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MODERN MATERIALS AND CONTEMPORARY ART

The future of looking younger: A new face for PMMA. Research into fill materials to repair poly(methyl methacrylate) in contemporary objects and photographs

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ABSTRACT

Clear poly(methyl methacrylate) (PMMA) has been used as an art medium for sculptures and objects since its production, and to face-mount photographs since the 1980s. The most common conservation issues affecting these objects are disfiguring surface damages, such as scratches and chips, commonly caused by handling and transportation. Treatment options to reduce surface damages on PMMA are currently limited, often highly invasive and results are rarely satisfactory. The aim of this study was to investigate less-invasive treatments able to successfully recover lost transparency. Fill materials and methods to repair scratches and chips were tested on both cast and extruded clear PMMA. Their aging behavior was also investigated. Two materials proved to be stable and able to dramatically improve the appearance of

INTRODUCTION

Poly(methyl methacrylate) (PMMA) was commercially introduced as a transparent cast sheet material by the company Imperial Chemicals Industries (ICI) in the early 1930s. Since then it has been used for innumerable applications. Because acrylic possesses the transparency of glass combined with the advantages of a thermoplastic material that can be easily shaped, it has been extensively used as an artistic medium to make sculptures, objects and as a paintings support. Artists Naum Gabo and Lázló Moholy-Nagy, both pioneers of modern sculpture, were early users of PMMA in their work, and many prominent artists and designers followed in their footsteps using either clear cast or extruded acrylic.

In the mid-1980s, photographers also started to adapt PMMA for mounting techniques such as the face-mounting process, in which a clear PMMA sheet is permanently adhered to the surface of a print, using either a silicone rubber adhesive or a double-sided pressure-sensitive adhesive. Face mounting provides several functional advantages: it eliminates the need of a heavy glazing, provides a lightweight yet rigid support to the photograph, facilitates handling, and reduces production costs (Pénichon and Jürgens 2002). It also has an aesthetic impact: the PMMA face mount adds depth and color saturation to photographs, creating the so-called "wet look".

Whereas PMMA is more impact-resistant than glass, it is also more susceptible to surface damages such as scratching, chipping, and gouging. Surface damages frequently occur during handling or transportation, and can be extremely disfiguring for works of art – especially on face-mounted photographs where damage appears directly in front of the image. Treatment options to reduce these damages using fill materials or fine polishing products are currently limited (Kim 2007, O'Connor 2015), and results are rarely satisfactory. Polishing is not always suitable, especially when scratches and chips are very deep, and often entails the removal of significant quantities of PMMA.

As part of its Preservation of Plastics project, the Getty Conservation Institute (GCI) is investigating suitable filling materials and methods to repair scratches and chips without modifying the PMMA surface in order to provide less-invasive solutions for this type of objects. The potential of

the damages: the hydrocarbon resin Regalrez 1094 and the epoxy HXTAL NYL-1. The results of the research were successfully applied on damaged objects and face-mounted photographs.

each filling material to improve the visual appearance of damaged PMMA surfaces was tested on test samples and mock-ups and assessed with naked-eye observations, as well as with optical microscopy. Refractive index (RI) measurements were carried out to determine the match between the RI of the filling products and that of PMMA. Composition of the fill materials was determined using Fourier transform infrared (FTIR) spectroscopy analysis, and their stability was evaluated before and after accelerated light aging using FTIR and color measurements. Subsequently, materials and techniques which provided the best results were used to treat scratches and chips on selected damaged PMMA works of art (objects and face-mounted photographs).

EXPERIMENTAL SET-UP

Test samples and mock-ups

Treatment tests were first conducted on samples (6.5 × 6.5 × 0.5 mm) sawed from commercially purchased clear cast PMMA sheets, as well as extruded. Superficial and deeper scratches (width of 0.2–0.5 mm) were simulated with sharp metal points, while hammers and chisels were used to recreate chips (Figure 1).

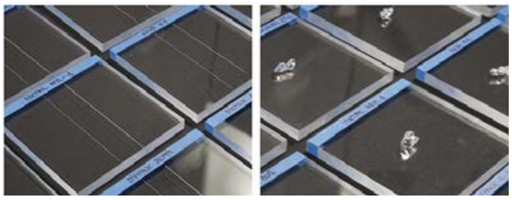


Figure 1. Damaged test sample

Fill materials and methods providing the best results were further tested on damaged mock-ups: clear PMMA objects bought at flea markets and face-mounted photographs donated by a photograph conservator. The face-mounted photographs included two kinds of images: a half-black/half-white image and a colored one (Figure 2). These images were selected to evaluate differences in the perception of repairs performed on clear PMMA placed against different colored backgrounds.

