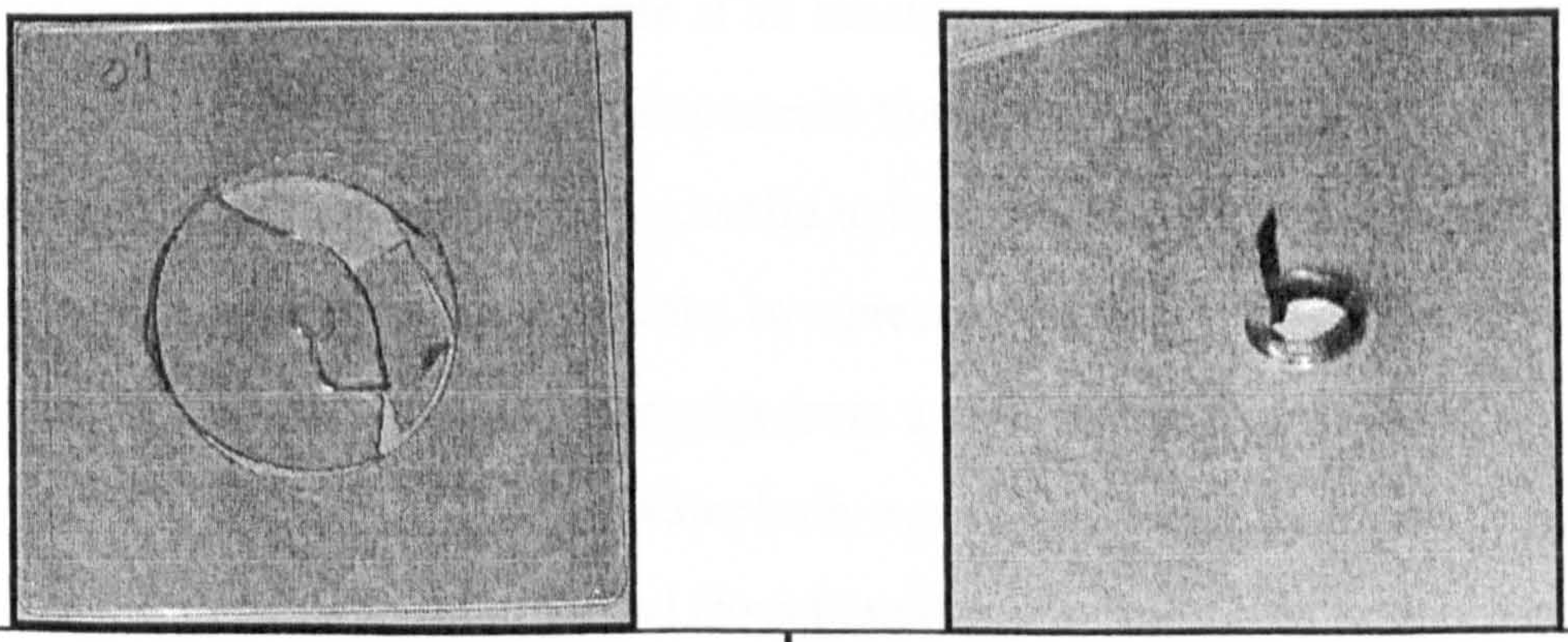


Figure 3.12: - Comparison Of The Impact Resistance Of Acrylic Backed Polycarbonate Impacted From Different Sides



(a) Film-Face Down	(b) Film-Face Up

Figure 3.13: - Different Breakage Patterns For Film-Face Down Impact And Film-Face Up Impact

Some samples were also made using a cast version of the acrylic film. Due to the different film manufacturing process, the cast film contained virtually no flaws and as such was not expected to initiate cracks at low energy levels. Practical tests confirmed that this 'directional failure' was not obtainable via the cast film with impact resistance being similar from both sides of the test components. This supports the hypothesis that the cause of the directional failure was the flaws generated during the manufacture of the blown film.

One sample did exhibit higher impact resistance than the others, although the overall impact resistance was still less than when the samples were impacted on the film-face. Closer inspection of the test piece revealed different failure characteristics. Firstly the component failed in a ductile manner, rather than in the dramatic brittle 'explosion' exhibited by the other samples. Secondly, film in the area of the impact was severely stressed and delaminated from the PC substrate in small pieces.

For a crack to progress through a medium it has to have sufficient energy at the crack tip to travel (i.e. it has reached a steady state of progression (Xia et al, 2000)) and there must also be a continuing medium for the crack to travel through, i.e. good adhesion at the interface.

If there is not good adhesion at the interface and delamination occurs as observed, the crack tip is blunted and cannot continue through the sample. This phenomenon is known as 'film-debonding' (Ye et al., 1992) and is caused by low interface toughness compared to that of the film and the substrate, suggesting that the interface was weak due to poor adhesion between the layers.

When the sample was exposed to the adhesion test outlined in Section 3.2.6, the film did not separate from the substrate at all meaning that, using this particular test, it performed as well as the other components that failed in a brittle manner.

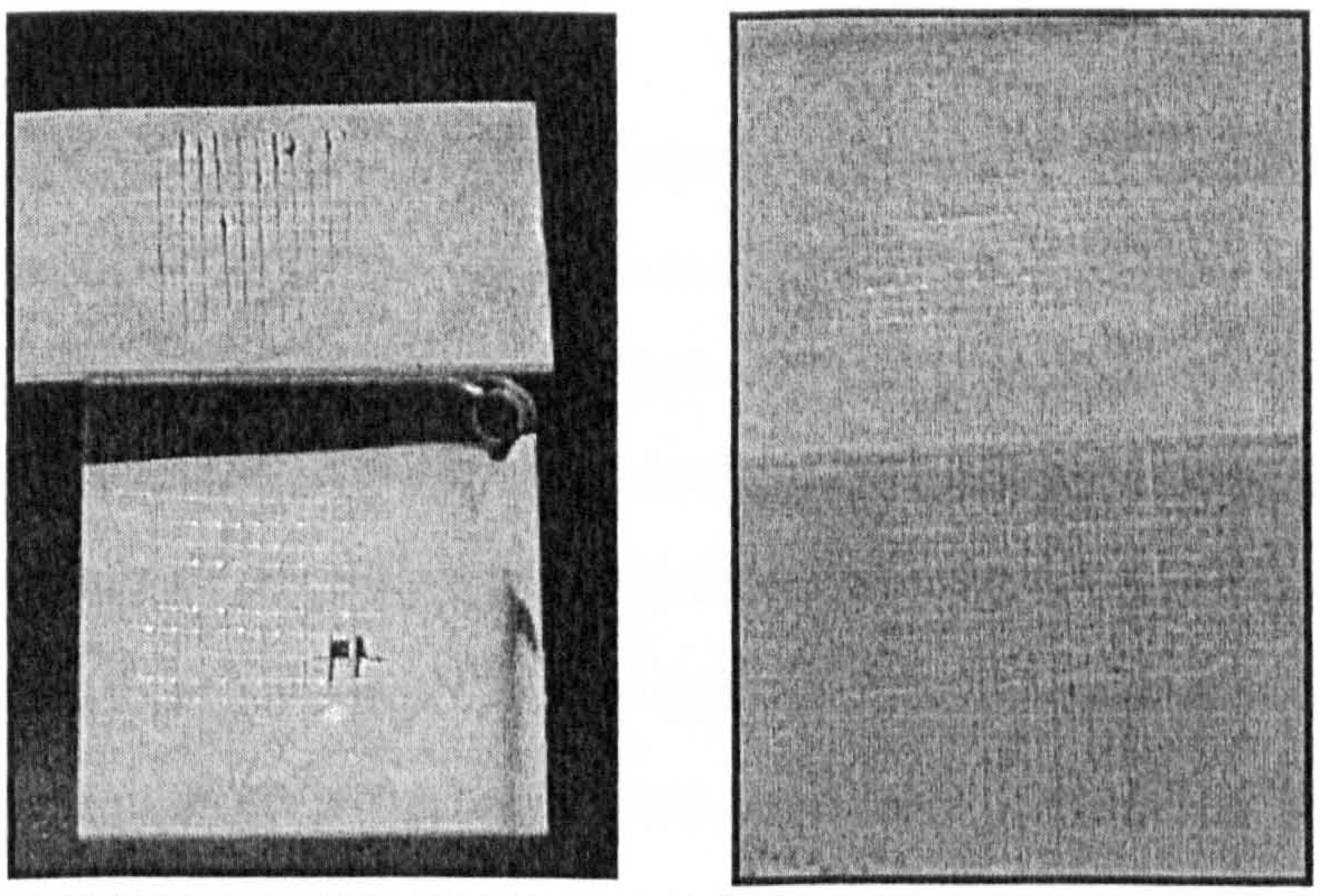
In order to ascertain whether the ductile nature of this component was due to lower adhesion between film and substrate, two pieces of the component were submerged in a bath of hot water along with samples from a component that failed in a brittle manner. The purpose of the hot water bath was to accelerate delamination of the film and if the acrylic film delaminated from the ductile sample first then the interfacial adhesion would be lower and the hypothesis proved.

After 8 hours submersion time, both of the suspected low adhesion samples started to show a small level of delamination along the cross hatching, but no squares were removed when the adhesion test was carried out. No damage was exhibited by the high adhesion samples.

After 12 hours, the visual damage along the crosshatching was worsening and when the tape was applied to one sample of poor adhesion, one square of film was lifted. At

16 hours this had increased to 3 squares and after 20 hours, 5 squares were obviously delaminated. The second low adhesion sample was also showing a high level of delamination adjacent to the cross hatching lines, although no squares were removed by application of the tape.

The trial was stopped at this point as the high adhesion samples showed no signs of delamination anywhere and the final results of the trial are shown in Figure 3.14a (low adhesion performance) and 3.14b (high adhesion performance).



(a) Low Film Adhesion – Ductile Failure

(b) High Film Adhesion – Brittle Failure

Figure 3.14: -The Effect of Film Adhesion upon Impact Behaviour

The discovery of this 'directional' behaviour provides an opportunity to address one of the key concerns discussed earlier about being trapped in a vehicle. If the production process can be controlled to guarantee excellent adhesion between polycarbonate and film then if lamination only occurs on the outside of the glazing, it is feasible that intruder resistance can be maintained whilst the occupant could break the window with a sharp object in an emergency.

3.5 Summary

This chapter has discussed the work performed to assess the suitability of an acrylic film – polycarbonate hybrid component as a solution for alternative glazing applications.

The inclusion of the chosen film was intended to improve the overall performance of any final component when compared with current polycarbonate glazing by providing a buffer to protect the substrate from UV and chemical degradation in the event of any applied hardcoat being breached.

Early trials found that the gating arrangement of any final component tooling must be located entirely on one side of the mould otherwise the polycarbonate has to 'puncture' the film in order to enter the cavity. If this occurs, the film is free to float within the cavity and is generally pushed against the edge of the mould by the melt front, where it wrinkles.

The injection gate also needs to be of constant cross section to avoid any localised increase in pressure during injection which can generate heat that can cause the film to melt and mix with injected polycarbonate if melt fracture is induced.

Accelerated weather testing revealed that the acrylic film did greatly improve the systems' UV resistance even without a hardcoat present. However it is likely that a 150µm or 200µm thick film would be needed if clear component were to be made via this approach as test samples still exhibited unacceptable levels of yellowing when exposed to intense UV light.

It was also found that tinting pigments in coloured polycarbonate masked the onset of yellowing through UV degradation, meaning that coloured components are likely to pass the 5 year outdoor weathering requirement required by automotive OEM's.

Final test components were coated with a new type of hardcoat called Vitresyn and were subjected to two different scratch and abrasion tests, namely the industrially recognised 'Taber' and the in-house developed 'Lab Scour'. In all instances, several other combinations of commercially available coatings and substrates were also tested alongside the Vitresyn coated samples to provide a performance benchmark.

The system of Vitresyn applied to the acrylic film-backed samples developed within this programme was shown to be superior to commercially available solutions such as AS4000 from GE-Bayer and CrystalCoat from SDC, which had proved to be the best hardcoat during previous practical Brush & Scrub trials at Land Rover, Gaydon earlier in the development programme.

There was evidence of low adhesion on some Vitresyn samples and subsequent tests revealed very varied behaviour. Whilst some samples exhibited complete adhesion, other exhibited near complete non-adhesion between the applied hardcoat and the acrylic film. Clearly there remain some processing issues that the manufacturer of Vitresyn needs to identify and address before the coating can be used commercially.

The final area of investigation was the impact behaviour of film-backed samples. Laboratory trials showed that although there was a slight decrease in impact strength, attributable to the lower impact strength of the acrylic film and the notch sensitive behaviour of the polycarbonate, all of samples exhibited satisfactory impact resistance and failed in a ductile manner.

It was also found that the application of a brittle hardcoat did not affect the impact strength of test components as the acrylic film was an effective buffer that stopped any crack initiated in the coating from travelling into the polycarbonate.

Very interesting behaviour was observed when laminated samples were impacted from the non-film face (i.e. film face down) with components failing at very low energy levels in a dramatic and brittle manner.

When the film is placed into tension, any flaws present on the surface are opened upon impact and a crack is initiated, which then travels rapidly backwards though the test sample, resulting in catastrophic failure.

The level of adhesion between the polycarbonate and the acrylic film appears to be the critical issue with low adhesion meaning that any crack initiated does not propagate easily through the interface and structural integrity is maintained.

If this failure mechanism can be guaranteed, then it is feasible that units made with this film on the outside would exhibit excellent intruder resistance, but could be broken from the inside in an emergency. This would address the concern of being trapped within a vehicle that was identified during the concept validation.

4.0 Creating a Polymer Glazing System through Dual Injection Moulding

The film system discussed in Section 3 was the major focus of the overall research programme, but a feasibility study was undertaken to investigate the potential of simultaneous dual injection (2K) moulding as a means of producing similarly constructed components. The 2K process has previously been used to produce coloured components, but never for transparent applications. (Ferromatic, 1996) As such it was unclear whether it would be possible to produce components via this technology.

2K moulding employs two independently controlled concentric injection channels so that it is possible to have a phase of simultaneous injection moulding as shown in Figure 4.1 (i.e. both materials are injected at the same time), which avoids the skin defects associated with changeover from one material to another during sequential moulding.

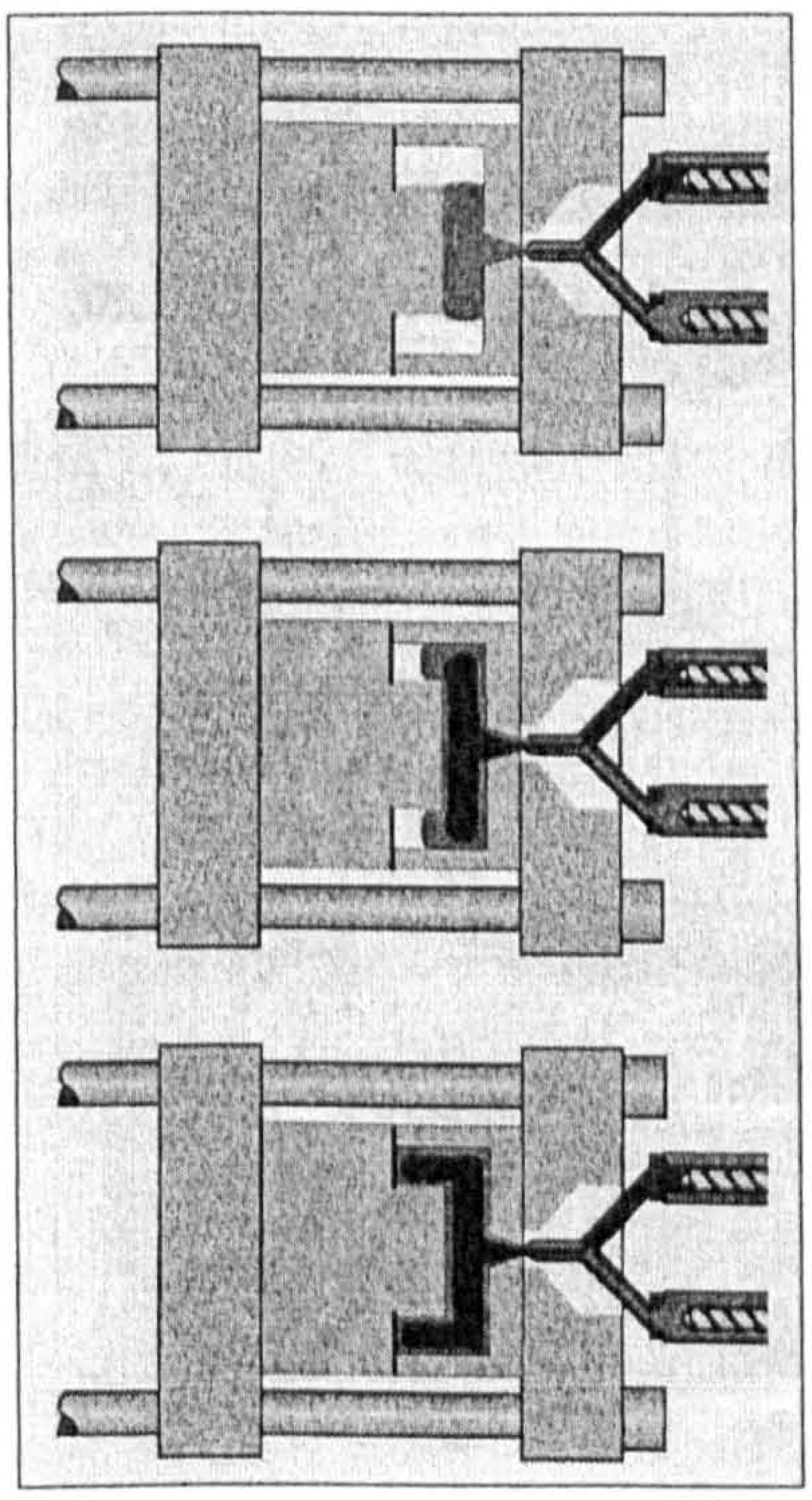


Figure 4.1:-The Simultaneous Dual Injection Moulding Process

In theory, a resin grade of the final material utilised in the film system could be used to produce similarly structured and performing 3rd Generation components. The key benefits of the approach were thought to be the removal of the process stages associated with film handling and forming, resulting in lower production costs and reduced potential for error, making polymer glazing technology more attractive for mass application.

The required deliverables from this part of the programme were: -

1. Transparent test pieces exhibiting excellent adhesion between core and skin layers in order to show that it is technically possible to combine different materials and retain clarity.
2. Information and understanding of the production process and how different system variables affect the output.

These deliverables could then form the basis for future decisions as to whether the research should be progressed further.

4.1 Testing the Concept

The first experiments employed a simple 4mm thick, centre-gated tool installed on a Battenfeld 110 tonne 2K injection moulding machine. The selected materials were Polycarbonate being processed at 280°C and PMMA being processed at 260°C. The mould cavity was held at a relatively cool 40°C

It soon became apparent that a centre-gated tool was not suitable for development use as it generated a wedge-shaped core with a significant amount of non-uniformity near the injection point as simply illustrated in Figure 4.2.

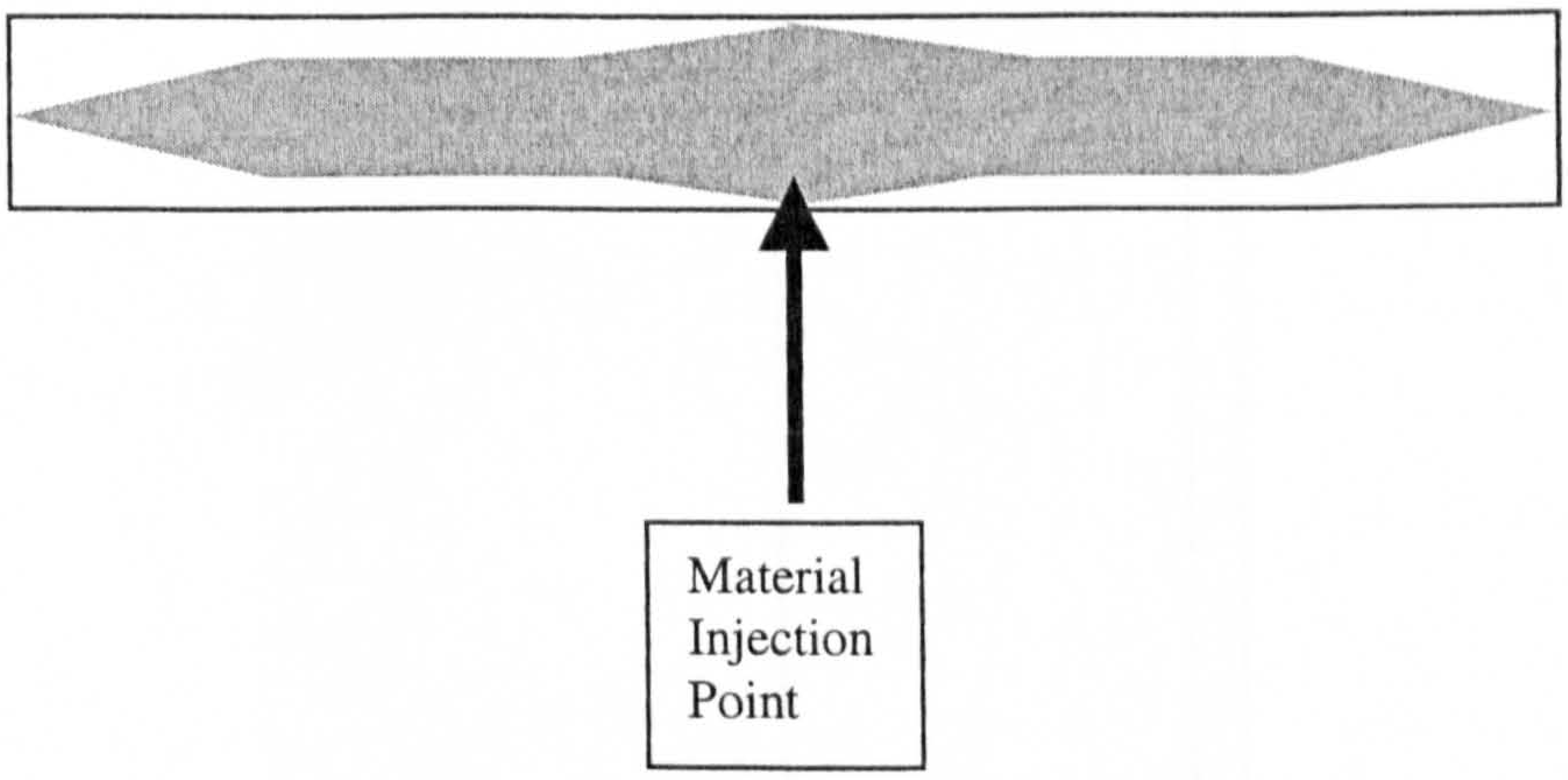


Figure 4.2: - Typical Profile Showing Core-Skin Non-uniformity With Centre-Gated Test Pieces.

The thinning of the skin material close to the gate area is caused by frictional heat from the flowing melts, which remelts the frozen skin and flushes it away from the region. This is a common problem with two-channel injection moulding. (Selden, 1997) It was also noted that components showed very little transparency and optical clarity.

An edge-gated flat plaque tool, shown in Figure 4.3, was used for subsequent mouldings because it was thought that the flow behaviour within the mould would be more suitable.

The components that were produced using this new tool, whilst more transparent, still contained a high level of white haze. Laboratory investigation of clear and hazy areas revealed that there was mixing at the skin-core interface in the hazy areas as shown in Figure 4.4.