Figure 2. Damaged mock-ups

Fill materials

Conservation materials tested were selected on the basis of their desired aesthetic and physical properties: they had to be clear and colorless, have an RI as close as possible to PMMA (RI 1.49), low viscosity, suitable working and curing time, exhibit no exothermic reaction, have low shrinkage upon curing, and not be harmful to the plastic. PMMA is sensitive to many chemicals, limiting considerably the type of fill materials that may be used. Only water and aliphatic hydrocarbons with low aromatic content are considered safe to use on PMMA (Sale 1993, Wright 1996). Based on these considerations, 18 products representing four chemical categories were selected and tested as fill materials: acrylic polymers and hydrocarbon resins in solvents; two-component epoxy resins; and single-component UV curing materials. The products tested are listed in Table 1.

Acrylic (Paraloid B-67, Paraloid F-10, a mixture of Paraloid F-10 and Paraloid B-67) and hydrocarbon resins (Regalrez 1094, Regalrez 1126) were chosen for their solubility in aliphatic hydrocarbons with low aromatic content and reversibility in these solvents. Acrylic resins were selected in particular for their near-identical RI to that of PMMA, and based on previous studies (Laganà 2011, Sale 2011). Regalrez resins were chosen for their low molecular weight which tends to produce low-viscosity solutions. The addition of Tinuvin 292 was also evaluated as it is often preferred for its stability (De la Rie 1993).

Epoxy resins (HXTAL NYL-1, EPO-TEK 305) were selected for their very low viscosity and low shrinkage. UV curing optical adhesives (Dymax 4-20638, Dymax 4-20418, Dymax D3099; EPO-TEK UD1355, EPO-TEK OG603; NOA 74, NOA 76, NOA 89, NBA 107 by Norland Products, Inc.) were investigated for their optical properties and remarkably fast curing time; NBA 107 also for its reversibility in water. These adhesives were

Table 1. Materials tested. Composition and properties

Type	Commercial product	Composition (datasheet information)	FTIR results	Ratio	Viscosity of product. cP (datasheet)	RI (Becke line test)*
Acrylic resins	Paraloid™ F-10	Butyl methacrylate copolymer. 40% solids in 9:1 mixture Mineral Spirits : Aromatic 150	Butyl methacrylate	10, 20 and 40% w/w. Dilution with Mineral Spirits (100–140°C aromatic content ≤0.05% CAS 64742-49-0)	1400–2800	1.476
	Paraloid™ B-67	Isobutyl methacrylate	Isobutyl methacrylate	10, 20 and 40% w/w in Mineral Spirits (100–140°C aromatic content ≤0.05% CAS 64742-49-0)	-	1.486
	Paraloid™ F-10 + Paraloid™ B-67	Mixture of two previous products	Butyl methacrylate + Isobutyl methacrylate	1:1 mixture F-10 + B-67 at 40% in Mineral Spirits (100–140°C aromatic content ≤0.05% CAS 64742-49-0)	-	1.486
Hydrocarbon resins	Regalrez® 1094	Hydrogenated hydrocarbon resin	Hydrocarbon resin	40% w/w in ShellSol D40	-	1.518
	Regalrez® 1094 + Tinuvin® 292	Hydrogenated hydrocarbon resin + sterically hindered amines (light stabilizer mixture)	Hydrocarbon resin + sebacate	40% w/w Regalrez in ShellSol D40 with 2%w to resin Tinuvin	-	1.518
	Regalrez® 1126	Hydrogenated hydrocarbon resin	Hydrocarbon resin	40% w/w in ShellSol D40	-	1.518
	Regalrez® 1094 + Tinuvin® 292	Hydrogenated hydrocarbon resin + sterically hindered amines (light stabilizer mixture)	Hydrocarbon resin + sebacate	40% w/w Regalrez in ShellSol D40 with 2%w to resin Tinuvin	-	1.518
Epoxy resins	Hxtal NYL-1	Hydrogenated Bisphenol A. diglycidyl ether	Hydrogenated Bisphenol A. diglycidyl ether	3:1 by weight component A to component B	200–300	1.516
	EPO-TEK® 305	Substituted glycidyl ether resin	Bisphenol A diglycidylether	10:2.8 by weight component A to component B	150–250	1.482
Single component UV curing materials	Dymax Ultra Light-Weld® 4-20638	Mixture of acrylated urethanes CAS 5888-33-5. 15625-89. 868-77-9. 2680-03-7 and proprietary products.	Urethane, acrylate	-	65	1.510
	Dymax Ultra Light-Weld® 4-20418	Mixture of acrylated urethanes CAS 2680-03-7. 868-77-9. 79-10-7 and proprietary products.	Urethane, methacrylate	-	450	1.510
	Dymax Ultra Light-Weld® 3099	Acrylated urethane CAS 5888-33-5 and proprietary products	Urethane, acrylate	-	150	1.510
	Norland Optical Adhesive 74	Mixture of proprietary mercapto-ester and CAS 39423-51-3. 1330-61-6	Urethane, acrylate	-	80–95	1.520
	Norland Optical Adhesive 76	Mix of proprietary aliphatic urethane acrylate and CAS 7328-17-8. 2455-24-5	Urethane, methacrylate	-	3500–5500	1.510
	Norland Optical Adhesive 89	Mixture of proprietary mercapto-ester and 1.6 Hexanediol Diacrylate	Acrylate	-	15–20	1.512
	Norland Blocking Adhesive 107	Mixture of proprietary mercapto-esters and CAS 120-55-8. 94-51-9	Acrylate, phthalate	-	350	1.512
	EPO-TEK® OG603	Proprietary specialty acrylate blend.	Urethane, acrylate	-	150–250	1.504
	EPO-TEK® UD1355	Proprietary epoxy resin	Urethane, acrylate	-	447	1.493