These effects are known as 'laminates' – local layered structures of core and skin material that tend to be generated when the simultaneous phase of injection lasts a long time. The geometry of the flow channel, the loading speeds of the individual components and the viscoelastic behaviour of the melts influence the occurrence of these boundary layer instabilities. (Eigl et al, 1998)

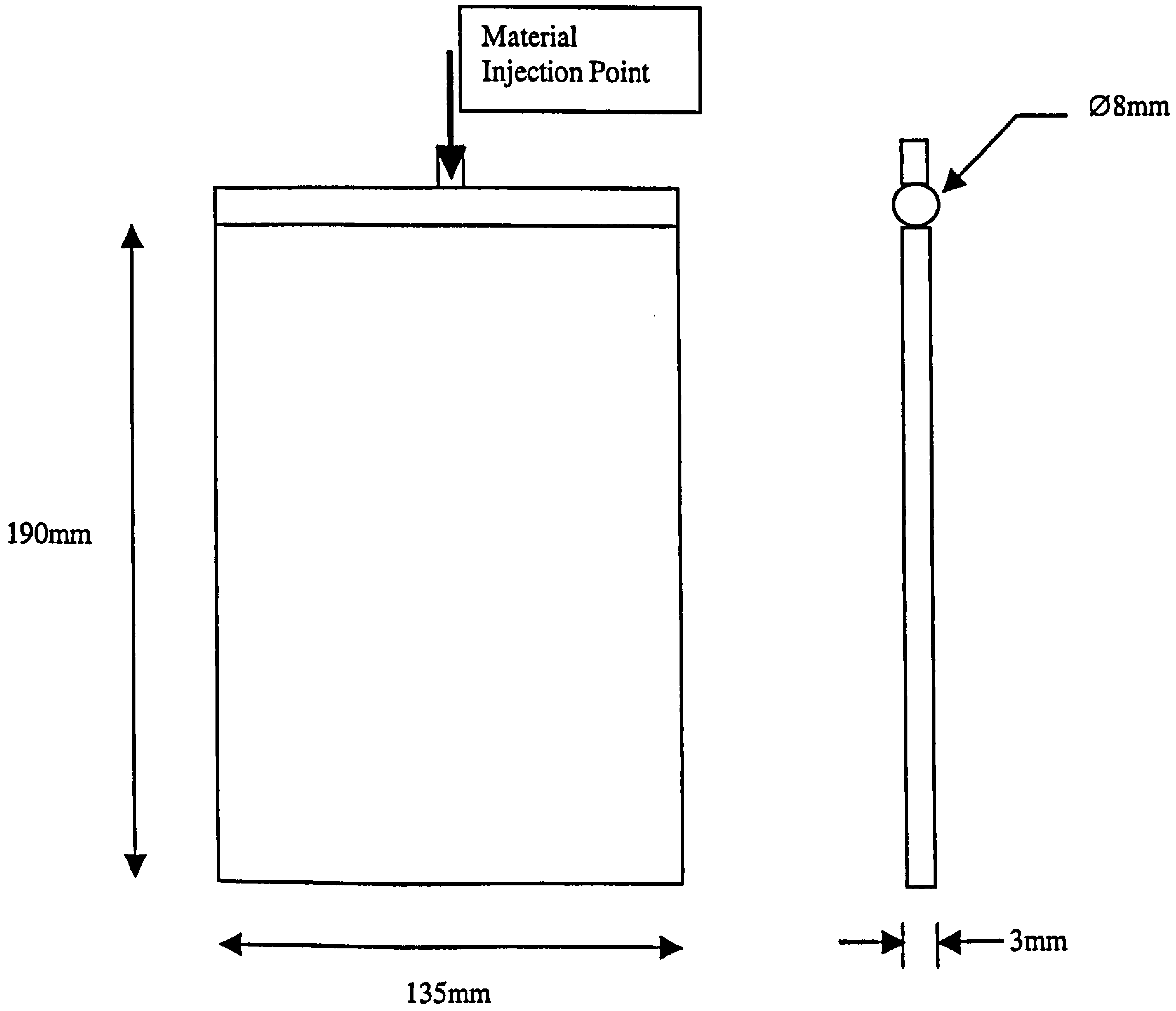


Figure 4.3: - The Edge-Gated Mould Tool

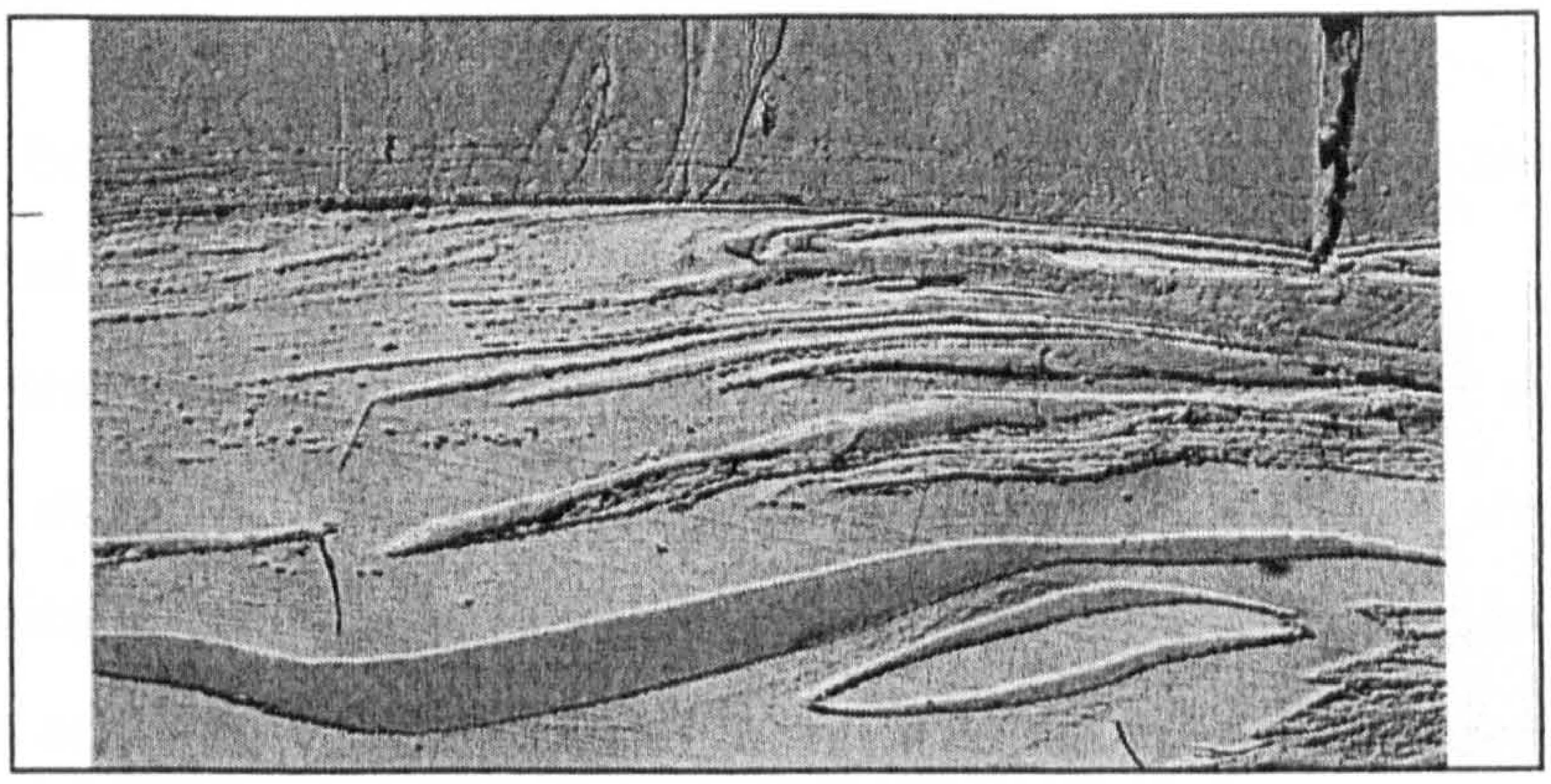


Figure 4.4: - Transparent Cross Section Showing Significant Interfacial Mixing

Subsequent investigation suggested that a high injection speed produced a lot of clouding and streaking, with the main cause being disutrubed laminar flow through the injection gate where hazing was worst.

The injection speeds of both barrels were repeatedly lowered until an injection speed of 25mms^{-1} was reached. This resulted in a continuing improvement of transparency as illustrated in Figure 4.5. It was found that if the injection speeds for either material were reduced below 25mms^{-1} then defects including core breakthrough and material hesitation were generated due to the materials freezing off before they had filled the mould.

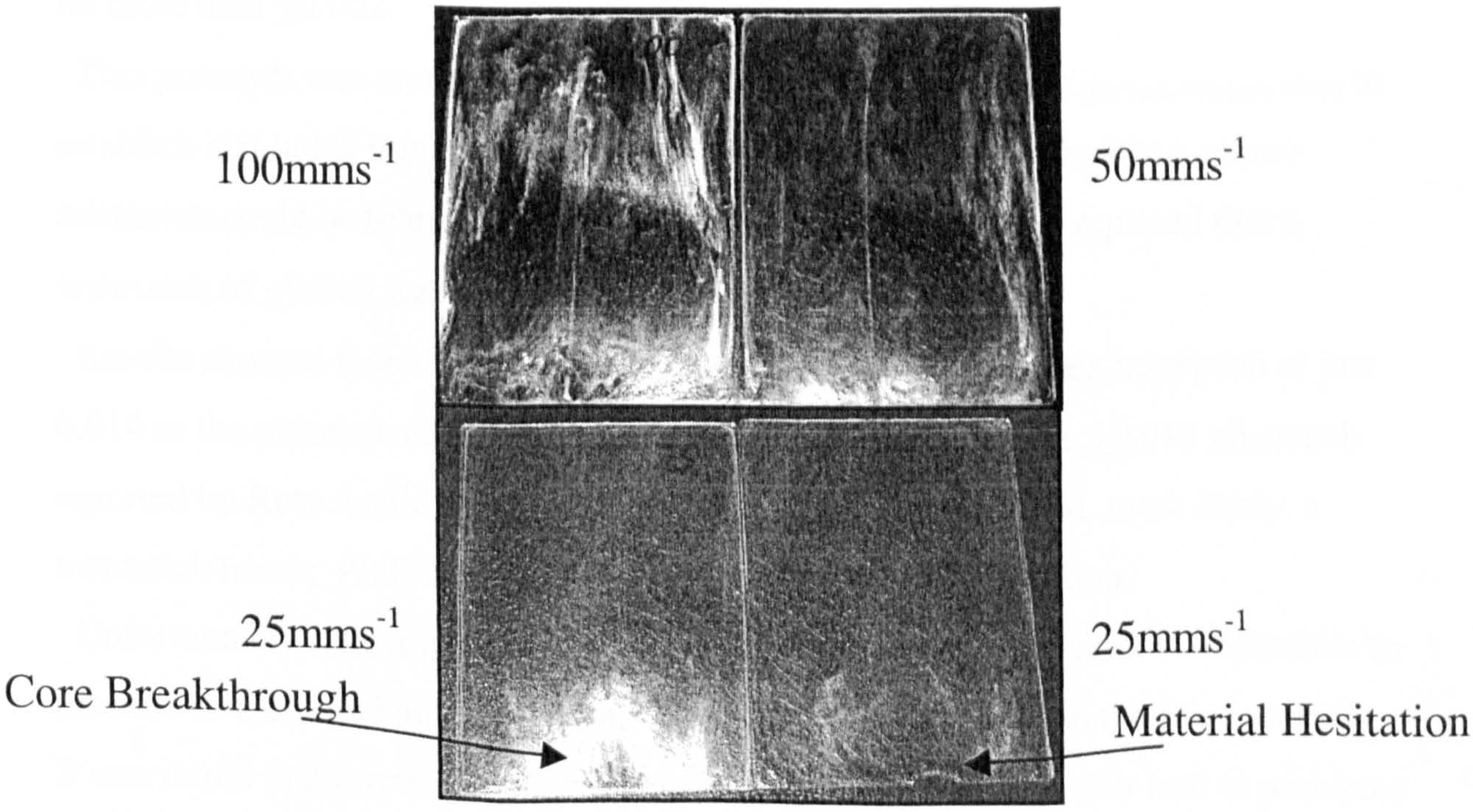


Figure 4.5: - Varying Transparency With Different Injection Speeds

4.2 Investigating Interfacial Instabilities

It is generally believed that interfacial instabilities are detrimental to mechanical and optical properties of the resulting polymeric structure.

Whilst this is true in cases of severe interfacial instabilities that result in significant depth variation in one of the layers, a controlled amount of interfacial instability could lead to mechanical interlocking which should improve the tensile toughness of the component and could potentially obviate the need for an adhesive layer in processing incompatible polymer pairs. (Ranjbaran et al., 1996; Goodship, 2001)

Therefore controlled interfacial mixing may be a desirable feature, particularly if incompatible materials (i.e. there is no interaction on a molecular level and hence negligible interfacial strength) are to be considered for an application. However, for transparent applications, the chosen materials must have matched refractive indices to avoid streaking.

Significant interfacial mixing on its own is not enough to generate hazing in samples; there also has to be a difference in the refractive indices of the two materials. If the refractive indices of the two materials are the same then any amount of interfacial mixing can theoretically occur without any haze being generated.

It has been shown elsewhere (Olson, 1988, Lin et al, 1993) that glass fibres remain invisible within a transparent polymer matrix if the RI's of both materials have a mismatch of no more than ±0.002.

This principle was examined within this part of the programme (Kirwan, February 2002) to establish if it holds true for two plastics in a single system, or whether a greater mismatch could be tolerated as suggested by Rutz (Rutz, 1988) who reported that a mismatch of ±0.010 was permissible.

Results showed that hazing was generated with a refractive index mismatch of just 0.014 in the presence of interfacial laminates, suggesting that the ±0.010 mismatch reported by Rutz would be the highest that could be tolerated and, more likely, a mismatch nearer ±0.002 would be necessary for optical applications.

Unfortunately selecting materials with exactly the same RI's is almost impossible in practice as there will almost certainly be some mismatch between the two materials. It was found that processing the same material differently could also lead to problems with birefringence due to different frozen molecular orientation, which changed the resultant refractive index by a significant amount. (Kirwan, February 2002)

As such, attention was turned towards understanding the causes of the laminates observed in many of the samples to see if they could be eradicated. If the structure of the skin and core is such that only laminar flow is present (i.e. no interfacial mixing) then any degree of RI mismatch is theoretically permissible.

The distribution of core and skin material is affected by geometric, material and process parameters. Academic texts suggest that it is mainly determined by the velocities of the two components, the viscosity ratio between the core and skin materials, the length of the simultaneous phase of the injection cycle and the speed of the flow front. (Eigl, 1998)

Previous studies (White et al, Young et al) have shown that the ratio of skin and core viscosities should be in the range of 0.5 – 5 for optimum results, however it was found that simply matching the relevant viscosities of the two materials does not guarantee laminar flow.

In single injection moulding machines the flow is pressure-driven and shear rates at the die wall may sometimes exceed 100000 s^{-1}. For injection moulding processes the maximum wall shear rate normally occurs in the sprue and (for a single material) may be estimated as (Cogswell, 1981): -

$$\text{Shear rate} = 10M/D^3TN\ (s^{-1}) \quad [1]$$

Where

M is the mass of the component (g)

D is the sprue diameter (cm)

T is the injection time = 5s

N is the number of injection points = 1

Note: - Formula [1] should have the material density included on the bottom line in order to give the correct units of measurement. For the ease of calculation, Cogswell has approximated all polymeric densities as $1gcm^{-3}$. (Coates, 2003)

When the shear rate has been calculated, the relevant viscosity can be taken from a suitable viscosity-shear rate graph, which can be obtained from the material manufacturer and are reproduced in Appendix B for the materials used in these experiments.

For a dual-injection component this formula is not entirely representative as there are in effect two flows occurring within the cavity and two areas of high shear stress as shown in Figure 4.6. (Goodship, 2001) There is no known model that can be used to establish what the relevant shear rates of the two materials are during the injection phase, so a few simple assumptions had to be made in order to estimate the values.

For the shear rate of the PMMA it was assumed that the component was made from a single material and the above formula applied. Appendix C contains the detailed arithmetic and the viscosity (η_{PMMA}) was found to equal 70 Pa(s).

For the polycarbonate, it was assumed that the PMMA had frozen, there was no wall slip, laminar flow was achieved, and effectively the injection area had been reduced. The skin:core ratio was 30:70 and the new values of M and D were calculated giving a polycarbonate viscosity (η_{PC}) of 90 Pa(s) and a viscosity ratio R (η_{PC}/η_{PMMA}) of 1.28 which was within the range recommended by the academic texts discussed previously. The skin viscosity was also slightly lower than the core viscosity as suggested by Cogswell, but still disturbed laminar flow and subsequent hazing was generated within the components.

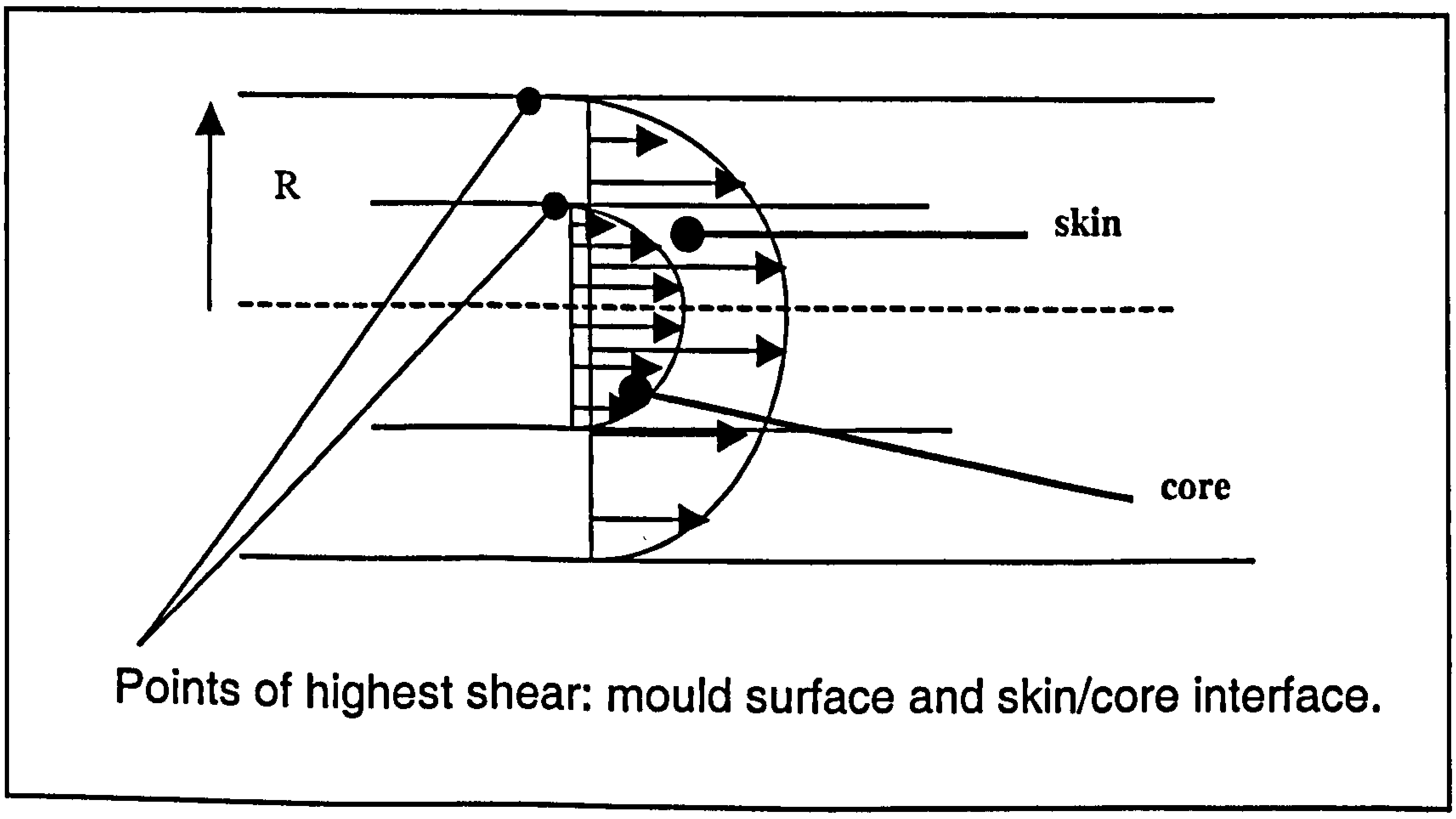


Figure 4.6: - Melt Flow and Shear Stress During Dual Injection

(Goodship, 2001)

Another important measure of how two materials will behave is the interface interaction. (Cogswell, 1981) If we consider the velocity of the centre point of the interface, then an acceleration factor N can be defined so that the velocity of the interface is NV, where V is the centreline velocity of uniform viscosity in a cylindrical tube.

N = Centreline Velocity Ratio = $1 - 0.5 \tanh(0.4 \log_{10} R)$ [2]

$= 1 - 0.5 \tanh(0.4 \log_{10} 1.28)$
$= 0.98$

Empirical studies have shown that if N lies between 0.8 and 1.2 then optimum stable flow has theoretically been attained, but it clearly was not in this instance. These findings suggest that the rheological properties of materials to be used in transparent systems need to be more closely matched than those for non-transparent applications. The most likely reason for this is that minor interfacial mixing will not be seen in coloured components unless it leads to a mechanical problem, whereas mixing in transparent systems is easily identified through hazing of the component. It was decided that further experimentation was needed to assess if it was possible to eliminate interfacial mixing or abandon the process because a degree of mixing would always occur.

4.2.1 The Effect of Different Rheologies

In order to further investigate the effects of rheology, a second (proprietary) acrylic (DP1) was selected as the skin material. This was considered to be better as it had a lower viscosity than the PMMA previously used and it was felt that the original match of viscosities resulted in R being too low, i.e. the new material combination allowed R to be moved towards the centre of the suggested range.

The original shear rate corresponded with a new viscosity (η_{DP1}) of 60 Pa s, giving a viscosity ratio (R) of 1.5 and a centre line velocity ratio (N) of 0.96.

Having hypothesised that the new material parameters would improve the structure of produced components, i.e. prevent interfacial mixing and hence streaking, some new test samples were made to see if real improvements were gained. The same process settings were used as previously and it should be noted that the holding time and pressures were kept constant for all mouldings.

The new mouldings proved to be successful with components that had no streaking or interfacial mixing as shown in Figure 4.7. It was found that if injection speeds were again increased, then streaking and hazing could be reintroduced through disturbed laminar flow.

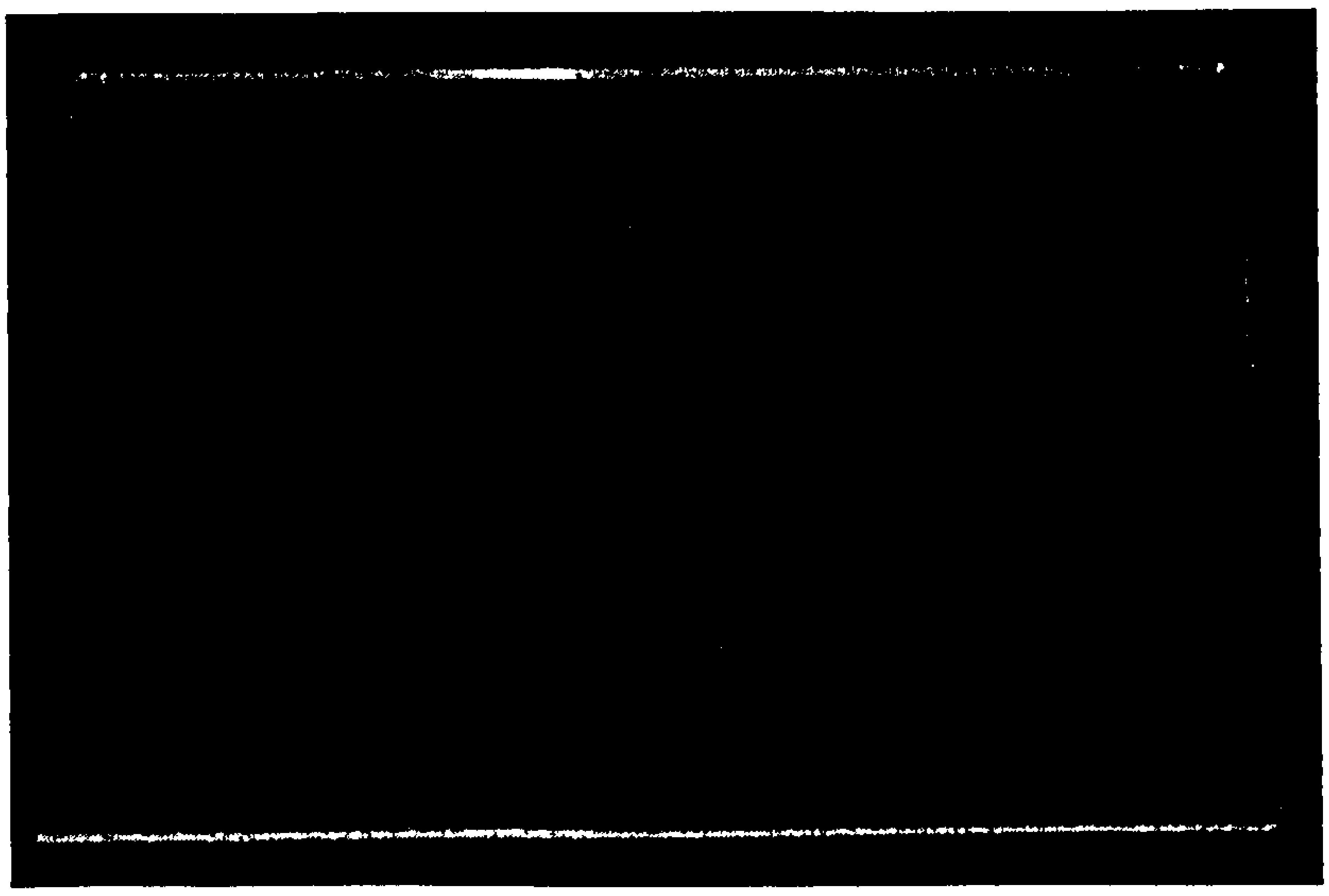


Figure 4.7: - Modified Rheology PMMA and PC component

These results suggest that the viscosity ratio R is a more important parameter than N, the centre line velocity ratio. Injection speed is also a dominant parameter because it has a direct influence on interfacial mixing and the subsequent haze generation.

These findings suggest that the use of the 2K process for the production of glazing components is more difficult than first thought and further investigation is needed to identify and understand the critical process parameters.

4.3 Simultaneous Dual Injection Feasibility Summary

The feasibility of using the 2K process has been proved and transparent components produced. However there remains a very large amount of work that needs to be carried out to take the technology to a usable level.

A much greater level of control is required for transparent applications, both in terms of material rheological properties and process parameters, to avoid mixing at the skin-core interface which causes hazing through a mismatch between the material's refractive indices.

It has been found that the generally accepted academic principles concerned with obtaining laminar flow during simultaneous dual injection moulding and controlling the skin and core distributions during the injection cycle are too simplistic and cannot be relied upon to guarantee good results.

The ratio of viscosities of the skin and core materials appears to be a more dominant parameter than the centre line velocity ratio, whilst the injection speeds of the skin and core materials have been found to have a direct influence on interfacial mixing and haze generation.

An alternative approach would be to use skin and core materials whose refractive indices are matched to within ±0.002 when mixing would be permissible. Unfortunately this is unlikely to be possible because of the complexity of altering the refractive index of thermoplastic materials.

The use of the 2K process as a means of producing glazing components is more difficult than first thought and whilst material rheological properties can be matched in theory, the reality is that there are a number of other influencing parameters, some of which may not yet have been identified, that need to be controlled if interfacial mixing is to be avoided.

As such, more investigation will be needed to identify and further understand the critical process parameters so that quality and reproducibility may be guaranteed.

5.0 Glass Reinforced Transparent Systems

The final area of technical research undertaken within this programme was concerned with improving the stiffness of polymer glazing components. In order for polymers to be used in large flat applications, they need to be thicker than a glass equivalent due to the reduced rigidity of the materials. This leads to an increase in mass and counteracts some of the weight saving benefit whilst increasing material costs.

It had previously been found that whilst it was possible to introduce glass spheres into polymers within a laboratory environment, the level of generated haze and distortion made any transparent components opaque, even at low levels of inclusion. (Manton, 1996)

It was evident from this early work that glass beads were not a suitable medium as they exhibited a large level of inherent haze due to the process used to manufacture them. A better reinforcement would be glass fibres that have a much greater level of clarity and excellent transparency.

Traditionally glass fibres have been used to reinforce polymer components, however this practice has always been confined to non-transparent applications. A feasibility study was undertaken to investigate whether glass fibres could be used for reinforcing transparent components with no loss of optical quality resulting.

5.0.1 Preliminary Research

Initial literary research revealed that there are two key requirements for optical clarity: -

1. The polymer matrix and glass fibres must theoretically have a refractive index (RI) mismatch of no more than ± 0.010 (Rutz, 1988), although a mismatch of no more than ±0.002 has been found to be a more practical requirement. (Lin et al., 1993)

2. Excellent wetting must be achieved between fibres and matrix to impart maximum mechanical benefits and remove any air that may distort light transmission. (Olson et al., 1992)

However all of the research to date has been limited to thin film applications, and primarily carried out through several costly, time-consuming stages not compatible with industrial applications.

There are several recognised methods of matching the refractive indices of glass fibres and polymers (Mitsubishi, 1981; Dorrer et al., 1974; Olson, 1988) however the practical requirements for such activities are highly complex and not a capability possessed within the ATC. Consequently attention was focussed upon developing a process that would allow the inclusion of glass fibres if the refractive indices within the system could be matched at a later date.

It should be noted that any component manufactured with a transparent pre-preg would still require a hardcoat to be applied to afford scratch resistance, as polymer would still be present on the outer surfaces.

5.1 A First Approach – Direct Injection

The first experimental approach concentrated upon direct injection of a polymer matrix through a glass fibre mat laid into a suitable mould cavity, in order to see if glass fibres could be simply introduced.

It was soon recognised that the resin cooled too rapidly when it was injected into the cavity under conventional moulding conditions, resulting in little or no wetting of the glass fibres as shown in Figure 5.1.

In order to reduce the cooling rate of the resin, and give the polymer time to penetrate the fibre weave, external heating was applied. A redesign of the tooling arrangement was undertaken to allow an elevated cavity temperature to be maintained for any period of time. This meant that the resin could be kept molten, permitting more time for wetting to occur and the cavity could be cooled by pumping oil through the oil channels. Figure 5.2 illustrates the basic arrangement.

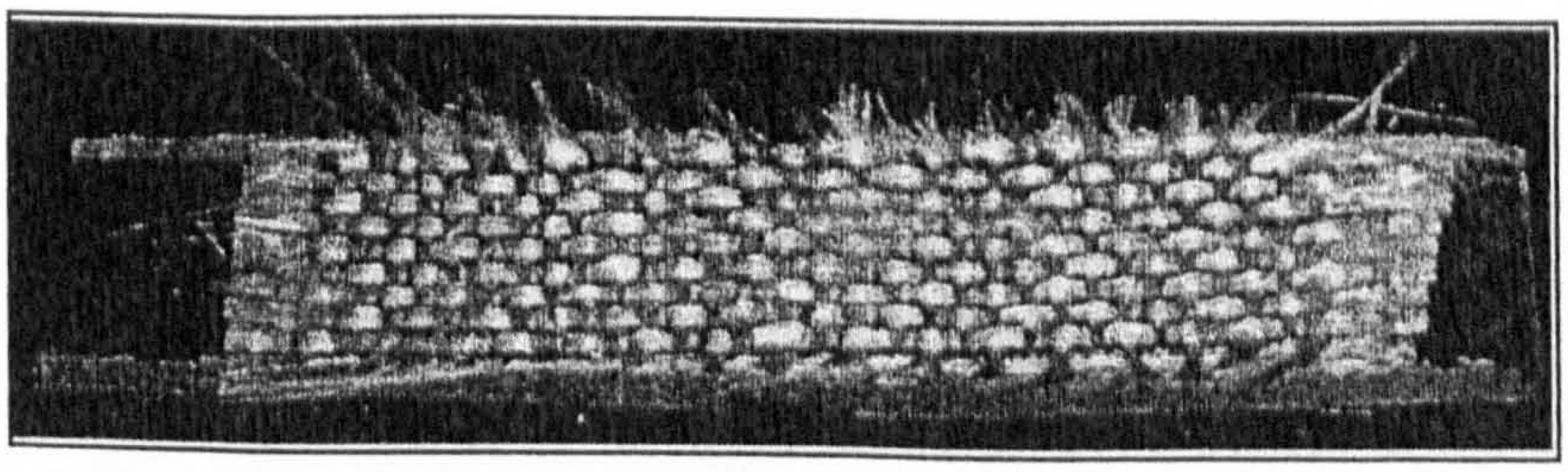


Figure 5.1: - Unwetted Glass Reinforced Polycarbonate Sample

Initial results suggested that total wetting could be achieved via this new, thermally controlled tool and a patent (WO000338 – Improved Polymer Glazing) was filed and published.

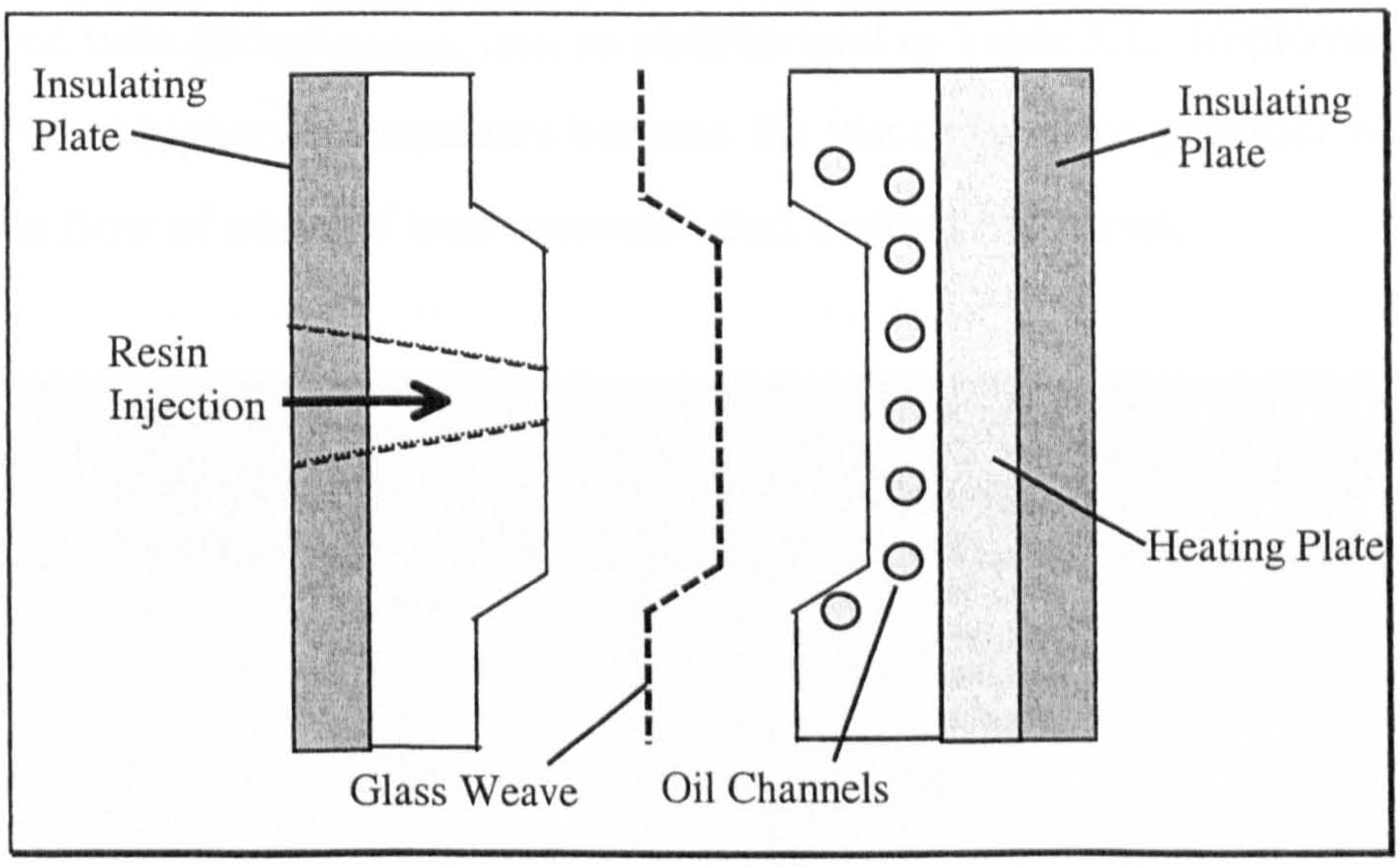


Figure 5.2: - The Thermal Control Tooling Arrangement

However it soon became apparent that simply increasing melt temperature and allowing more time for wetting was not sufficient to achieve total wetting. The best samples produced via this method exhibited approximately 40% fibre wetting and is reproduced in Figure 5.3

The samples took 10 minutes to produce at 320°C, in itself too long to be industrially viable and increasing the wetting time revealed that nothing was happening after this period - in effect the system had reached equilibrium and there was no movement of polymer material in the mould to increase penetration into the weave.

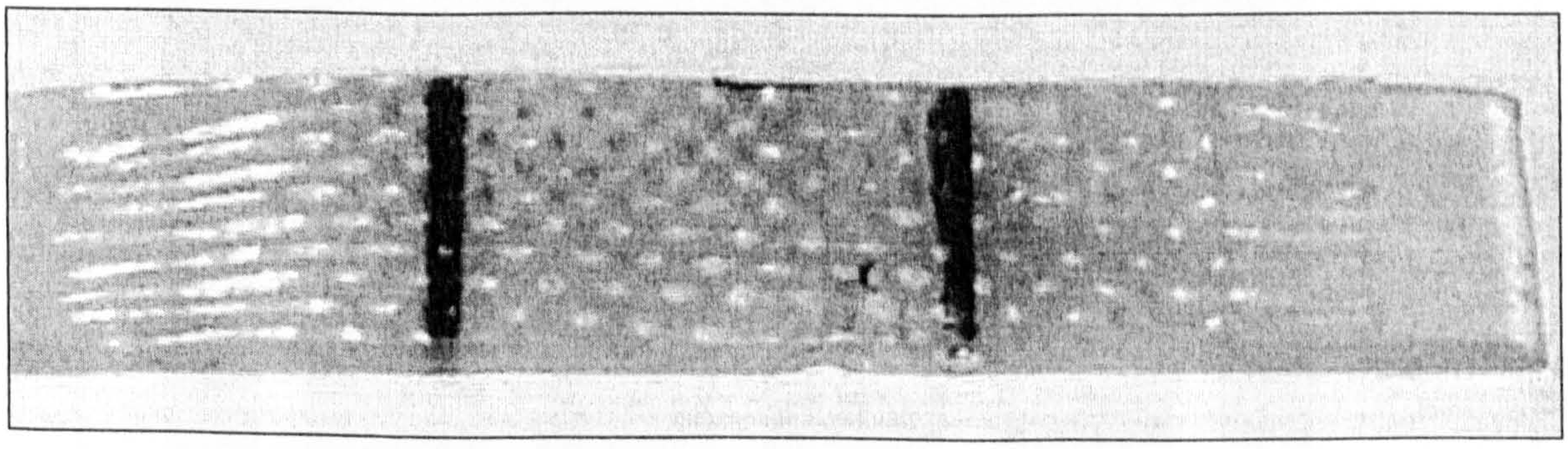


Figure 5.3: - Partially Wetted Glass Fibres

It was found that when the injection phase had finished, the only movement of polymer was through natural flow, which due to the high viscosity of the material was negligible, and certainly insufficient to expel any air remaining within the mould. As such, air became trapped within the glass weave and at the surface, leading to exposed fibres and relatively low wetting.

However an important observation was that elevated temperature improved wetting for any given time period (Manton, 1999) as summarised in Table 5.1. Improved wetting was achieved at higher temperatures because the viscosity of the polymer was lower and thus the flow of material was increased and wetting enhanced.

Sample Group	Mould Temperature (°C)	Processing Time	Approximate Level Of Wetting Achieved
A	280	10 Minutes	0%
B	300	10 Minutes	10%
C	320	10 Minutes	40%

Table 5.1: - The Effect of Elevated Temperature Upon Fibre Wetting

3-Point flexural tests suggested that there was an improvement due to the addition of fibres, even though only partial wetting had been achieved with the flexural resistance of the 40% wetted samples being approximately twice that of non-reinforced polycarbonate as shown in Figure 5.4.

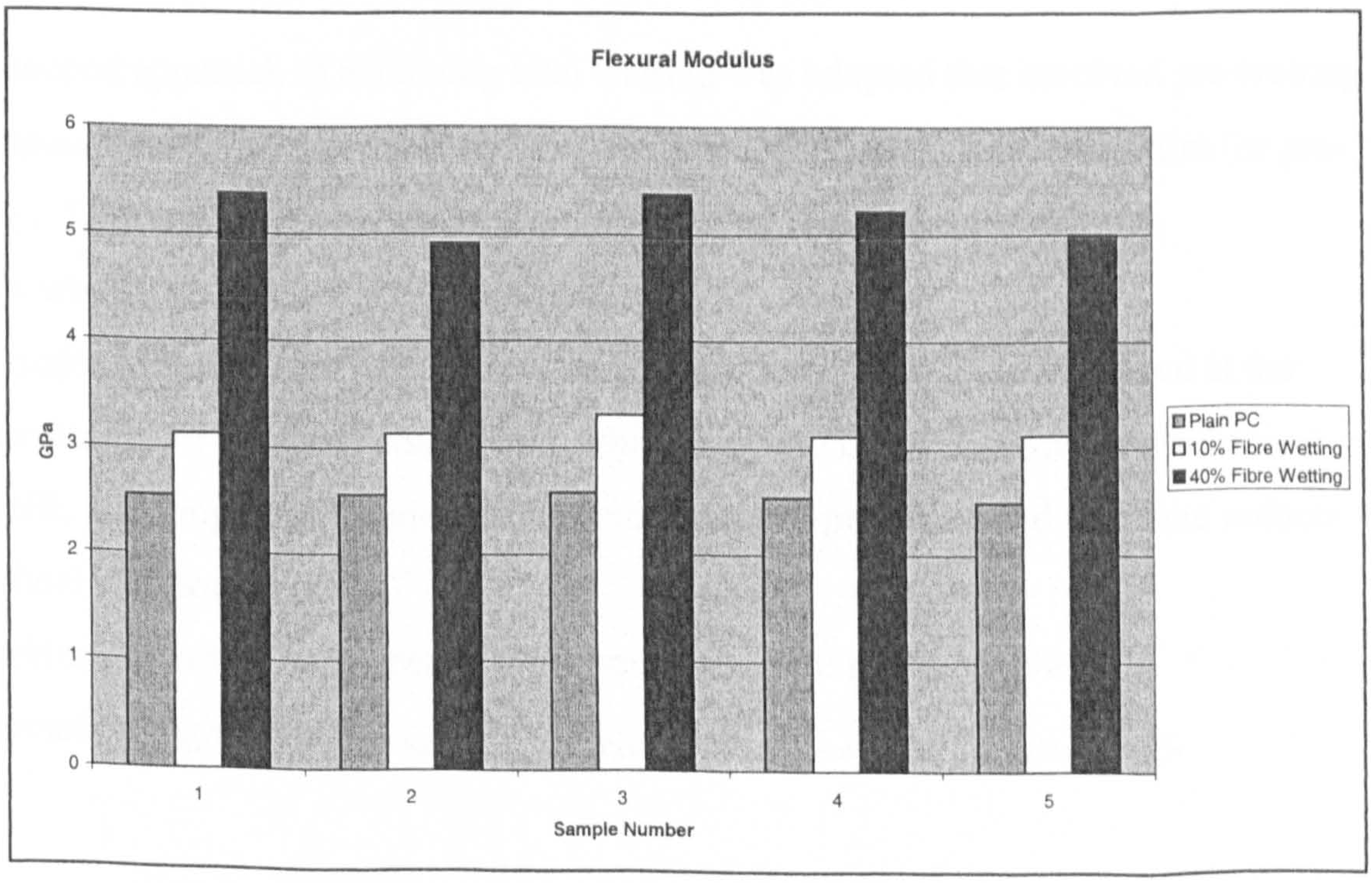


Figure 5.4: - The Effect of Improved Fibre Wetting Upon Flexural Rigidity

Two theoretical solutions were proposed to improve wetting still further. The first was to perform the operation under a vacuum condition in order to remove the problem of trapped air and improve flow of the polymer within the mould.

The second proposal involved inducing polymer movement through the use of an external pumping mechanism as found in the SCORIM process developed at Brunel University (Eureka, 2002), or preferably using a dual injection machine (i.e. with two barrels) to cycle the material between the two extruders, via the mould cavity.

Whilst both of these proposals were theoretically possible, they were at the time considered impractical for an industrial application without significant process development and investment and a different approach was adopted.

5.2 A Glass Reinforced Transparent Pre-Preg

The initial approach added some important information to the academic knowledge base, namely: -

- The polymer needs to flow in relation to the fibres in order to achieve total wetting.
- If glass fibres are pushed against the mould surface then air becomes trapped and wetting would be incomplete.
- Fibre wetting is improved if the polymer viscosity is lowered.

A second approach to achieving total wetting was adopted that involved pre-wetting the glass fibres with a suitable material to form a transparent reinforced film (or pre-preg). This could then be laid in the mould cavity and back injected with polycarbonate to form a laminate structure.

A major benefit of this approach is that the reinforcement could be placed at the outer surface of any final component, where it would impart maximum mechanical benefit, allowing minimisation of the amount of pre-preg used and therefore reduce the final component costs.

Previous attempts have been made to reinforce clear resins such as Polymethylmethacrylate (Olson et al., 1992; Lin et al., 1994; Six et al., 1991; Stoffer et al., 1991), Polychlorotrifluoroethylene (Dechent et al., 1993) and epoxy resins (Kagawa et al., 1998) by prewetting fibres with a liquid monomer and then laying them in a mould that is subsequently filled with more liquid monomer. In all cases, pre-preg production time ranged from many hours to several days for full polymerisation to be achieved. One of the key goals of this investigation was to develop a much quicker and simpler process to make it more attractive to industry.

5.2.1 The Wetting Agent

A thermoset polyester material was identified as being a suitable wetting agent and it was available in a fine powder so it could be easily dispersed over the surface of the weave. When heated, the powder became a transparent liquid with very low viscosity that flowed easily.

Whilst the refractive index of the wetting agent was not within ±0.002 of the glass fibres used, the development team behind the material confirmed that the refractive index could be matched to the glass fibres through doping with certain chemicals. (Bell et al., 2001) As such the intention of the research described here was to develop a process that guaranteed 100% fibre wetting.

The project objectives can be summarised thus: -

- Development of a quick and economic process capable of producing highly transparent pre-pregs that could be used to reinforce materials such as polycarbonate.
- Achievement of total fibre wetting by the pre-preg matrix such that no air gaps or voids existed, either before flexural testing or after, intimating that adhesion between fibres and matrix existed.
- Evaluation of any increase in sample stiffness attributable to the pre-pregs.

5.2.2 Making a Pre-Preg Reinforced Component

The simplest method of producing small batches of pre-preg was found to be via a hot press which facilitated excellent heat transmission to the wetting agent and allowed cyclic pressure to be applied that induced constant movement of the wetting polymer.

The pre-pregs were constructed as in Figure 5.5. The acrylic film was used because it was known to exhibit excellent adhesion to polycarbonate and would facilitate subsequent back-injection. The preferred hardcoat (at the time) that was to be applied to any final component was also only compatible with acrylic materials. The PTFE film was used purely as a release mechanism

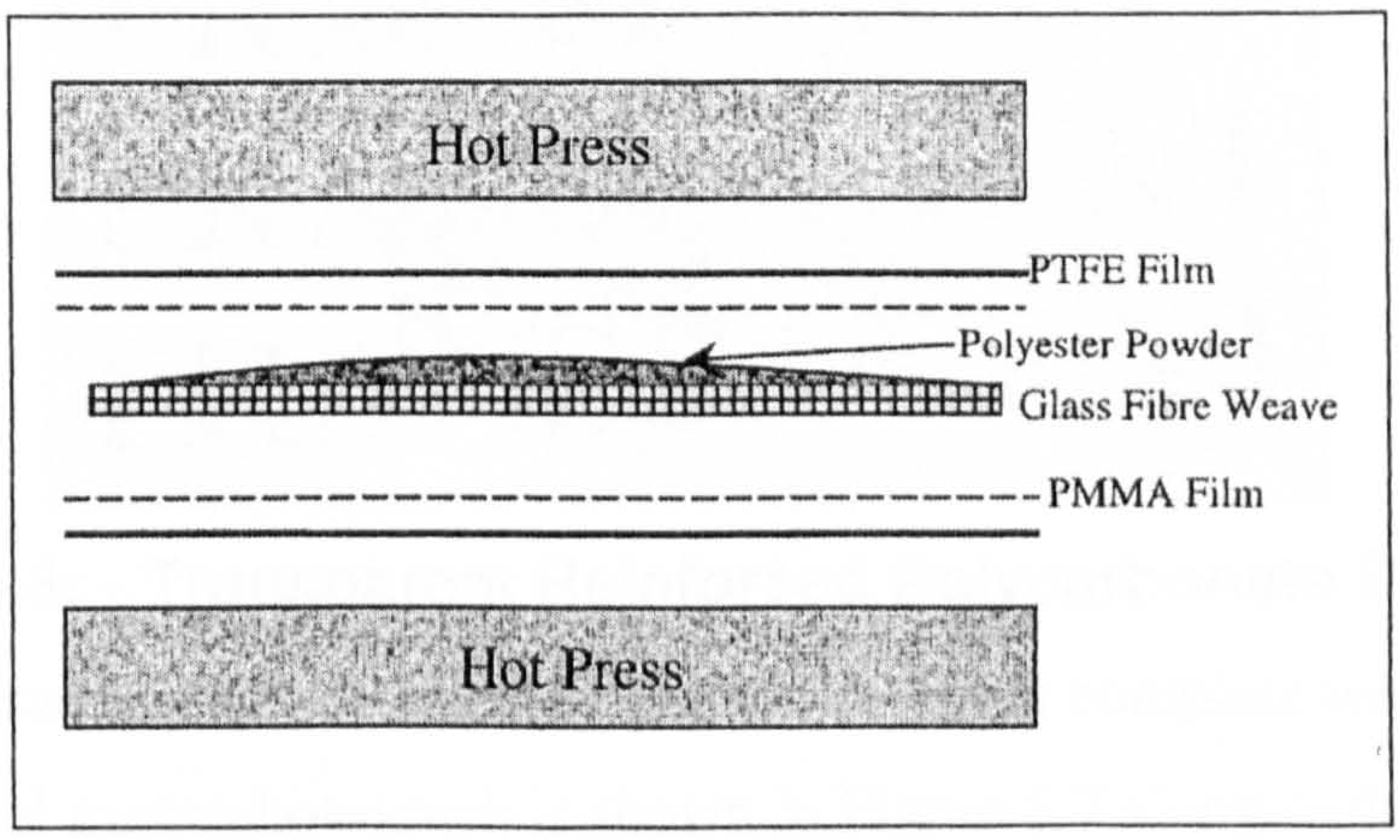


Figure 5.5: - The Pre-preg Structure

The sandwich was laid between the platens of the hot press, which had been heated to 200°C, and the platens were brought together to just touch. After 2 ½ minutes a load of 10 tons was applied for 30 seconds and then released. This was repeated twice more and the sample removed.

When the pre-preg films had cooled they were cut into 120 x 120 mm squares and laid into a centre gated flat plaque injection-moulding tool and hot PC injected onto the back of the film. No shrinkage distortion was observed in any of the plaques produced, despite fibre reinforcement being present on only one face.

The samples were 4mm thick and showed excellent adhesion between film and substrate. The samples were subjected to a standard peel test (Kirwan, Dec 2001) and no separation of film and matrix was witnessed. Further investigation showed that the glass fibre weave had physically stopped the knife edge passing through the pre-preg into the polycarbonate, suggesting that an extremely effective protection mechanism had been afforded to the polycarbonate.

The samples were then laser-cut into 25mm wide strips and exhibited a high level of transparency, fibre wetting and reproducibility as shown in Figure 5.6. Unfortunately the structure of the weave was still slightly visible because of the mismatch between the refractive indices of the chosen polyester and glass fibres.

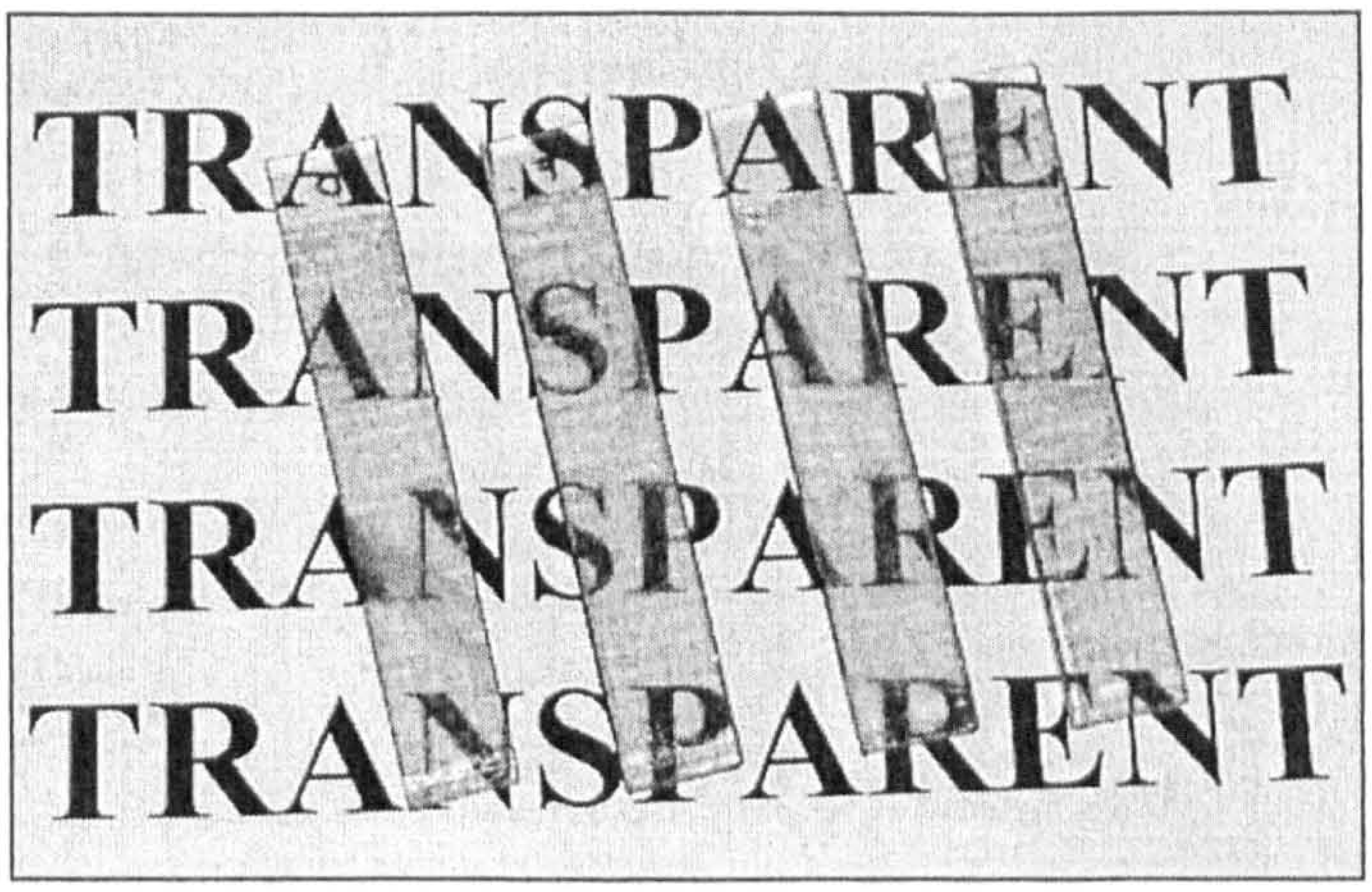
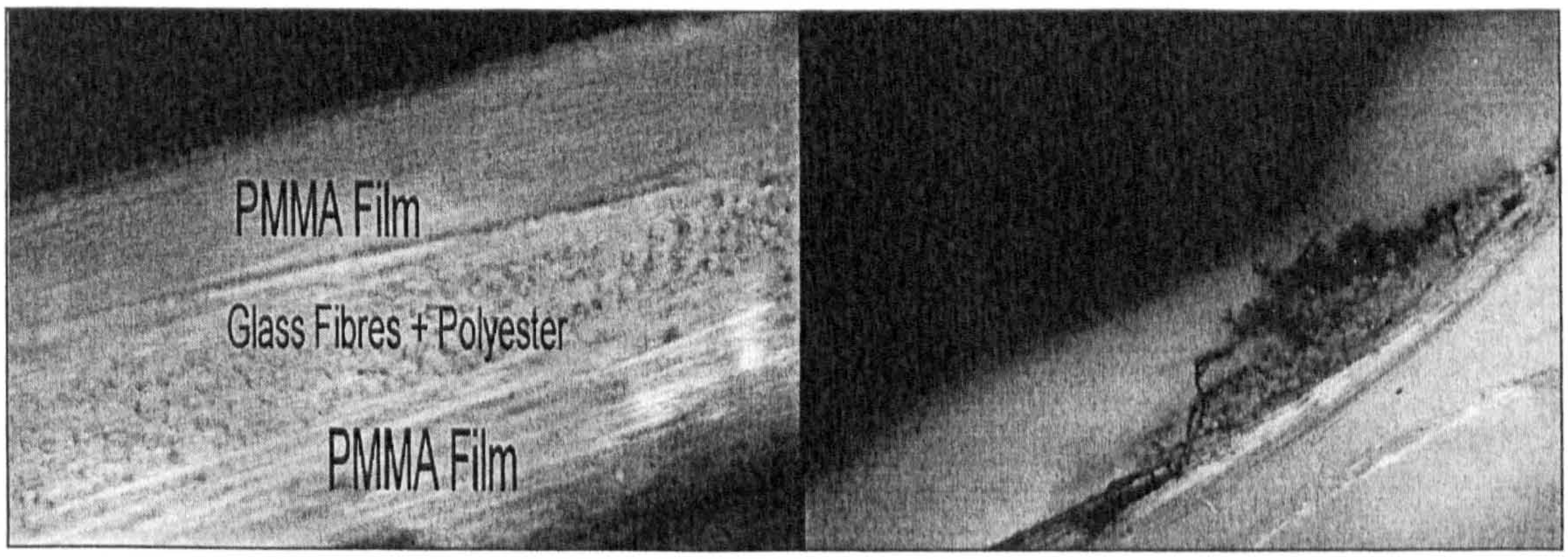


Figure 5.6: - Transparent Reinforced Polycarbonate Samples

Samples were studied under a microscope to ensure that complete wetting had taken place and a typical microphotograph is shown in Figure 5.7 along with a photograph of the partially wetted sample shown in Figure 5.3. It can be seen that total wetting of the glass fibres was achieved, confirming that any optical distortion was indeed due to the mismatch of refractive indices in the system.



Total Wetting Partial Wetting

Figure 5.7: - Microphotographs Showing Complete and Partial Wetting of Glass Fibres by Wetting Agent

5.2.3 Assessing the Success of the Reinforcement

The 25mm strips were subjected to three point flexural tests to assess what improvement in stiffness was achieved and Figure 5.8 shows a summary of the results. It can be seen that the flexural modulus of the reinforced samples (A - I) is approximately three times greater than the unreinforced samples (PC). The results also demonstrate a high level of consistency from this process, which can be expected to improve, as the process is further refined.

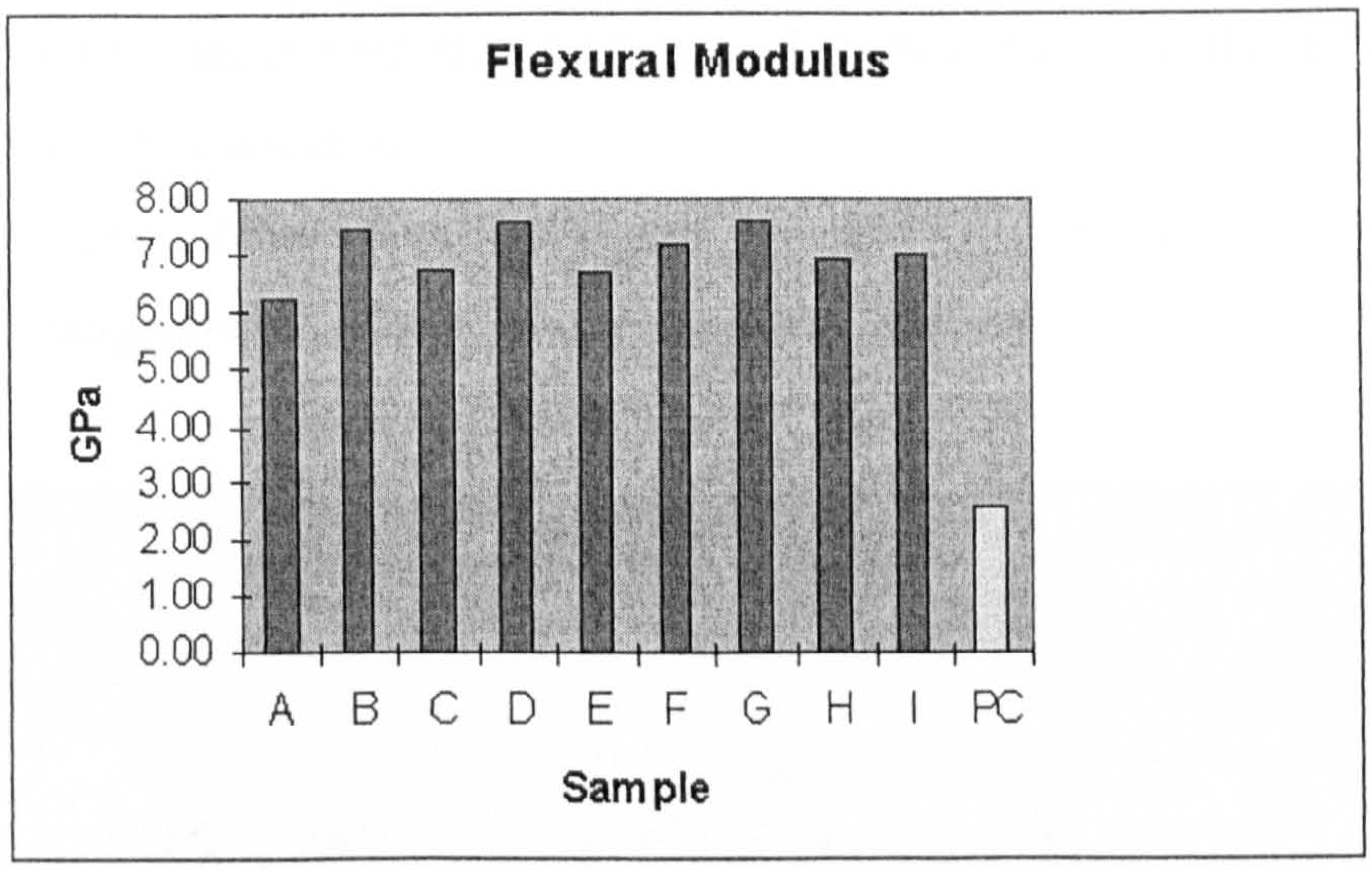


Figure 5.8: - Summary of Mechanical Improvement Obtained

5.3 Improving Optical Quality

Having shown that significant mechanical improvement had been achieved, attention was turned towards improving the optical quality of the pre-pregs.

It was noted that the processing temperature of the polyester powder was near the melting temperature of the acrylic film ($Tm_a \approx 215°C$) which, as discussed in Section 3, had been shown to sometimes degrade. If any film was melting then the cyclic loading may have induced mixing of the molten film and polyester resulting component hazing as witnessed during the 2K development work and discussed in Section 4.

Some more pre-pregs were made using a polyester thermoplastic film, rather than an acrylic film. The polyester film had a higher melting point ($Tm_p \approx 255°C$) and the same refractive index as the polyester powder, which meant that if any melting of the film did occur, no hazing would be generated upon mixing. The polyester film also exhibited an excellent surface finish, as it was a cast film rather than a blown variety. When the PTFE release film was removed, it was clear that a vast improvement in optical quality had been achieved.

The pre-pregs were again back injected with polycarbonate and the polyester film had been pre-treated with an adhesion coating so that full adhesion between pre-preg and polycarbonate was obtained.

Figure 5.9 illustrates the quality of the samples produced and it can be seen that the fibre visibility is much reduced, although some distortion was still generated by the refractive index mismatch between the polyester and the glass fibres. When this mismatch has been minimised, it is considered that the optical quality of the components will be excellent.

Given the success of these findings, a second patent (GB2352249 – Glass Reinforced Transparent Pre-Preg) was filed and published.

Figure 5.9: - Improved Reinforced Components

5.4 Summary

This chapter has discussed the development work undertaken to investigate the feasibility of introducing substantial glass fibre reinforcement into a transparent glazing system.

A review of the literature revealed that there are two known requirements for transparency to be maintained. The first is total wetting of the glass fibres by the polymer and the second it that the refractive indices of the fibres and matrix must be matched to within ±0.002.

Chemical alteration of refractive indices was not within the scope of the project and attention was focussed upon developing a quick and efficient process that could guarantee excellent wetting.

The first adopted approach involved direct injection of molten polycarbonate through a glass fibre weave using a thermally controlled tool that allowed the polymer to be kept molten after injection and permit more time for wetting to occur.

This first approach appeared to offer some hope of success and a patent was filed but it became apparent that total success would not be achieved without substantially complicating the process.

However this early work did increase the knowledge base as it was found that total fibre wetting also required the polymer to flow in relation to the fibres and using lower viscosity materials would achieve greater wetting. If fibres became trapped against the tool then wetting would not occur.

A second approach was adopted that involved the manufacture of a transparent pre-preg in a hot press and back injecting with polycarbonate. A thermoset powder was located that, when heated, demonstrated all of the desirable characteristics of a wetting agent, namely transparency, low viscosity and excellent adhesion to the glass fibres. Cyclic loading was used to induce constant movement of the polymer and microphotography revealed that total fibre wetting was repeatedly achieved.

Further refinements to the system resulted in transparency and clarity being improved and a second patent was published. Flexural testing revealed that an improvement in rigidity of a factor of 3 had been obtained with reinforcement on just one side.

This feasibility study has been very successful in bringing huge improvements in both academic and process knowledge, and further work will be undertaken outside of the EngD programme to bring this technology closer to fruition.

6.0 How Should the Innovation be Exploited?

It became apparent early in the research programme that Exatec's strategy of competing directly with glass en-mass was seriously flawed, hence there have been no emerging applications to date despite their technical claims. An investigation of the potential market for an alternative glazing system is presented to examine what the focus of such a technology should be.

Whilst the programme has been concerned with delivering technical solutions to existing problems with polymer glazing, it was important to achieve this in a cost-effective manner. Technical improvements are required by the automotive companies, but they are unwilling to achieve these at any cost. The right product has to be at the right price. As such, a financial examination of the cost benefits or penalties associated with 2nd and 3rd generation technology as developed within this programme is also presented.

6.1 Analysing the Market Potential of Polymer Glazing

Polymer glazing is an emerging technology and the market is still very much in its infancy, with a few speciality applications such as the MCC Smart Car being evident.

Two different aspects of the polymer glazing market have been investigated within this programme. The first was a penetration forecast of the technology into the conventional glazing market. The model was based upon the previous adoption of RIM fascias as a replacement for steel components and the penetration curve was superimposed upon a vehicle production forecast to 2015.

The RIM model is analogous to polymer glazing because the market forces behind the change were similar to those today for polymer glazing, namely weight reduction, recycling and styling freedom. The RIM data also indicates that the technology achieved 50% penetration in 15 years, which is the same target that Doug Nutter (President of Exatec) stated they expected to achieve for polycarbonate glazing. (ACG, 2000, pg.171)

It was first thought that the replacement of glass headlamp lenses with polycarbonate would provide a valid market penetration curve to superimpose upon the vehicle production forecast as the lens technology was a forerunner to today's glazing activity. However it soon became clear that the lens penetration data would not be valid for this exercise simply because of the rapid acceptance of the technology in Western Europe, going from 0% to 90 % penetration in approximately 5 years. (Bayer, December 2001) Legislative barriers and product approval requirements mean that glazing will be a much more difficult area to introduce polymers and hence the timeframe needed for acceptance of alternative technologies will be greater.

The second aspect investigated what area of focus would most likely make polymer glazing a financially viable exercise. The model was based upon the Exatec business plan, which was intended to bring polymer glazing into direct competition for en-mass glass applications.

The detailed data and analysis for this section can be found elsewhere in the portfolio. (Kirwan, October 2002)

6.1.1 Forecasting the Market Penetration of Polymer Glazing Technology

The first aspect of the analysis was the generation of a Western European vehicle production forecast. (Kirwan, October 2001) Western Europe was chosen as the forecast model for several reasons: -

- It is the worlds largest production region for passenger cars.
- The market is mature and expected to exhibit stable demand, at least for the foreseeable future. (Auto Industry, 2001)
- It is also the market most likely to readily accept polymer glazing, especially within 'green' countries such as Holland and Switzerland who will be appreciative of the environmental benefits that polymer glazing can bring, both in terms of fuel economy and recycling.

The forecast utilises data only from 1995 onwards as the statistics prior to 1995 had been subjected to hugely influential political and economic impacts such as the fall of the Soviet Union, the reunification of Germany and the collapse of the ERM.

Figure 6.1 graphically shows the production data for Western Europe from 1995 (Autostat, 2001) and the industry forecasted production to 2006. (GCAT, 2001) It can be seen that the existing data follows almost a straight-line trend with an accuracy of more than 97.5 % over the entire period.

By projecting this 'best-fit' line forward 9 stages from 2006, it is possible to generate a future projection for production levels as also shown in Figure 6.1.

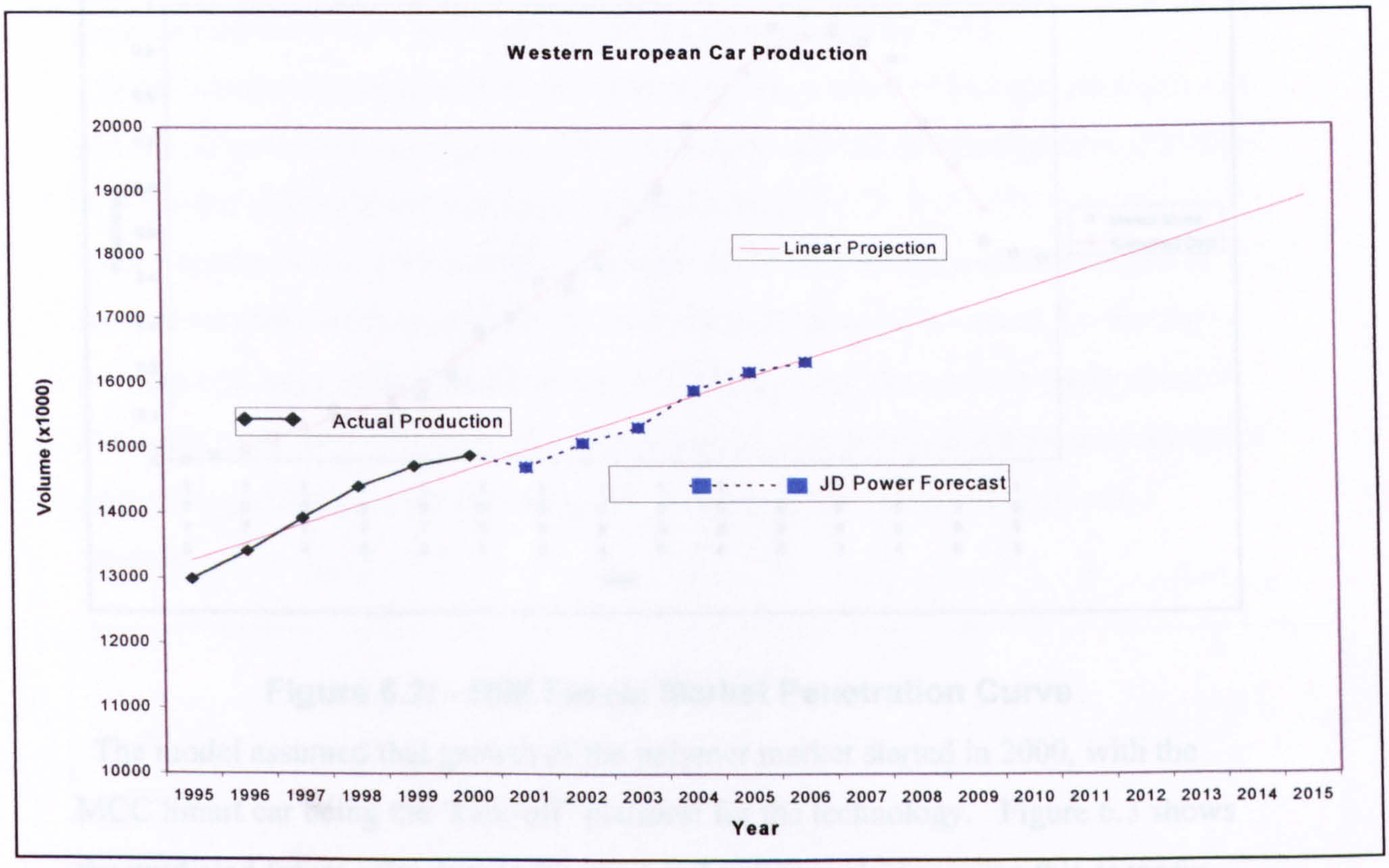


Figure 6.1: - Forecasted Vehicle production in Western Europe to 2015

Figure 6.2 shows the graph of market penetration for RIM fascia units. It can be seen that that fascia growth followed a typical 'S' curve that is commonly found with most new products when they successfully enter a market.

It was possible to predict the sale of glazing units to 2015 by assuming that there was an average of 6.5 glazing components in every vehicle produced. This ignored the fixed front and rear screens as it is not thought that polymers will ever replace them because of the structural importance of the components.

By superimposing the RIM fascia 'S' curve over the top of these glazing figures, it was possible to generate values of glass and polymer unit sales until 2015 when approximately 50% market penetration will be achieved..

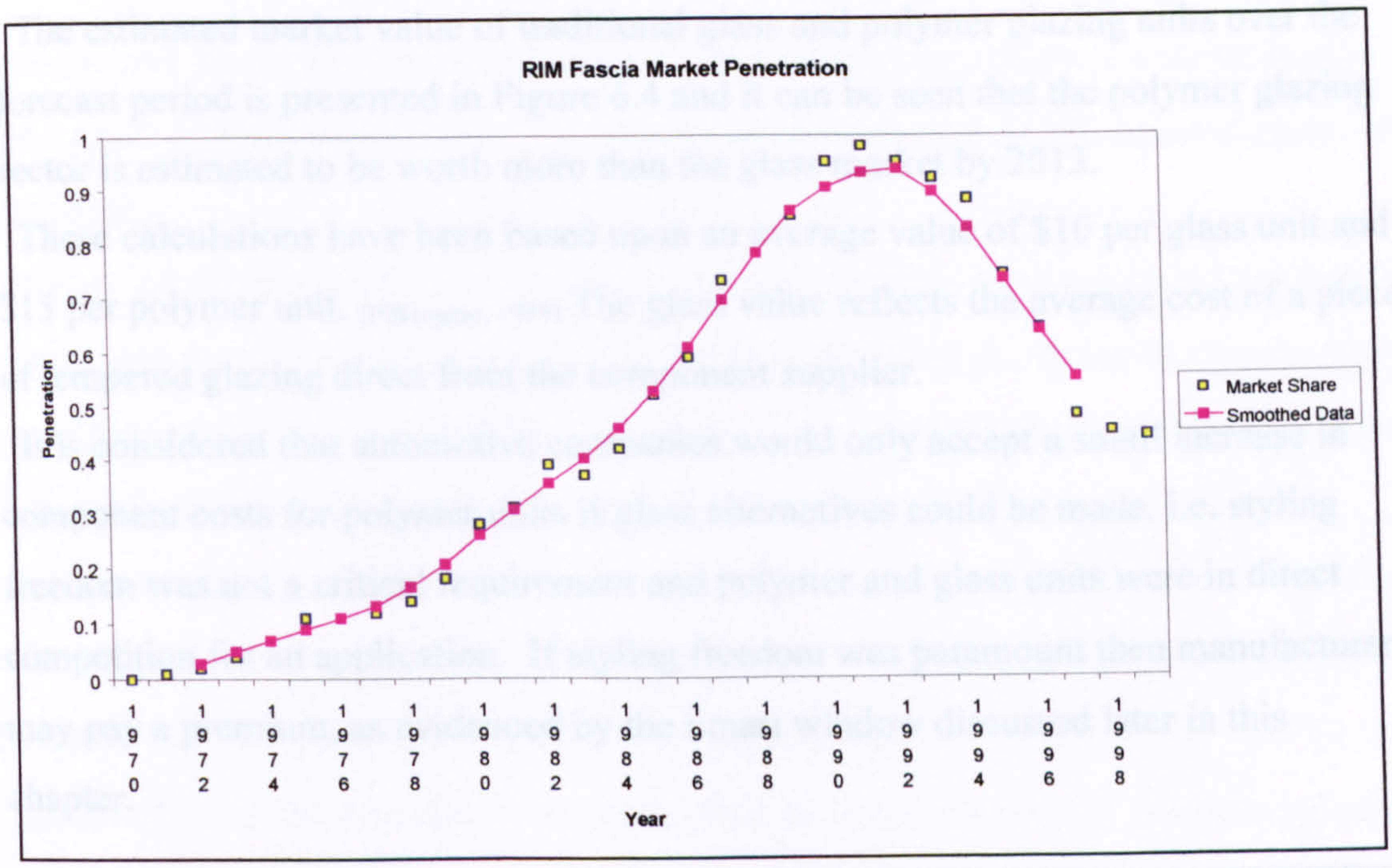


Figure 6.2: - RIM Fascia Market Penetration Curve

The model assumed that growth of the polymer market started in 2000, with the MCC Smart car being the 'kick-off' platform for the technology. Figure 6.3 shows the predicted future sales curves for glass and polymer glazing using this scenario.

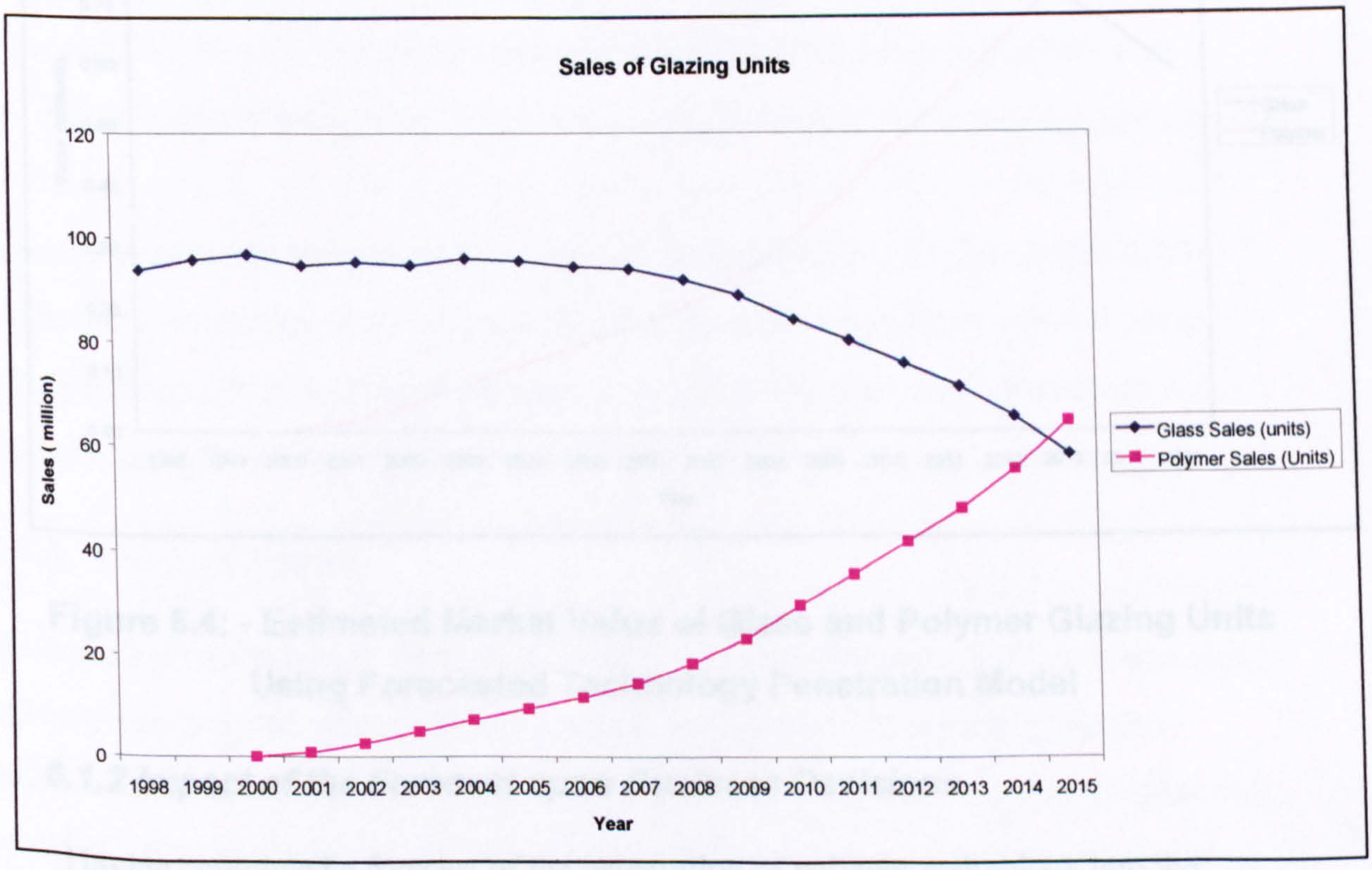


Figure 6.3: - Total Sales of Polymer and Glass Glazing Units Using RIM Fascia Technology Penetration Model

The estimated market value of traditional glass and polymer glazing units over the forecast period is presented in Figure 6.4 and it can be seen that the polymer glazing sector is estimated to be worth more than the glass market by 2013.

These calculations have been based upon an average value of $10 per glass unit and $15 per polymer unit. (Pilkington, 1999) The glass value reflects the average cost of a piece of tempered glazing direct from the component supplier.

It is considered that automotive companies would only accept a small increase in component costs for polymer units if glass alternatives could be made, i.e. styling freedom was not a critical requirement and polymer and glass units were in direct competition for an application. If styling freedom was paramount then manufacturers may pay a premium, as evidenced by the Smart window discussed later in this chapter.

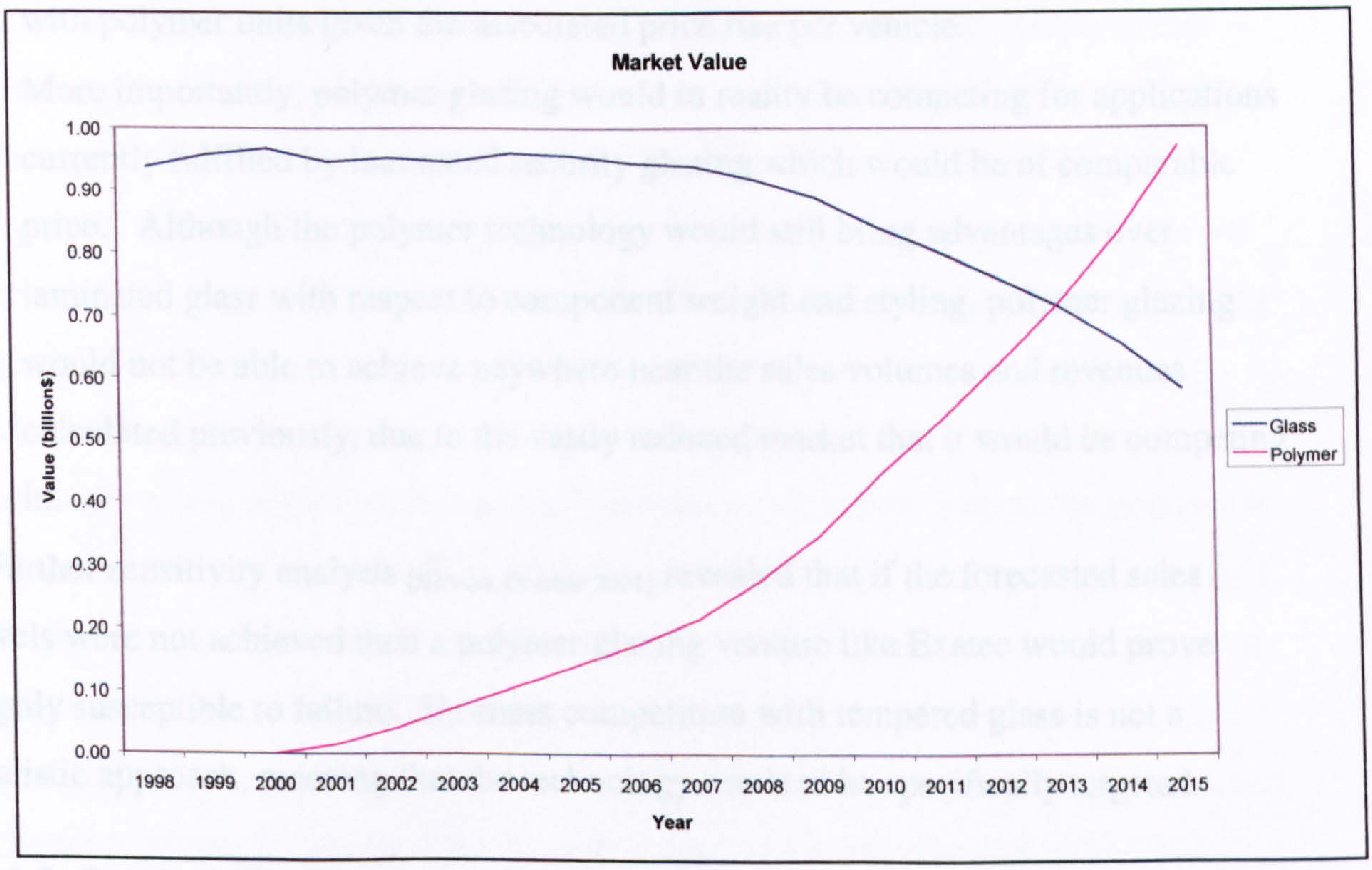


Figure 6.4: - Estimated Market Value of Glass and Polymer Glazing Units Using Forecasted Technology Penetration Model

6.1.2 Impact of the Forecast upon Business Decisions

Having completed a forecast of the penetration of polymer technology into the glazing market, a second analysis was conducted that utilised the Exatec business plan to investigate the feasibility of such an enterprise. (Kirwan, October 2001)

It was found that if the forecasted market penetration was achieved with an initial selling price of $15 per unit, then the venture would return a 24.7% internal return on investment.

However a key strategy of Exatec was to compete directly with tempered en-mass meaning that the $15 selling price may be unrealistically high. A sensitivity analysis showed that whilst it is possible to profitably sell a polymer component for less than $15, the risk associated with such a product is very high.

It was also suggested that simply raising mass-produced component prices would also be very risky. If polymer unit costs were nearer to $20 then the overall revenue generated could be greatly reduced for two key reasons: -

- Automotive OEM's would be very resistant to replacing normal tempered glazing with polymer units given the associated price rise per vehicle.
- More importantly, polymer glazing would in reality be competing for applications currently fulfilled by laminated security glazing which would be of comparable price. Although the polymer technology would still bring advantages over laminated glass with respect to component weight and styling, polymer glazing would not be able to achieve anywhere near the sales volumes and revenues calculated previously, due to the vastly reduced market that it would be competing in.

Further sensitivity analysis (Kirwan, October 2001) revealed that if the forecasted sales levels were not achieved then a polymer glazing venture like Exatec would prove highly susceptible to failure. En-mass competition with tempered glass is not a realistic approach, meaning that the technology needs to be specifically targeted.

6.1.3. Product Focus

The market analysis and subsequent sensitivity evaluation revealed that it was highly unlikely that polymer glazing could compete en-mass with tempered glass and concluded that a more realistic reason for polymer glazing being used at a higher cost would be that the styling of the glazing unit could not be produced in tempered glass. In this instance a much higher chargeable premium would be possible, as no alternative would exist. (Kirwan, October 2001)

Examining the evolving nature of the automotive manufacturing environment can support this conclusion.

Because of the high investment costs associated with automotive development, there is an ever-increasing trend of technology sharing between platforms. This is set to increase in the future as consolidation between manufacturers occurs to obtain opportunities of scale in purchasing price and power. A good example of this is Ford's Premier Automotive Group (PAG) which consists of Volvo, Lincoln, Jaguar, Aston Martin and Land Rover brands, who enjoy the purchasing power of the 'blue-oval' brands and transfer 'elite' technology back to the mass-produced vehicles in return.

Unfortunately this form of standardisation conflicts directly with the need for different products to satisfy a large consumer base, meaning that the ways to distinguish different vehicles is becoming more difficult.

Huge development costs also mean that the life span of important components is longer and the ability to change critical areas becomes limited. For example a typical chassis system will now be used for at least 10 years before redevelopment, a powertrain system will survive for approximately 15 years and engine platforms can take up to 25 years before replacement. However consumers demand ever-increasing choice, with the average new vehicle rollout being 4-5 years. (Land Rover, 2002)

All of this means that styling of body panels and glazing has become a very important method of distinguishing and maintaining a model's life, so the freedom of styling that polymer glazing offers represents the technology's strongest selling point.

If a piece of glazing cannot be made in glass then a high premium can be charged for a polymer version. This is illustrated by the Smart window, which costs approximately £13 per unit to the manufacturer. A similar component in glass on a different platform, but without the pointed corner, has been estimated to be £3.50 (Land Rover, 2002) which represents a substantial premium that the automotive manufacturers were prepared to pay to achieve the styling requirement.

6.2 The Costs of Exploiting the Research

This section presents a cost analysis of the different glazing generations discussed throughout the portfolio, comparing them against the cost of current polycarbonate glazing for a hypothetical application where glass could not be used. As such no cost comparison is made with glass.

For this cost evaluation exercise, the product was a stylised rear quarter window of modest size, being of similar shape and size to the Smart car window. All costings were based upon realistic estimates from relevant industrial sources.

Variations in window applications and glazing modules were not considered because of uncertainty over whether the automotive industry will adopt polymer technology for applications if equivalent glass components are available.

The key assumptions for this analysis were: -

1: - The Polycarbonate window had an area of $0.25m^2$ *and a thickness of 5mm.*

Area	Thickness	Weight (PC density = $1200kg/m^3$)
$0.25\ m^2$	**0.005m**	**1.5Kg**

2: - The maximum production volume of the theoretical component was 200,000 units. There was no time scale for this production level to be reached.

3: - There were no changes in material costs between the different generations of glazing.

4: - A single cavity injection-moulding tool was used at a cost of £100k and incorporated into the financial analysis for each generation. Extra costs are discussed where relevant.

5: - All hardcoats were applied via the dip-coating method discussed elsewhere. (Kirwan, December 2001, pg. 27) *This process was assumed to be 100% material efficient as excess coating can be recycled back into the coating tank.*

6: - The equipment needed to apply the chosen hardcoat was assumed to already be available as coating normally occurs at a specialist facility. As such the capital costs of coating equipment were not incorporated into the analysis.

7: -Material, coating and moulding costs have sometimes been supplied in US dollars. The conversion rate employed was $1.40 = £1.

The three glazing formats investigated were: -

1st Generation – Polycarbonate coated with GE-Bayer AS 4000 hardcoat.

2nd Generation – Polycarbonate back injected onto 150μm acrylic film and coated with Vitresyn hardcoat.

3rd Generation – Dual injection of polycarbonate and acrylic, coated with Vitresyn.

The cost of polycarbonate will be $3 kg. (Bayer,2001) The hardcoating cost is taken to be $8 per m^2, as estimated by Fraunhöfer (ACG, 2000). Moulding costs have been estimated from a current headlight quote supplied by an automotive OEM.

Moulding costs in this instance are calculated upon a 'recovery rate', which is a commonly accepted practice within the moulding industry. (Craddock, 2002) The basic principle is that each machine will have a charge per hour depending upon the size that will cover overhead costs, maintenance, depreciation etc.

The recovery charge associated with each moulding is calculated simply by dividing the adopted recovery rate by the number of units produced per hour. It is assumed that a 500 tonne machine is required to produce 80 1st generation glazing components an hour. A reasonable recovery rate for such a machine would be $110 per hour, which gives a recovery charge of $1.375 per unit. (Craddock,2002)

Moulding costs also include items such as labour, scrap allowance, material transfer and process set-up. The total cost of moulding a 1st generation unit has been calculated to be $1.75 in 2001. (Land Rover, 2001)

Both sides of the component are hardcoated through the 'dip-coating' process using a thermal curing system (Kirwan, December 2001, pp 23 – 27) and a further 10% of the total cost is added to account for administration, transportation, quality control etc.

6.2.1 1st Generation Cost Analysis

The 1st generation of polymer glazing evaluated was polycarbonate coated on both sides with a suitable exterior hardcoat as already available. The component would be of similar construction to existing polycarbonate glazing. A breakdown of the total component cost is presented in Table 6.1 and the full cost of producing 200,000 units is presented in Table 6.4 alongside the costs of the other generations.

Component Breakdown	Cost
Material Cost	4.50
Moulding Costs	1.75
Coating Cost	4.00
Component Cost	10.25
10% administration, transport, quality etc	1.03
Total Cost ($)	11.28

Total Cost (£)($1.4 = £1)	8.06

Table 6.1: - 1st Generation Component Costs

6.2.2 2nd Generation Cost Analysis

The 2nd generation of polymer glazing was assumed to utilise a 0.7m x 0.7m footprint of 150μm acrylic film on both sides of the component at a cost of $2.16 per unit. The final material cost for 2nd generation components has been calculated to be $6.53 per unit.

Because the film would need to be automatically rolled across the cavity, an extra capital cost of £10,000 was incorporated into the analysis to provide this capability. A slightly longer cycle time (+10 seconds) will be required to allow the film rolling stage and trimming of excess film from final components and therefore the recovery cost per unit will be increased as the number of components produced per hour will be less. The original recovery charge was based upon a 45 second cycle time. The number of second generation mouldings per hour will be 65, based upon a 55 second cycle time which equates to a recovery charge of $1.69 and a total moulding cost of $2.06.

The 2nd generation components were to be coated with 'Vitresyn' and the total cost of coating has been estimated as $0.41 per unit. (TWI, 2002)

A breakdown of the total component costs is presented in Table 6.2 and the full cost of producing 200,000 units is again presented in Table 6.4.

Component Breakdown	Cost
Material Cost	6.53
Moulding Costs	2.06
Coating Cost	0.41
Component Cost	9.00
10% administration, transport, quality etc	.90
Total Cost ($)	9.90

Total Cost (£)($1.4 = £1)	7.07

Table 6.2: - 2nd Generation Component Costs

6.2.3 3rd Generation Cost Analysis

The 3rd generation of glazing is based upon the dual injection moulding technology discussed in Section 4 meaning there is no need for the film to be applied to the surface of the component.

The dual injection process requires the skin layer to be thicker than the film employed in the 2nd generation due to processing constraints. The structure of the component has been assumed to be 80% core material and 20% skin material, i.e. 0.5mm acrylic: 4mm PC: 0.5mm acrylic.

The resultant material usage and costs have been calculated as \$5.97. The coating costs for the 3rd generation components will be the same as the 2nd generation.

The moulding costs will again be higher than 1st Generation technology for two reasons: -

1. It has been found that the injection cycle time needs to be longer to allow the acrylic to solidify. (The polycarbonate is processed at a higher temperature and dissipates heat into the acrylic meaning that the skin remains molten for longer than if a single material was being used). Production cycle time will be increased by 5seconds in order to allow sufficient cooling to occur.
2. The physical cost of a dual-injection machine is approximately 30% greater than a normal machine. This cost will be reflected in the recovery rate to account for depreciation. The accounting life of the machine is assumed to be the same as a normal machine.

The new recovery rate is \$145 and 72 3rd generation components will be produced per hour, giving a recovery charge of \$2.01 per unit, and a component moulding cost of \$2.38

A breakdown of the total component cost is presented in Table 6.3 and the full cost of producing 200,000 units of all three technologies is presented in Table 6.4.

Component Breakdown	Cost
Material Cost	5.97
Moulding Costs	2.38
Coating Cost	0.41
Component Cost	8.76
10% administration, transport, quality etc	.88
Total Cost (\$) (Including)	9.64

Total Cost (£)(\$1.4 = £1)	6.88

Table 6.3: - 3rd Generation Component Costs

At first glance, there does not appear to be a substantial cost benefit associated with adopting 3rd generation technology. However the 2K process that 3rd generation technology is based upon will allow much greater design freedom because it does not employ film technology, which can be limited by the formability of the actual film material.

It should also be noted that a further cost saving of ~ £0.29 per unit could be achieved if the requirement for a surface hardcoat could be removed. A future research programme has been established to deliver this capability through the development of a hardened nanoparticulate reinforced skin material to be used in the dual-injection process discussed in Section 4. (Kirwan, May 2002)

6.3 Alternative Exploitation Routes

The performance requirement of this technology for automotive applications is of a very high standard and there are a number of opportunities to satisfy applications of lower standard in other engineering areas. It is envisaged that this could be achieved before the technologies are applied within automotive applications.

The easiest and first commercial applications will involve flat sheets of the polycarbonate – acrylic film hybrid technology that could be easily used where stiffness is not critical but impact resistance and weatherability are. Interest has been shown by the construction and transport industries for applications such as telephone kiosks, bus shelters and advertising hoardings that are regularly vandalised through smashing of glass. (Edmunds, 2001) The polycarbonate sheets available at present do not exhibit sufficient chemical or weather resistance, but this has now been addressed.

The ability to create directional impact behaviour is also of commercial interest to the manufacturers of deluxe shower units that are manufactured to individual designs in tempered glass. At present manufacturers have to keep a huge range of pre-cut glass sizes in stock, as tempering is not normally possible on-site. This range is further increased by the need for specially curved glass that is expensive to buy and difficult to handle. (Showerlux, 2001)

Whilst polymer sheets could be easily cut to size and reduce the amount of material stored and the associated costs, one of the main problems is that components must be breakable from the outside by medics, fireman etc in the event that the shower occupant becomes incapacitated. By placing the acrylic film on one side of the polymer sheet, this requirement can be satisfied.

Each generation of technology has also provided valuable IPR in terms of technology, processing and research methodology and this information can be marketed to industry, disseminated to academia and, perhaps most importantly, used to attract funding for future research activities to further develop the technologies. One future programme has already been approved with significant backing from industry and a second is being conceived, based upon a large amount of the work carried out within this programme.

6.4 Summary

Analysis of the market potential of polymer glazing has revealed that en-mass competition with tempered glass will be a high-risk strategy because of the relatively high cost of manufacturing polymer components. At present, it is highly unlikely that automotive manufacturers will accept a substantial increase in glazing costs even if vehicle weight is reduced or security improved, although future environmental and consumer legislation may cause them to do so.

There is an ongoing trend of standardisation and platform sharing as development costs rapidly increase in the automotive sector. This means that product differentiation is becoming more difficult and this problem is likely to continue as the period needed to recover the investment costs of critical items such as powertrains and engines increases as well.

In a climate where consumers demand greater choice, vehicle styling is the key area where differentiation can be achieved with relative ease at comparatively low cost. This means that a better focus for polymer technology would be the freedom of styling that it offers. This approach may result in lower sales volumes, but does present the opportunity to charge a substantial premium, simply because no alternative would be available.

A large amount of technical innovation has been demonstrated throughout this programme and this provides an opportunity to improve the long-term performance of polymer glazing.

A cost analysis of each generation of technology has shown that the proposed combinations of materials and processes explored within this programme could provide a substantial cost saving over current polycarbonate glazing, whilst improving the overall long-term performance of the technology. This cost benefit could be greater if a future project that aims to incorporate nanoparticulate material into the skin material of the 3rd generation technology is successful as this would result in improved component hardness and remove the need for an applied hardcoat.

Table 6.4 summarises the production costs of each of the different generations of glazing discussed in this chapter. Figure 6.5 graphically illustrates the cost advantages of the technologies developed within this programme when compared to current polycarbonate glazing.

	Cost (£)					
Production Volume	**1st Generation**		**2nd Generation**		**3rd Generation**	
	Total Production Cost	**Unit Production Cost**	**Total Production Cost**	**Unit Production Cost**	**Total Production Cost**	**Unit Production Cost**
1	**100,008.06**	**100,008.06**	**110,007.07**	**110,007.07**	**100,006.88**	**100,006.88**
50,000	**503,000**	**10.06**	**463,500**	**9.27**	**444,000**	**8.88**
100,000	**906,000**	**9.06**	**817,000**	**8.17**	**788,000**	**7.88**
150,000	**1,309,000**	**8.73**	**1,170,500**	**7.80**	**1,132,000**	**7.55**
200,000	**1,712,000**	**8.56**	**1,524,000**	**7.62**	**1,476,000**	**7.38**

Table 6.4: - Comparison of the Production Costs of Each Technology Generation

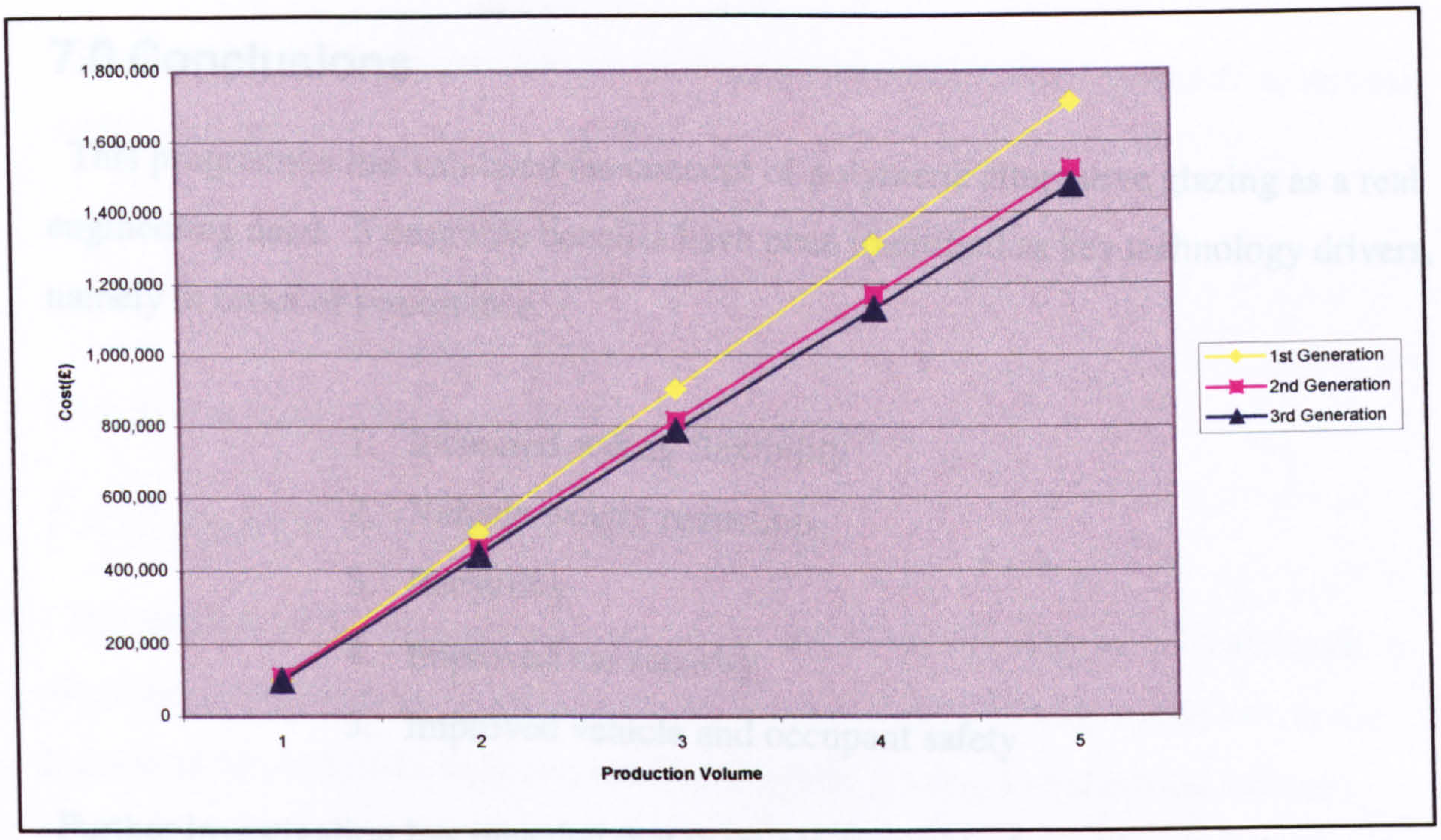


Figure 6.5: - Summary of Production Costs of Each Technology Generation

Spin-off applications of lower technical demand have also been identified, including bus-shelters, telephone kiosks and shower units. These applications are seen as suitable for near-to-medium term exploitation of the technology and could be pursued before any automotive applications occur.

7.0 Conclusions

This programme has validated the concept of polymeric alternative glazing as a real engineering need. 5 desirable benefits have been identified as key technology drivers, namely in order of importance: -

1. Increased styling flexibility
2. Vehicle weight reduction
3. Recycling
4. Improved car security
5. Improved vehicle and occupant safety

Further investigation has revealed that there are several technical barriers that are preventing en-mass acceptance of the technology. The critical technical barriers have been identified in order as: -

1. Poor long-term weatherability
2. Poor scratch and abrasion resistance
3. Low component stiffness

Analysis of these critical constraints has facilitated construction of a technology map that has focussed research activity within this programme at areas where most benefit could be achieved, given the resources available. Two new generations of technology have been proposed to permit ongoing utilisation of the research so that investment costs may be recouped at the earliest possible date.

This forward-thinking approach means that new products can be moved into the marketplace on an ongoing basis, but the latter generations do not supersede the earlier ones, as it is more appropriate to choose a specific technology for an application based upon complexity and cost.

Because of the skills and resources available to the programme, work focussed primarily upon polymer processing to improve the weatherability and rigidity of polymer glazing components. A watching brief was maintained over coating developments occurring elsewhere so that the constraint of scratch resistance could be addressed at a later date when a suitable technology emerged.

The conclusions from the research programme have been divided into three natural groups, namely:-

- Laminate Technology Development
- Process Development
- Exploitation

Each is discussed separately over the following pages.

7.0.1 Laminate Technology Development

The majority of the research focussed upon improving the long-term weatherability of polymer components. It was concluded that no single material would satisfy the legislative and industrial requirements for polymer glazing and attention has been successfully concentrated upon utilising novel production processes to create a hybrid system of polycarbonate and acrylic. These systems greatly increase the potential in-situ life of a glazing component and can be achieved at an ongoing cost advantage compared to current (or 1st generation) monolithic polycarbonate systems.

Two different processes were used to create the hybrid systems, representing the next two generations of polymer glazing. The two approaches were: -

- 2nd Generation – Back injection of polycarbonate onto thin acrylic film.
- 3rd Generation – Simultaneous dual injection (2K) of acrylic and polycarbonate to create a sandwich structure.

Both approaches have effectively provided a 'buffer' layer of chemical and UV resistant material between any applied hardcoat and the impact resistant, but environmentally vulnerable polycarbonate. There are several distinct advantages of this buffer approach compared to existing monolithic polymer glazing: -

- If the hardcoat is damaged, an effective protection mechanism remains in place
- The number of potential hardcoats is increased as the need for UV resistance within the coating is removed.
- Enhanced properties, such as solar control, can be imparted to the glazing in the future through the incorporation of different additives in the skin material alone.

Accelerated weather testing of the film-backed components revealed that a substantial improvement in UV resistance has been afforded to the polycarbonate, although a final production component will most likely require a thicker film to be employed. Tinting agents in the polycarbonate help to mask the onset of degradation and components produced via this method are predicted to survive the OEM requirements of 5 years Florida weathering.

The impact behaviour of film-backed samples was satisfactory with the rubberised film acting as a suitable buffer, preventing cracks initiated in the applied coating from travelling into the notch sensitive polycarbonate.

However when the film-backed samples were impacted in tension, they failed at very low energy levels because flaws in the film were able to easily propagate into the polycarbonate. This can be used to provide a very useful mechanism for addressing the identified consumer concern of being trapped in a vehicle fitted with polymer glazing. By laminating a film on the outer surface, intruder resistance can be maintained, whilst escape from a damaged vehicle becomes possible from the inside.

A further area of investigation regarding the inclusion of structured glass fibres into transparent components also represents ground-breaking work as the level of clarity, speed of production and increase in flexural rigidity imparted are greater than any other method known.

Literature research revealed that total wetting of the glass fibre by the polymer matrix is needed to maintain transparency. The refractive indices of the polymer and fibre must also be matched to within ± 0.002.

This research project has revealed that it is also necessary to maintain polymer flow in relation to the fibres to obtain wetting and that lower viscosity materials achieve a greater level of wetting. It was also found that if fibres became trapped against the tool face then wetting would not occur.

These findings led to the manufacture of a transparent pre-preg, which consisted of a structured glass fibre weave that was wetted with a thermoset polyester. Cyclic loading and heat were used to induce motion of the polymer and substantial fibre wetting was achieved. Flexural tests revealed that component rigidity was increased by a factor of 3 with the pre-preg present on just one side, addressing the critical constraint of rigidity and potentially satisfying the desirable property of thermal stability.

7.0.2 Process Development

Early trials with the acrylic film revealed that any mould tool required the injection gate to be of constant cross section and be located entirely on one side of the mould cavity, otherwise the film could be melted by the injected PC. If mixing of the two materials occurred then significant haze was generated due to a mismatch in the refractive indices. This behaviour was also observed during the 2K trials when turbulent flow and mixing at the skin-core interface occurred.

An alternative approach would be to use skin and core materials with refractive indices matched to within ±0.002, as mixing would be permissible, but this is unlikely to be possible because of the complexity of altering the refractive index of thermoplastic materials.

The 3rd generation of technology associated with dual injection is innovative simply because the process has never been used for transparent applications and the feasibility of producing glazing components through the 2K process has been demonstrated. However, there does still remain a significant amount of work that needs to be performed to bring the technology to a usable level.

The research has resulted in much greater understanding about interfacial interactions and shown that previously accepted academic knowledge does not guarantee the production of good components as the relative skin and core viscosities appear to be more dominant than previously thought. The injection speeds of the skin and core materials also have a direct influence on interfacial mixing and haze generation.

7.0.3 Exploitation

In depth analysis of the market potential of polymer glazing has revealed that en-mass competition with tempered glass, as advocated by Exatec, will be a high-risk manufacturing strategy because of the relatively high cost of manufacturing polymer components.

Polymer technology provides much greater freedom of styling for designers who are continually looking for ways of differentiating models to satisfy consumer demands for greater choice within a world-wide industry trend of standardisation and platform sharing. As such, polymer technology should be aimed at more niche applications that cannot be satisfied through glass. This approach may result in lower sales volumes, but it does present the opportunity to charge a substantial premium, simply because no alternative would be available.

The successful introduction of glass fibre reinforcement has the potential to open up a whole new area of application in the near-to-medium term for polymers, which cannot be used for large, flat structures such as bus shelters, telephone kiosks and shower units, due to a current lack of rigidity.

Automotive trends towards large areas of roof glazing mean that incredibly heavy glass is placed high on a vehicle and the use of polymers in such areas would be highly desirable as it would reduce vehicle weight and make road-handling much more comfortable for the driver.

As such, this technology represents a very important engineering capability of significant business value and the two patents that have been filed as a direct result of this development programme represent the project's most obvious IPR asset as they can be directly marketed to industry if desired.

7.1 Future Work

This research programme has delivered significant improvements in some aspects of polymer glazing. Further development of several technologies is needed to produce a complete glazing system. The proposals for future work are presented in separate technology sections.

7.1.1 Film Lamination

The film approach is seen as the first route to exploitation, but a number of laboratory tests need to be conducted before the expense of full-scale demonstrator components is incurred. More weathering data is needed to support the current findings and establish exactly what thickness of film is required to provide sufficient UV resistance. A series of chemical resistance, heat ageing, humidity etc. tests are also required by law.

The directional impact behaviour needs to be investigated more in order to further understand the failure mechanism as this will help to guarantee reproducibility if the property is desired or conversely, 'switch off' the property if it is not. More work is required by the manufacturers of Vitresyn to guarantee adhesion to the acrylic substrate and further scratch and abrasion trials will be required to verify the effectiveness of the coating.

7.1.2 Dual Injection Moulding

Future work on the 2K process is required to further identify and control the parameters that lead to interfacial mixing during the injection phase, which needs to be eradicated for transparent applications. There is also an opportunity to focus upon initialising and controlling the instabilities to generate mechanical interlocking and allow non-compatible materials to be used in non-transparent applications.

The interaction between the skin and core materials should also be investigated to ascertain whether the mechanical properties of the skin material dominate the system as suggested elsewhere. (Selden, 1997)

Both the film and the 2K approach provide a means of producing translucent body panels by pigmenting the skin material slightly. A future development programme has been constructed upon this idea to increase the styling flexibility available to designers. (Kirwan, May 2002) The incorporation of nanophase reinforcement into the skin material will permit the manufacture of larger flatter components through enhanced rigidity and improved surface hardness.

7.1.3. Glass Reinforced Transparent Composite System

The glass reinforced transparent composite needs work to be focussed upon more closely matching the refractive indices of the glass fibres and the wetting agent. Once this has been achieved then a production process more suitable to mass production needs to be developed to allow large sheets of pre-preg to be made and subsequently laminated with transparent polymer sheets.

A second programme is in the process of being established to address these issues.

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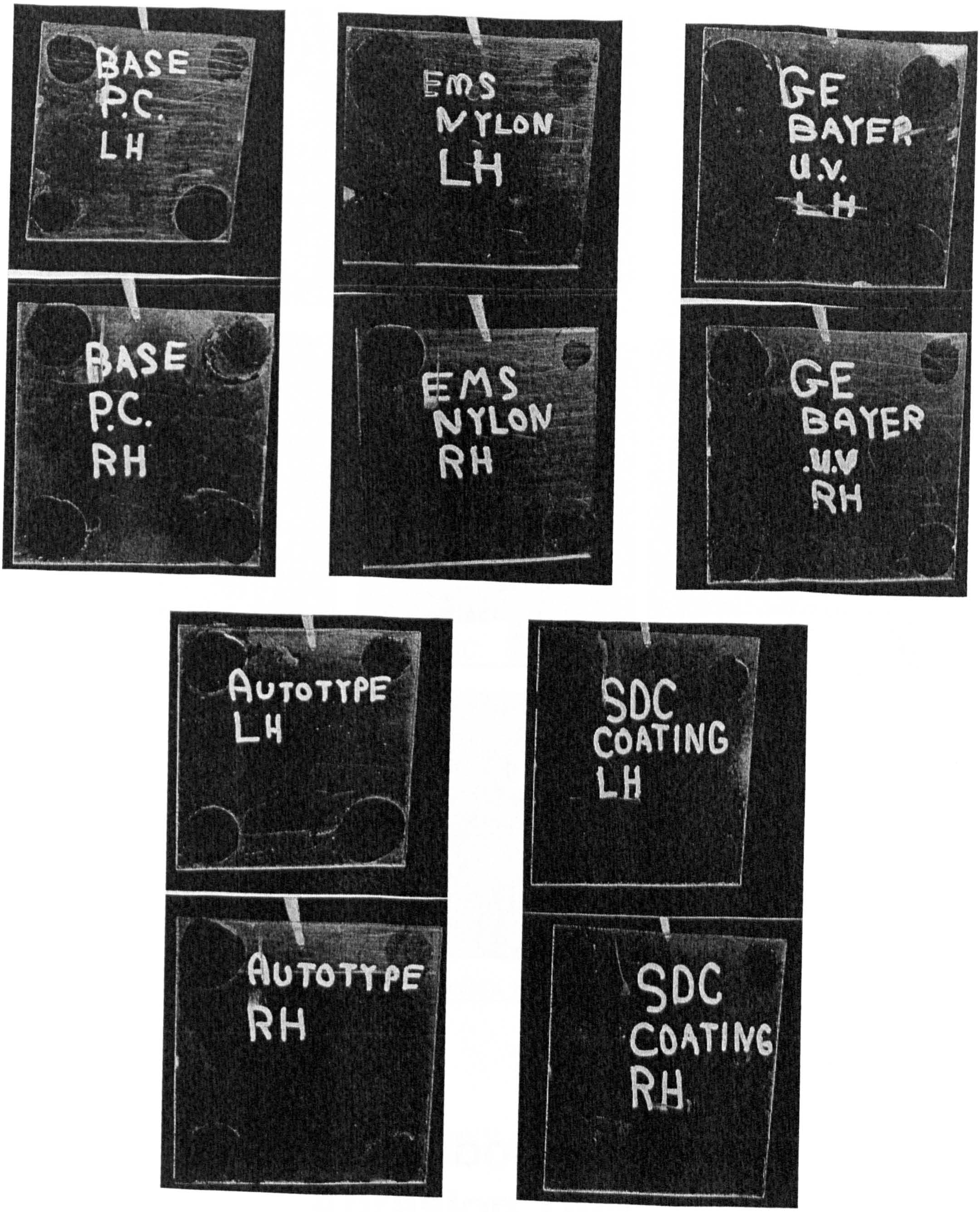
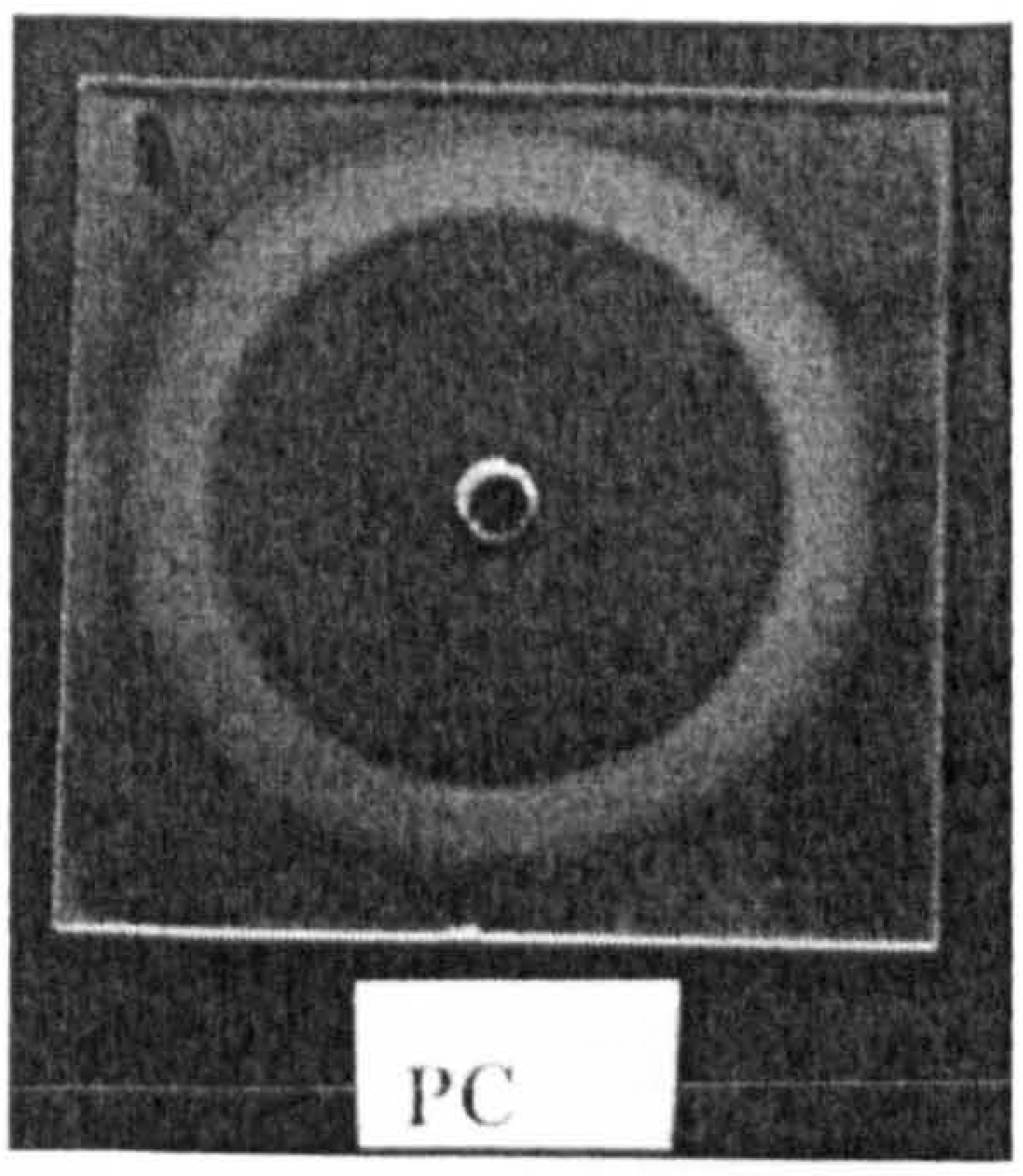
Appendix A: - Scratch & Abrasion Resistance Results



Results of Brush & Scrub Test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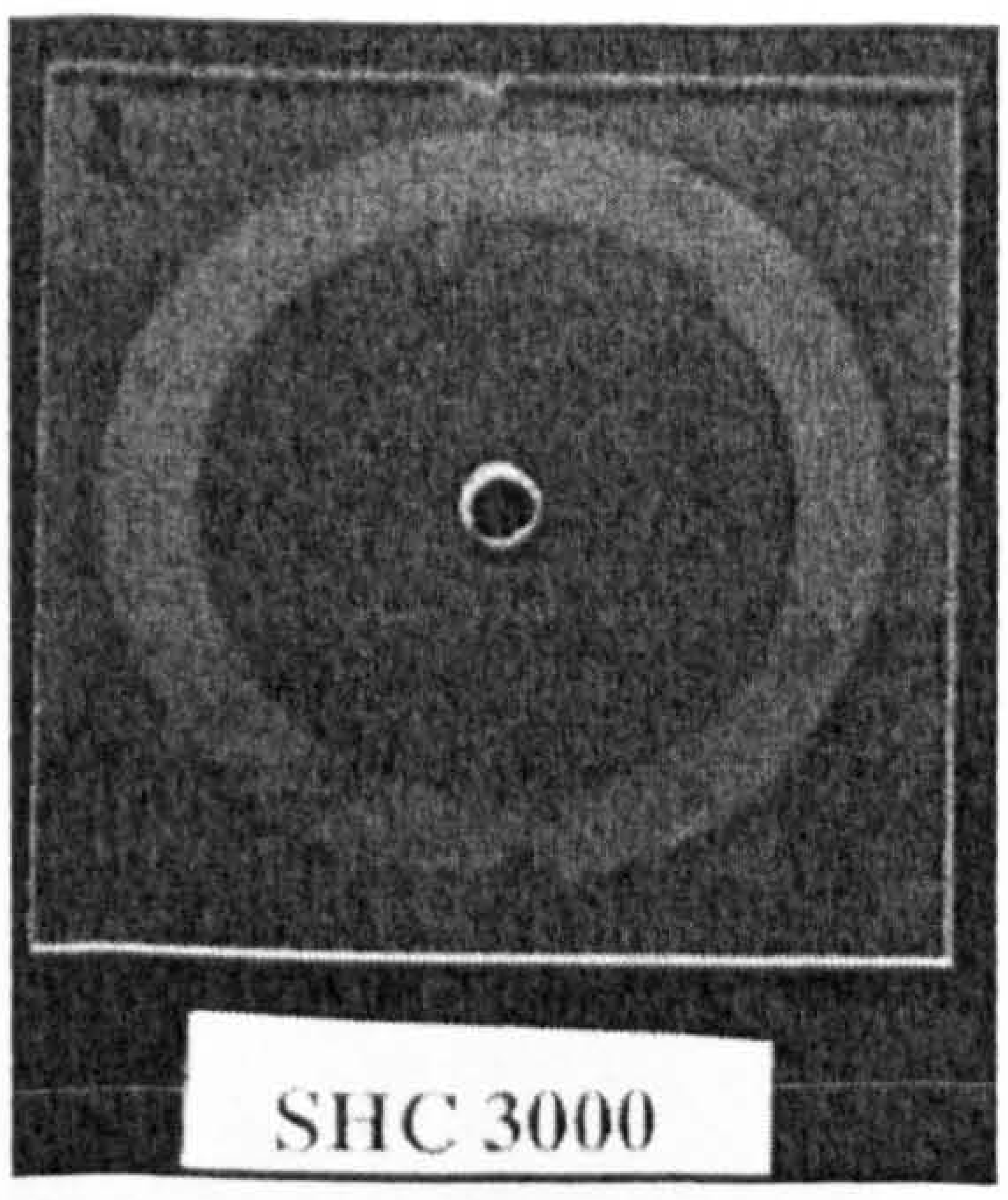
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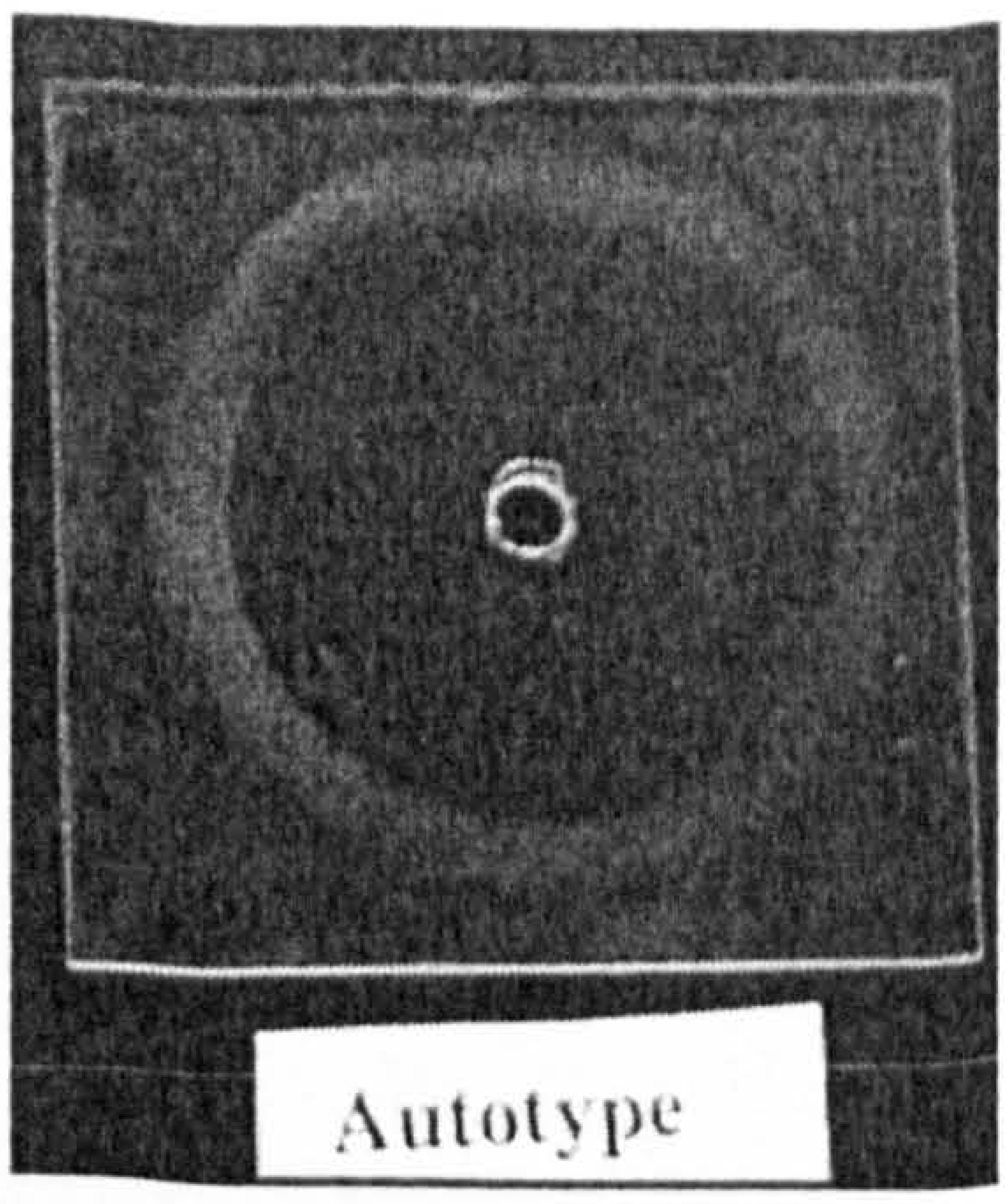
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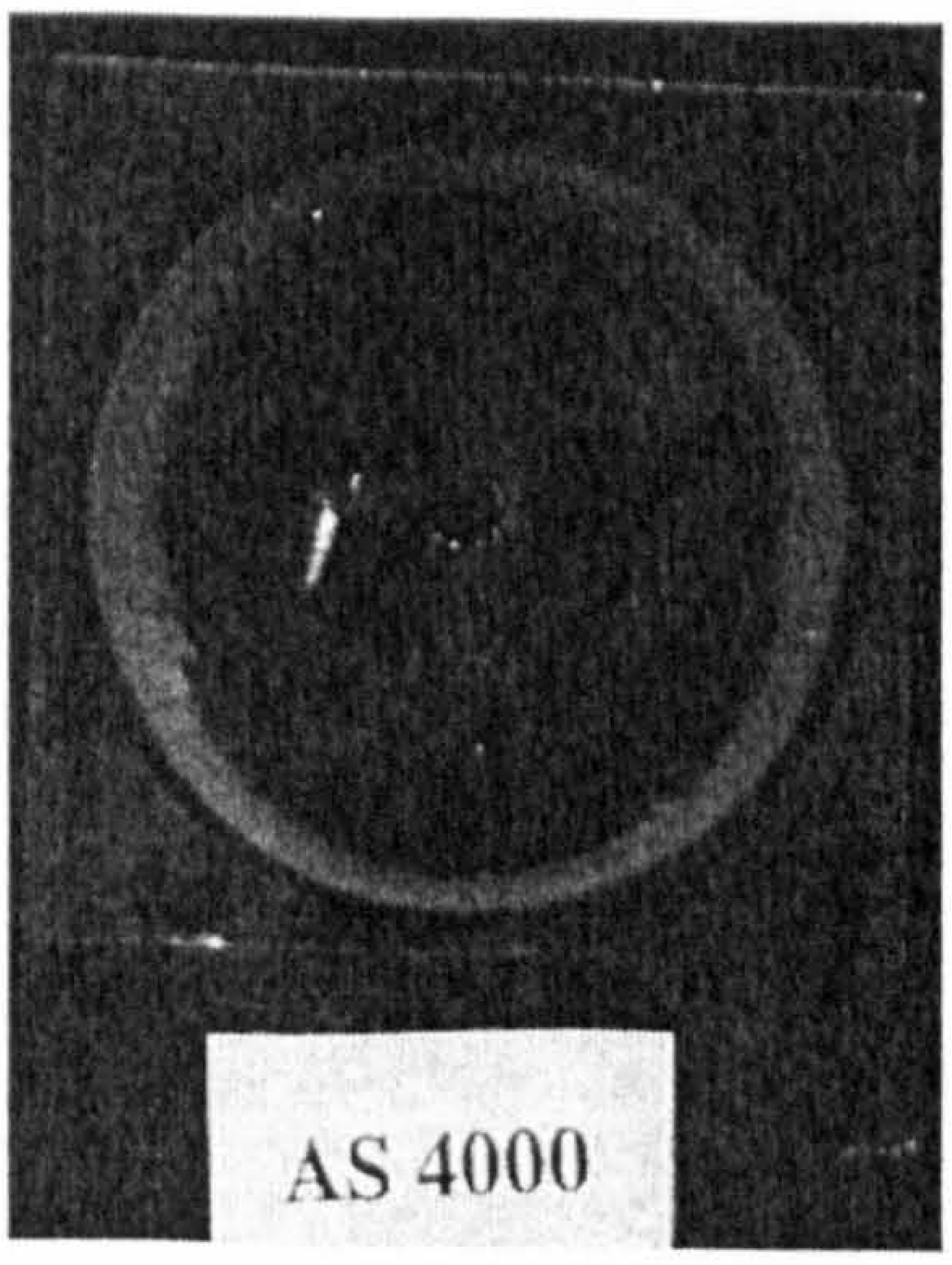
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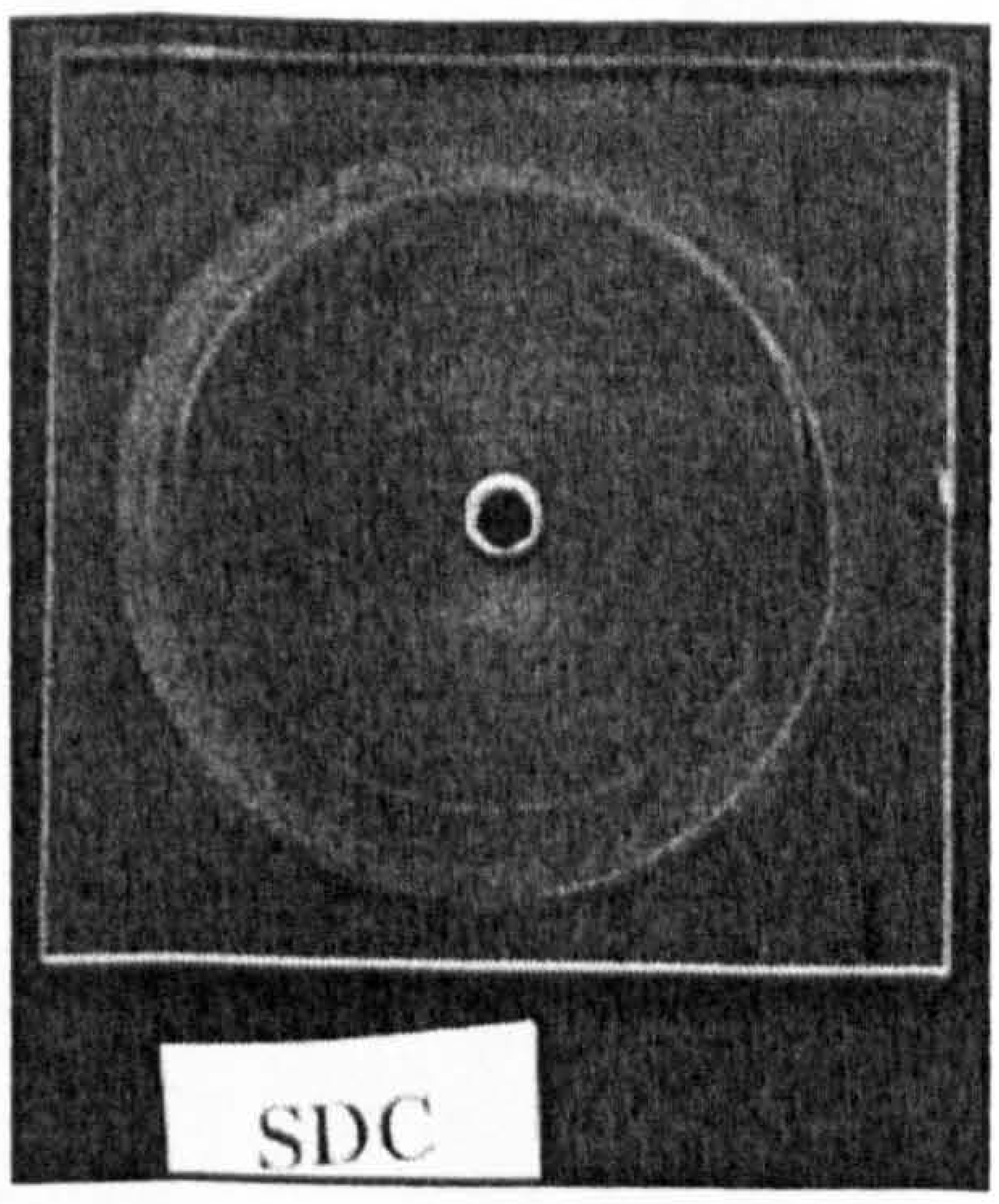
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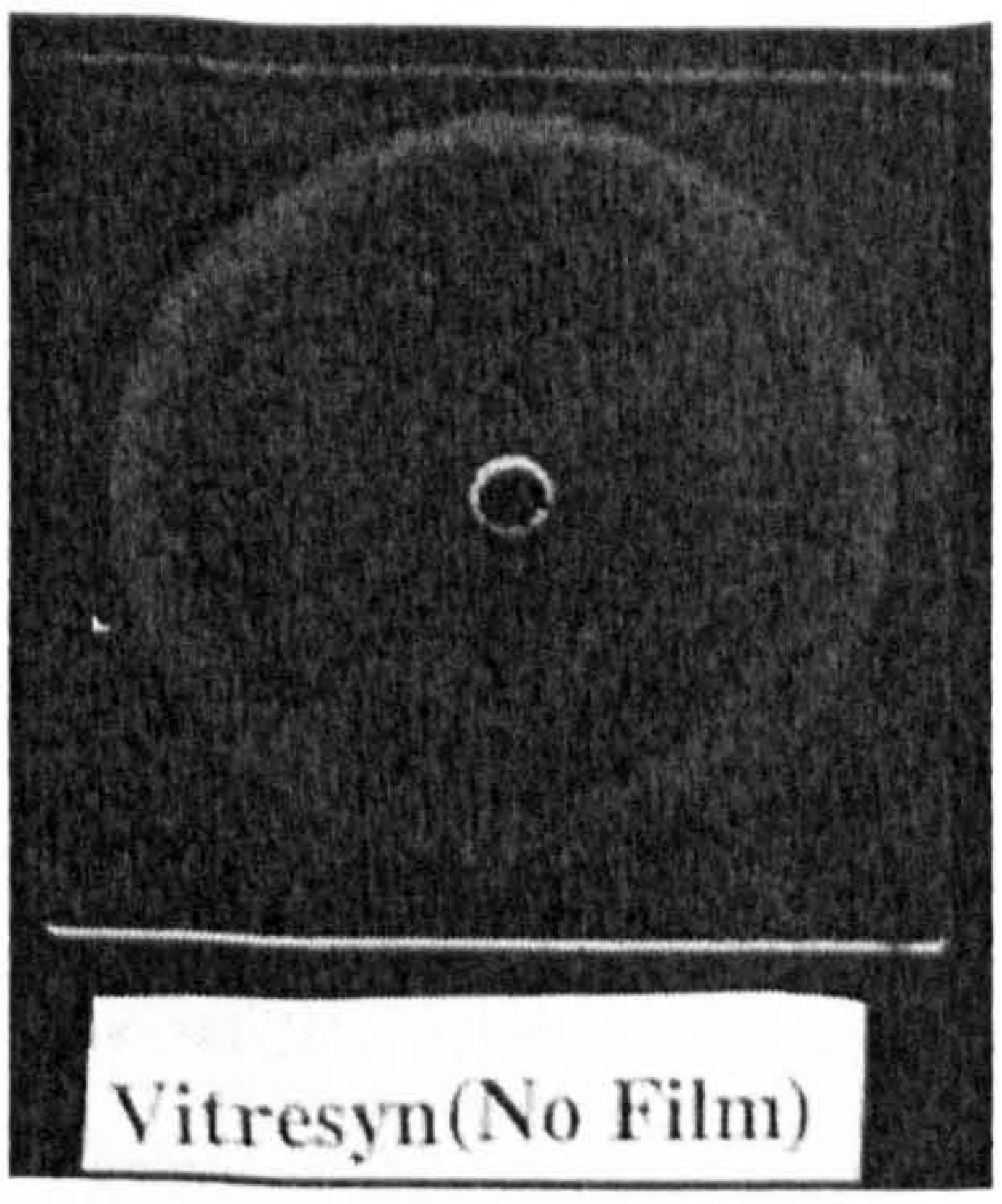
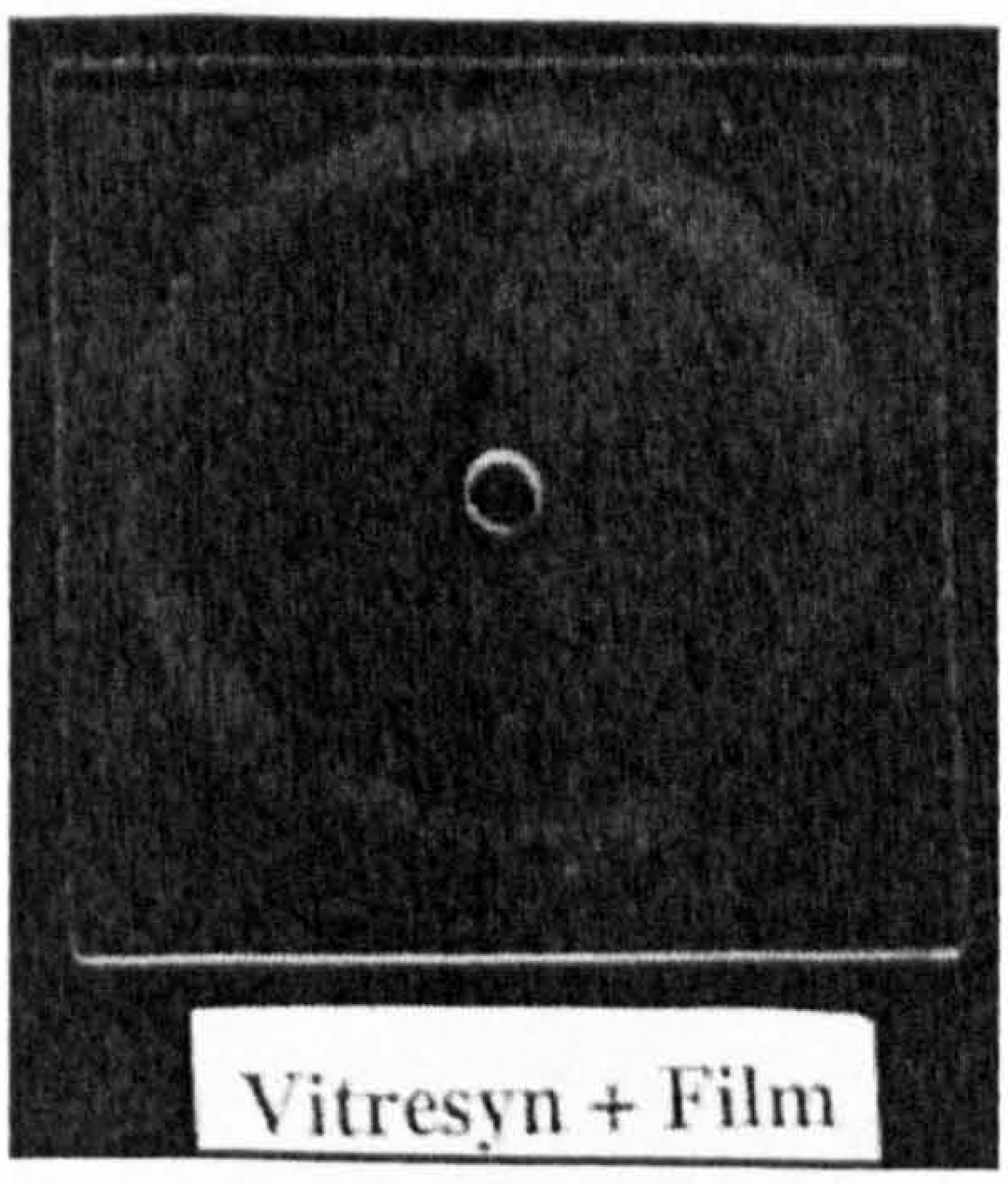
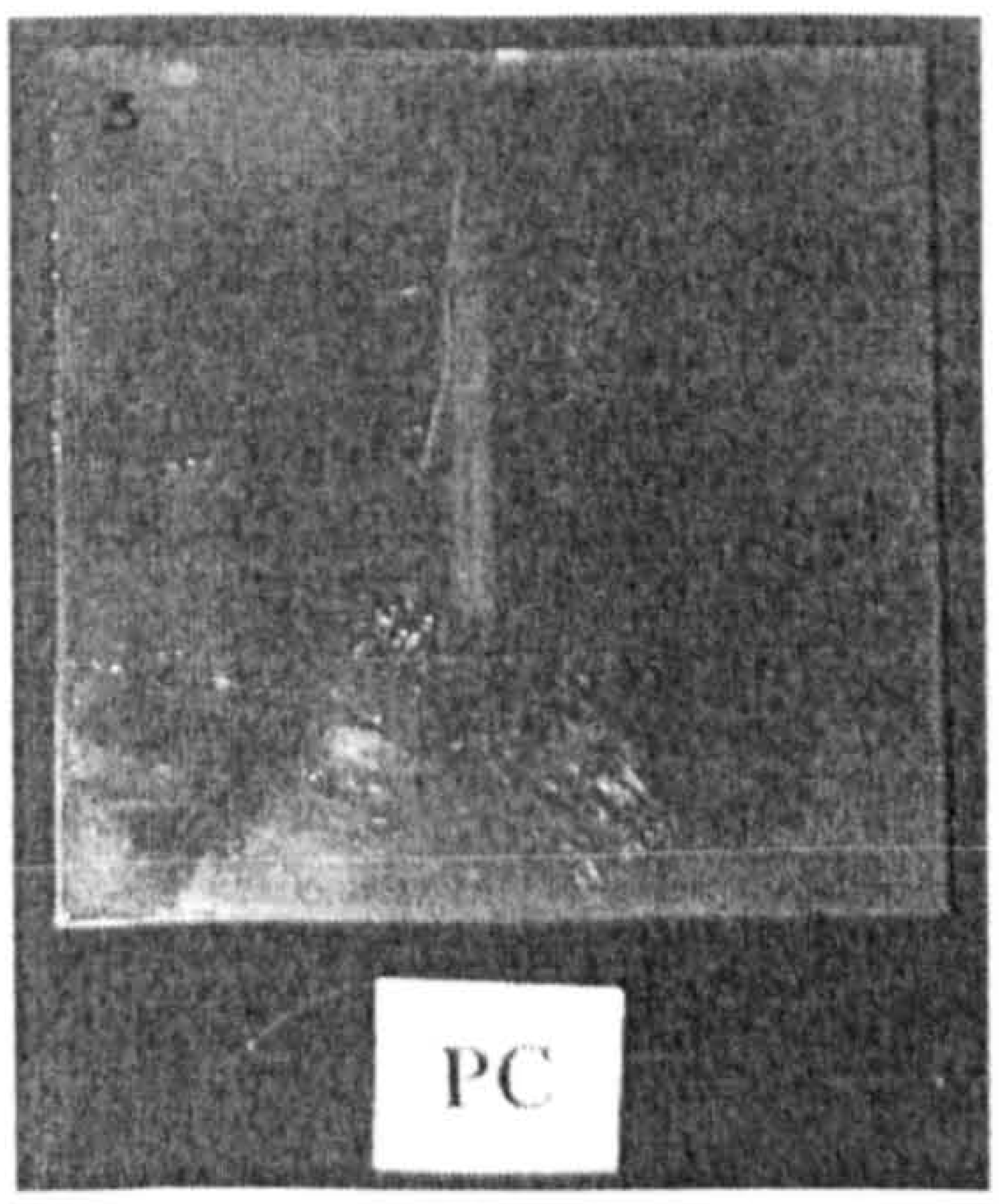

Vitresyn(No Film)


Vitresyn + Film

Results of Laboratory Taber Abrasion Test



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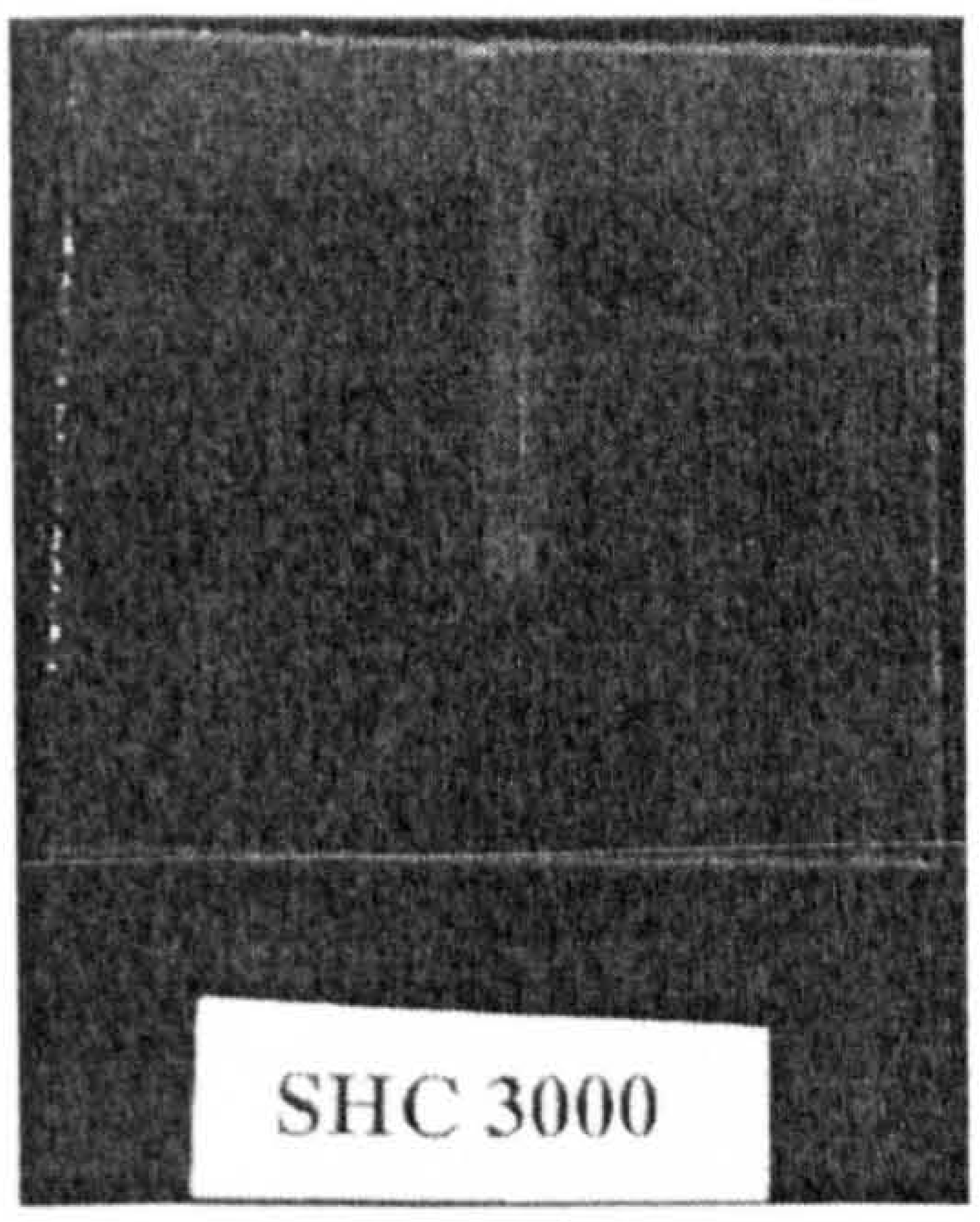

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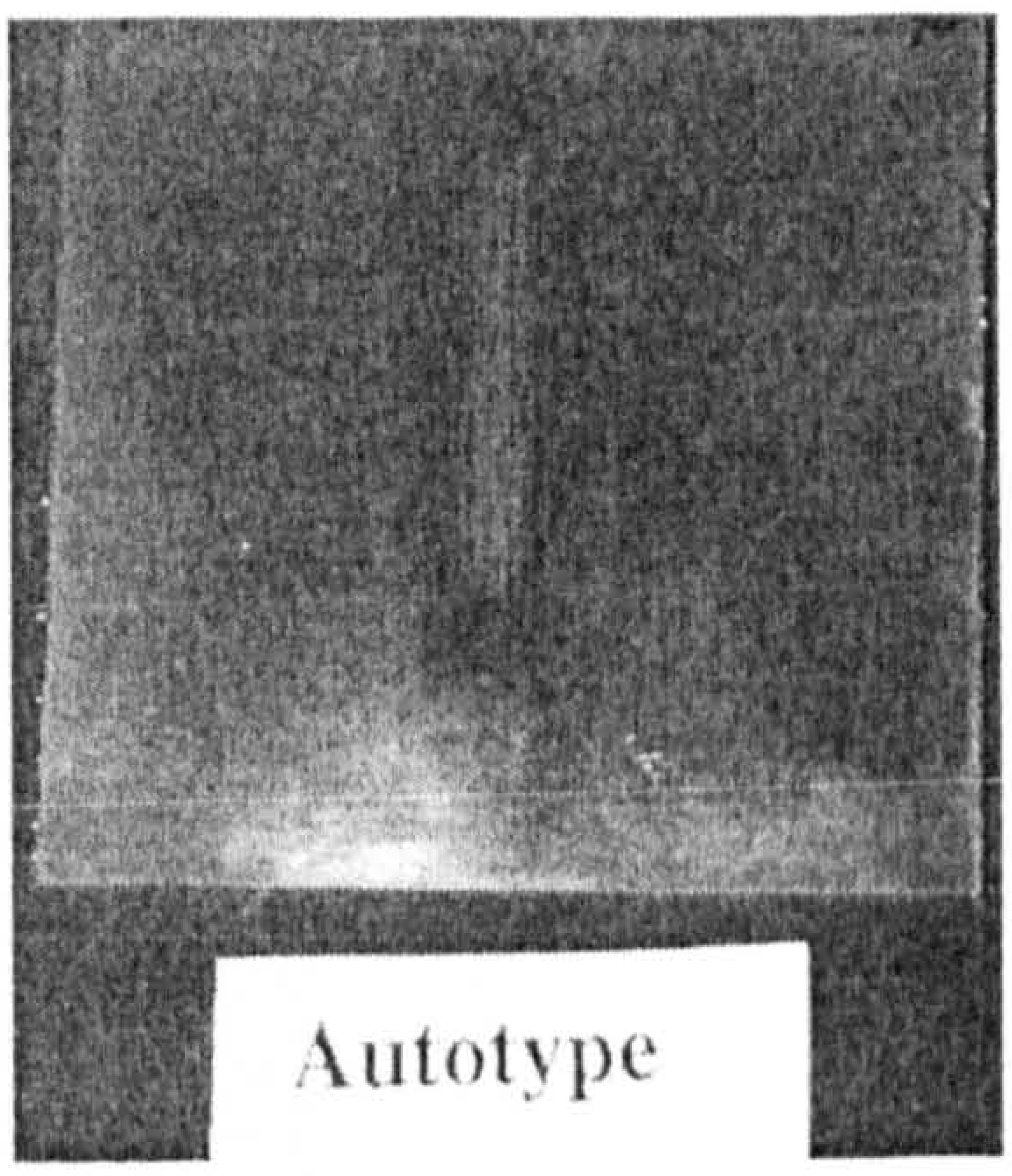

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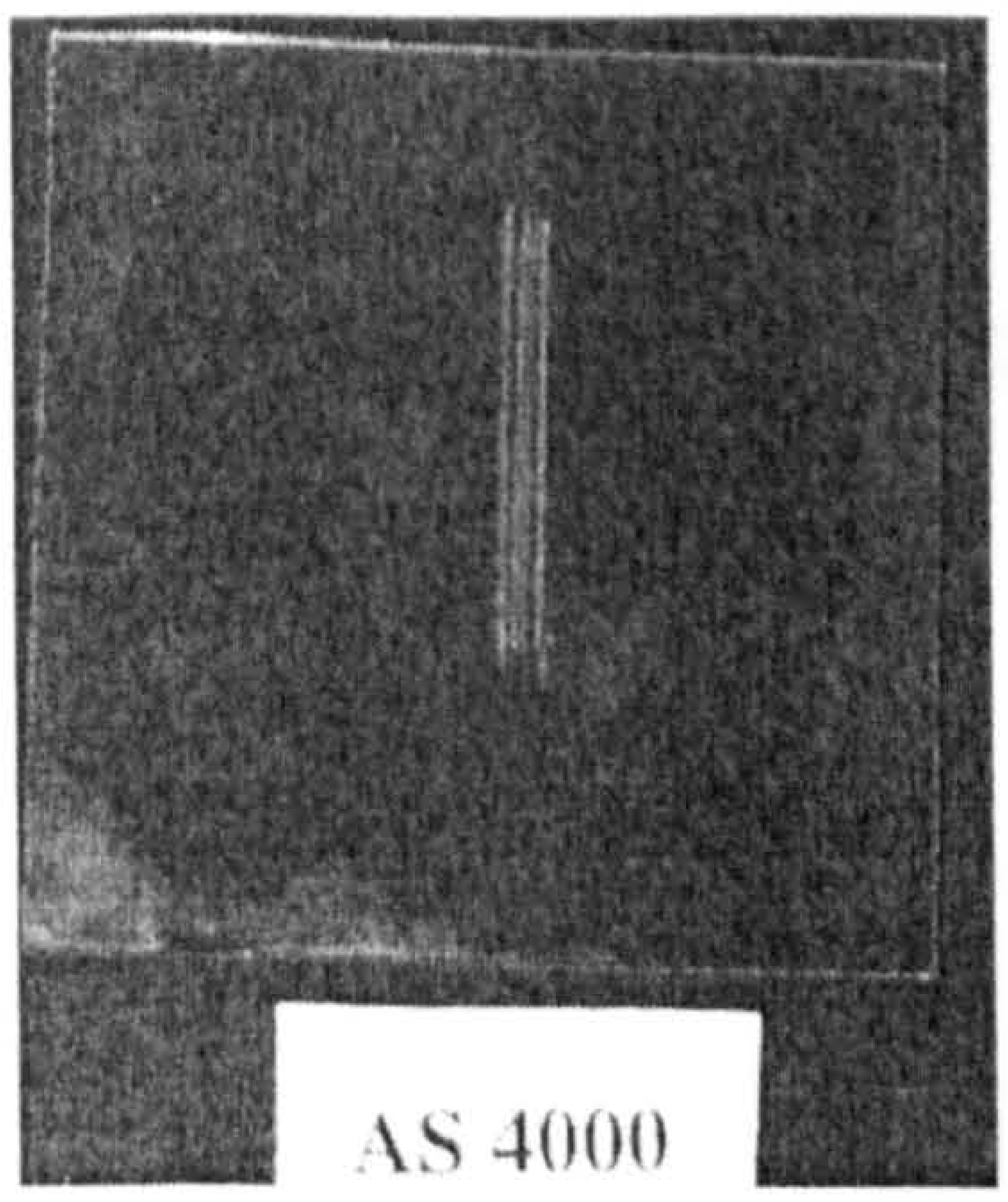

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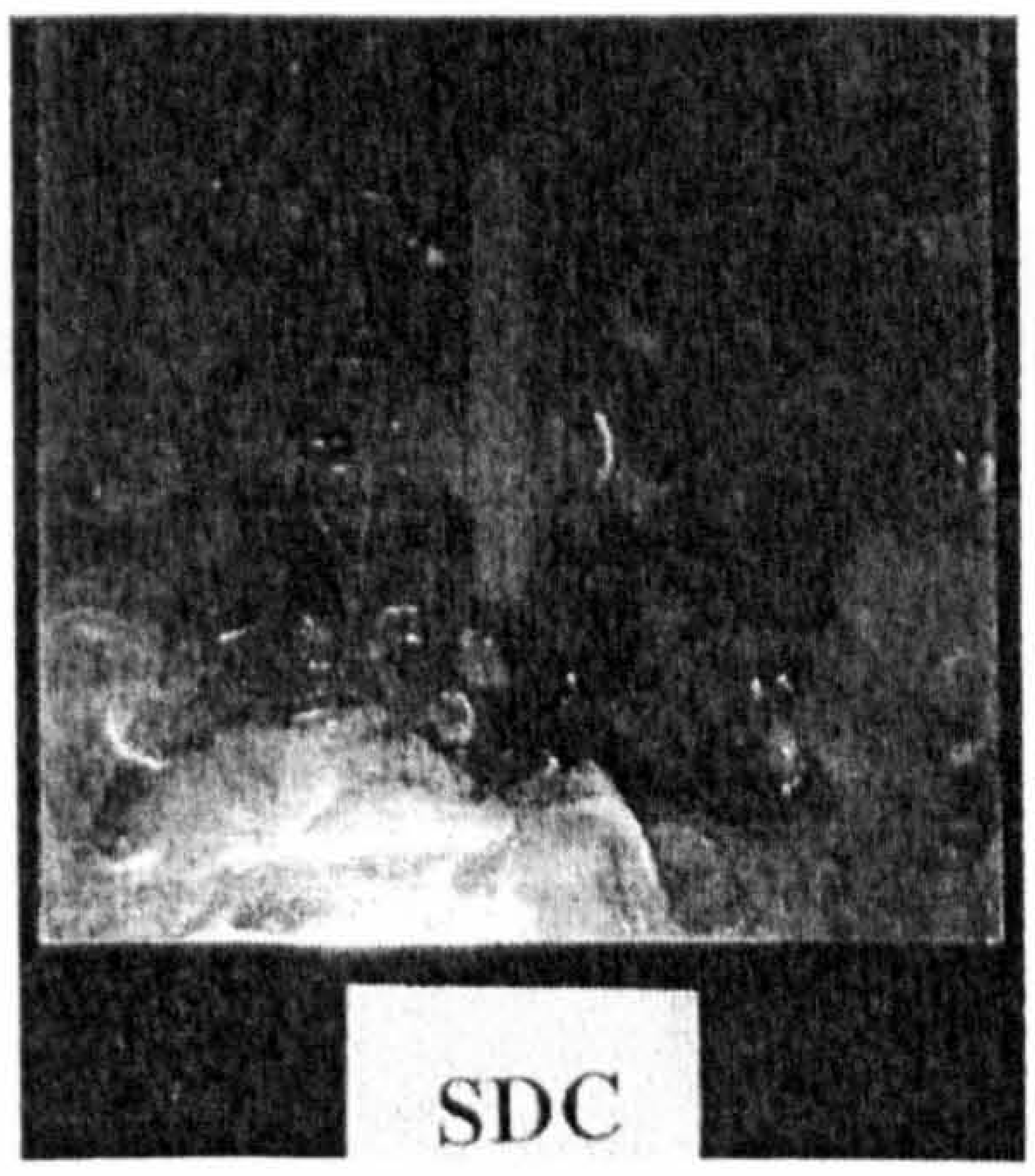

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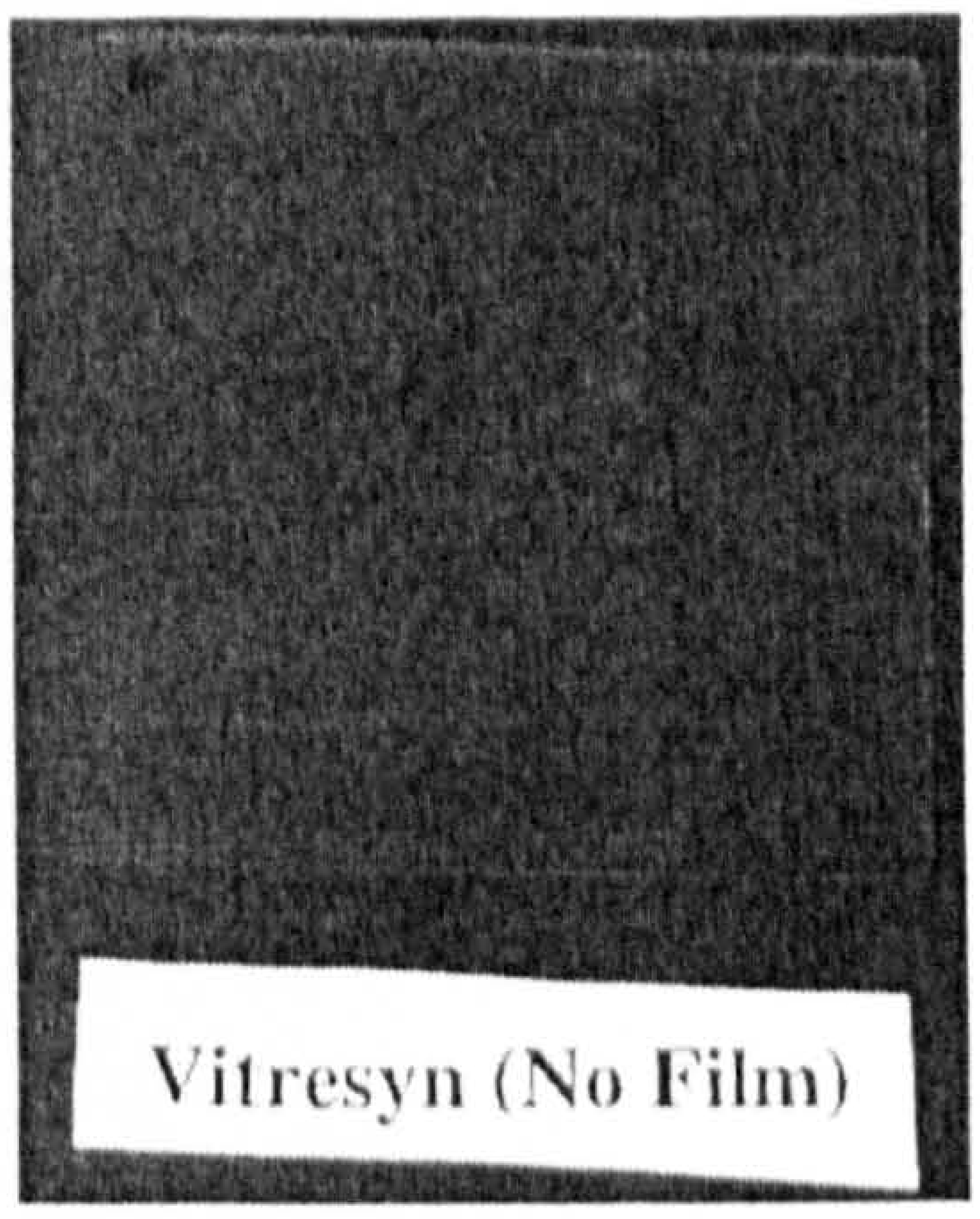
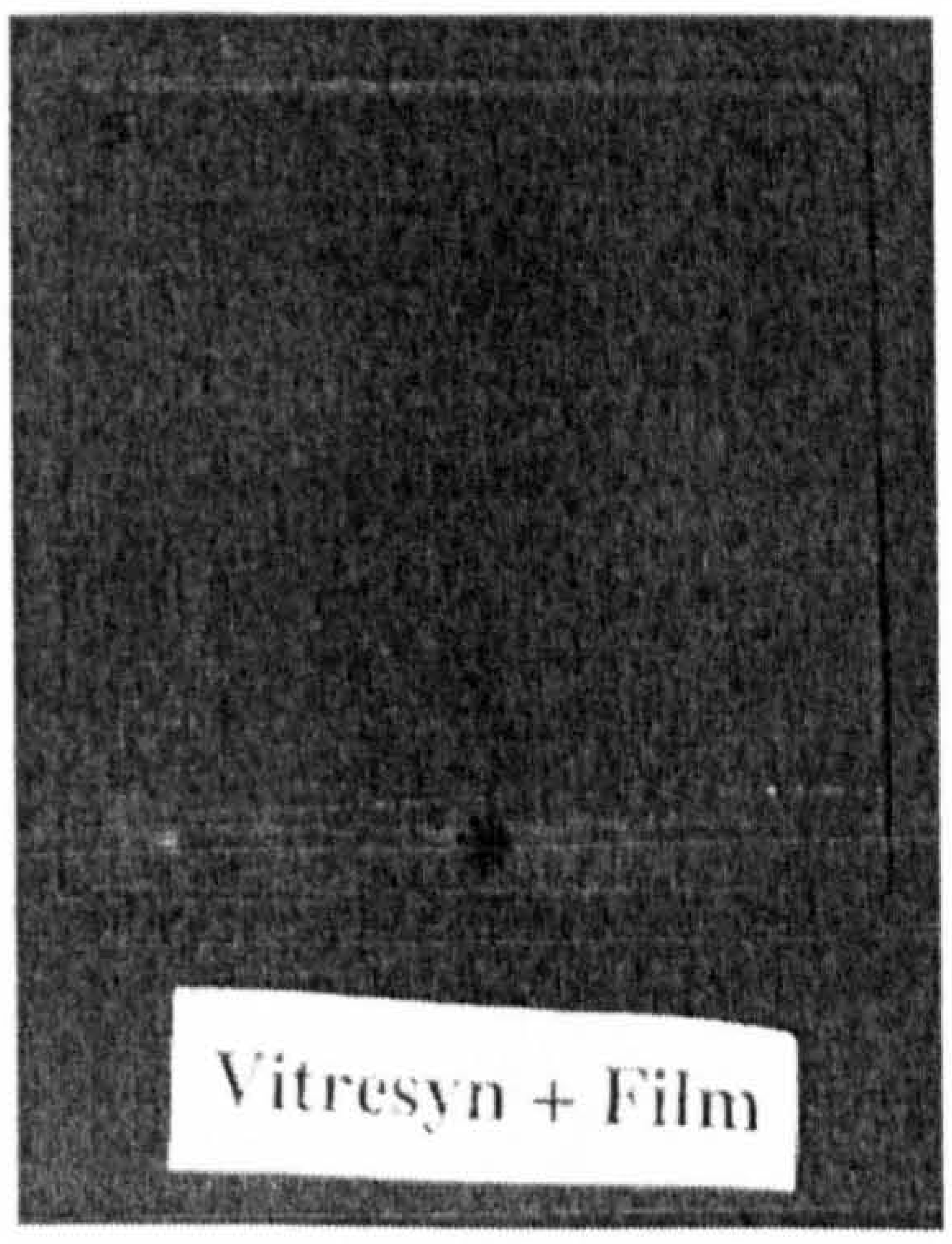


Vitresyn (No Film)

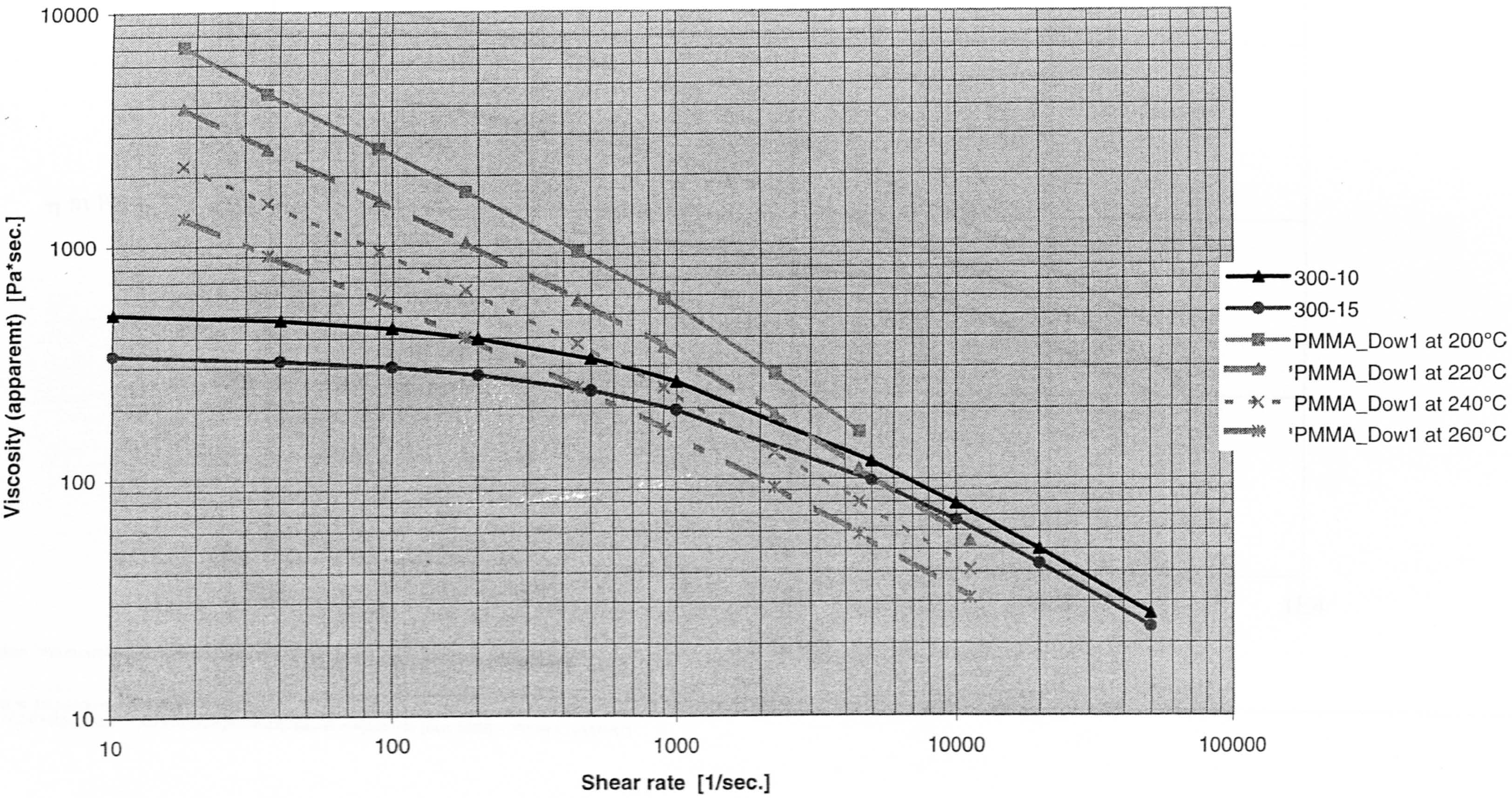


Vitresyn + Film

Results of Laboratory Scour Test

Appendix B: - Material Rheology Data

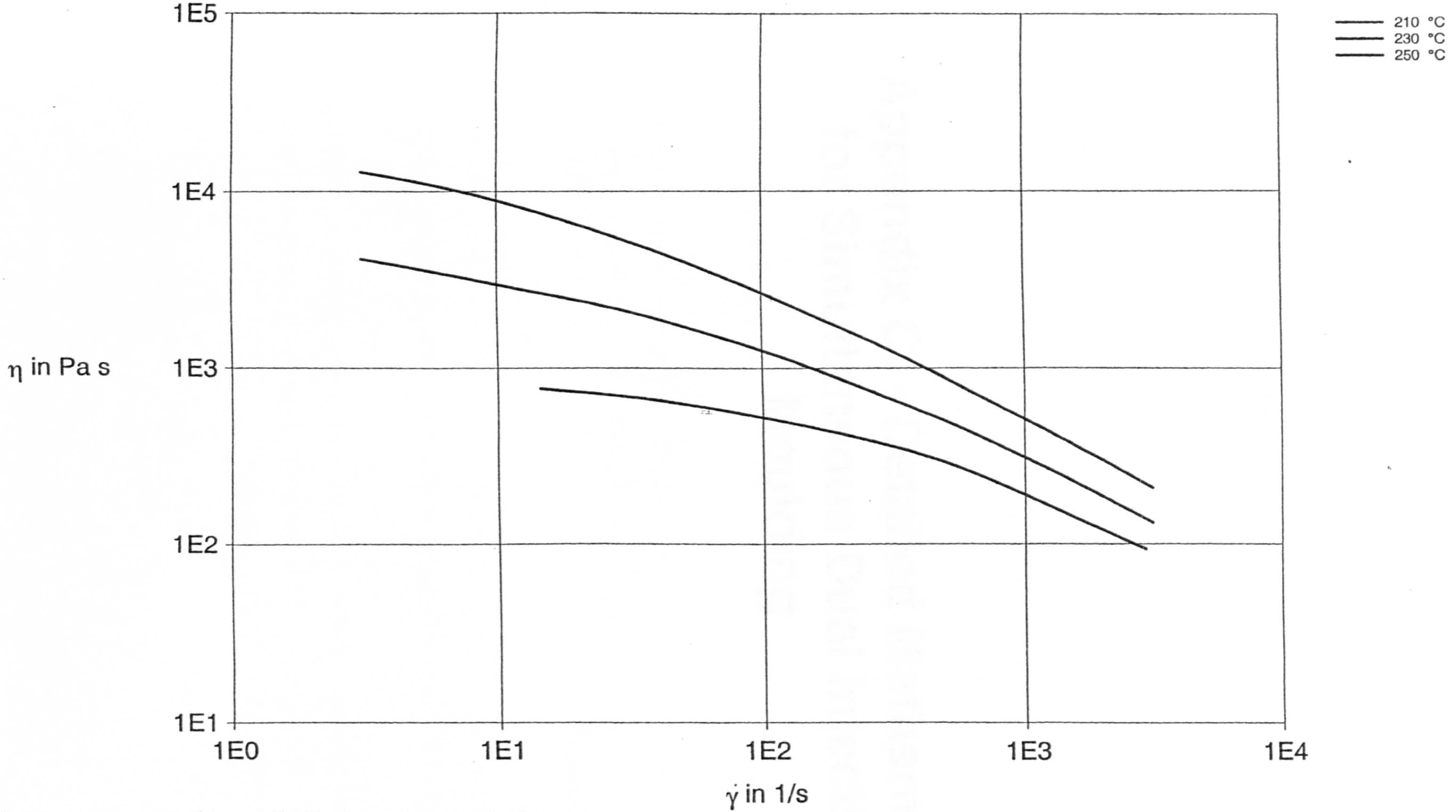
Viscosity of polycarbonate at 300°C and PMMA_Dow1 at 200, 220, 240 and 260°C



* Viscosity (Sarada) model for polycarbonate
* Cappilary data measured on PMMA_Dow1 in PTC-3 Terneuzen, Dec. 1998

Adri Ruiter, Dow Benelux N.V.
Terneuzen, January 1999

Viscosity-shear rate
OROGLAS V 920



Note: The program stores curve points (see table). The diagram shows approximations.

1E5□ °C□□ 920□r rate□ atochem/atoglas/appryl/aspell polymères) (Sep.1999) - Printed: 21/06/02

Appendix C: - Detailed Mathematics for Simultaneous Dual Injection Moulding

Previous studies (White et al, Young et al) have shown that the ratio of skin and core viscosities should be in the range of 0.5 – 5 for optimum results during processing. However simply matching the relevant viscosities of the two materials does not guarantee laminar flow as the following discussion demonstrates.

In single injection moulding machines the flow is pressure-driven and shear rates at the die wall may sometimes exceed 100000 s^{-1}.

A suitable equation for calculating the wall shear stress (γ) through a cylinder is (Coates, 2003): -

$\gamma = 8\bar{u}/D$ [1]

Where $\bar{u}$ is the mean material flow speed and D is the diameter of the flow area.

$\bar{u} = Q/A$ [2]

Where Q is the volume flow rate and A ($= \pi(D/2)^2$) is the area of the cylinder.

Substitution of A in [2] gives $\bar{u} = 4Q/\pi D^2$

Substituting for $\bar{u}$ in [1] gives: - $\gamma = 32Q/\pi D^3$ [3]

$Q = M/\rho T$, where M is the mass of material injected, ρ is the density of the material and T is the injection time. Substituting for Q in [3] gives: -

$\gamma = 32M/\pi\rho TD^3$ [4]

For a working approximation, ρ can be equated to 1 gcm^{-3} giving $32/\pi\rho \approx 10$. Substituting in [4] then gives the basis of the Cogswell formula [5] below.

For injection moulding processes the maximum shear rate normally occurs in the sprue and (for a single material) may be estimated as (Cogswell, 1981): -

Shear rate = $10M/D^3TN$ (s^{-1}) [5]

Where

M is the mass of the component (g)

D is the sprue diameter (cm)

T is the injection time = 5s

N is the number of injection points = 1

When the shear rate has been calculated, the relevant viscosity can be taken from a suitable viscosity-shear rate graph, usually supplied by the material manufacturer and reproduced in Appendix B.

For a dual-injection component this formula is not entirely representative as there are in effect two flows occurring within the cavity, with two areas of high shear stress as shown in Figure 4.5. (Goodship, 2001, pg. 133)

There is no known model that can be used to establish what the relevant shear rates of the two materials are during the injection phase, so a few simple assumptions will have to be made in order to estimate the values.

For the shear rate of the acrylic, it is assumed that the component is made from a single material so the above formula applies.

$M_{PMMA} = 132.16$ g
$D_{PMMA} = 0.4$ cm

Substitute in [5]: -
Shear rate of PMMA = $10 \times 132.16 / 0.4^3 \times 5 \times 1$ (s^{-1})
= 4130 (s^{-1})

Which gives a viscosity (η_{pmma}) = 70 Pa s

For the polycarbonate, it was assumed that the PMMA had frozen, there was no wall slip, laminar flow was achieved, and effectively the injection area had been reduced. The skin:core ratio was 30:70 and the new values of M and D were calculated accordingly: -
$M_{PC} = 94.1$ g
$D_{PC} = 0.4 \times 0.7 = 0.28$ cm
T and N were assumed to remain the same. Substitute in [5].
Shear rate of PC = $10 \times 94.1/0.28^3 \times 5 \times 1$ (s^{-1})
= 8554.5 (s^{-1})

Which equates to a viscosity (η_{PC}) = 90 Pa s

This gives a viscosity ratio, $R = \eta_{PC} / \eta_{PMMA} = 90/70 = 1.28$ which is within the range recommended by the academic texts discussed previously. The skin viscosity is also slightly lower than the core viscosity as suggested by Cogswell, but still disturbed laminar flow was generated within the cavity.