*The Becke line test accuracy is ± 0.001.

cured using Norland Opticure LED 200 curing system (energy output at full power: 2.5W/cm^2 at 365 nm). The intensity needed and curing time varied according to resin composition. The curing time of each UV adhesive was generally determined according to the manufacturer's instructions, although not all manufacturers state specific parameters on datasheets.

Fill methods

Based on the results of previous GCI research (Laganà et al. 2014), the Princeton round mini-brush 3050R size 20/0 was used to fill scratches. Insect needles or small glass pipettes were used to fill chips, depending on the viscosity of the material. Fill materials were applied neatly within the boundaries of damages until the loss was filled, taking care not to overfill to avoid any later finishing treatment or solvent use. Treatment tests were performed using a black background to make the small damages sharper to visual perception.

Fourier transform infrared (FTIR) spectroscopy

Test samples, mock-ups and fill materials were analyzed using a 15× Cassegrain objective on a Hyperion 3000 FTIR microscope (Bruker Optics) with a mid-band MCT detector and purged with dry air. Spectra were the sum of 64 scans at a resolution of 4 cm^{-1}.

Refractive index measurements (Becke line test)

Small particles of PMMA and different adhesives were immersed in a series of refractive index liquids by Cargille Labs and observed with a Leitz DMR microscope (Leica Mikroskopie GmbH) at 10× / 20× magnification, following the method described by McCrone (1985).

Accelerated light aging

Films of each fill material were prepared on Mylar using am 8 mil drawdown bar. UV curing materials were cured between two Mylar sheets to avoid oxygen inhibition. The films were exposed in an Atlas Weather-Ometer Ci4000, following ASTM standard D4459-99 for Xenon-Arc Exposure of Plastics Intended for Indoor Application. Irradiance was controlled at 0.33 W/m^2 at 340 nm; test pieces were evaluated every 100 hours for 400 hours of exposure.

Color measurements

Color measurements were performed on films before, during and after artificial light aging using a Konica Minolta 2600d spectrophotometer, relative to a magnesium oxide white standard (geometry of 0/45°, DRS spectral engine, aperture of 3 mm). Each sample was measured nine times. Results for L*, a*, b* and ΔE94 (color difference) were averaged using Spectra Magic software.

Assessing visual appearance

The potential of each fill material to improve the visual appearance of damaged PMMA surfaces was assessed visually with the naked eye as well as optical microscopy. Photographs of the damages before and after treatment were taken using a Spot RT color microscope under 6× and 25× magnification.

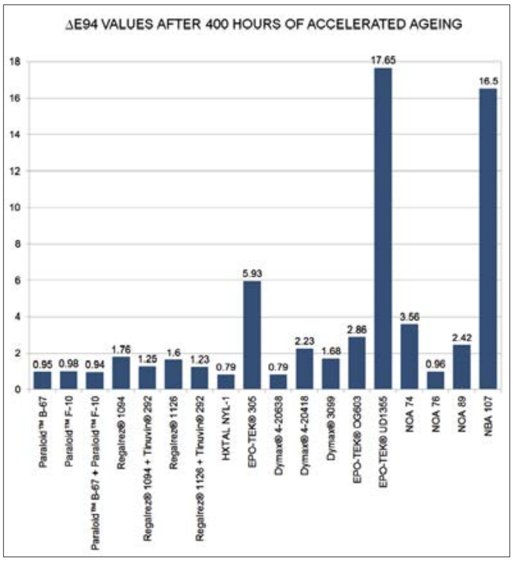


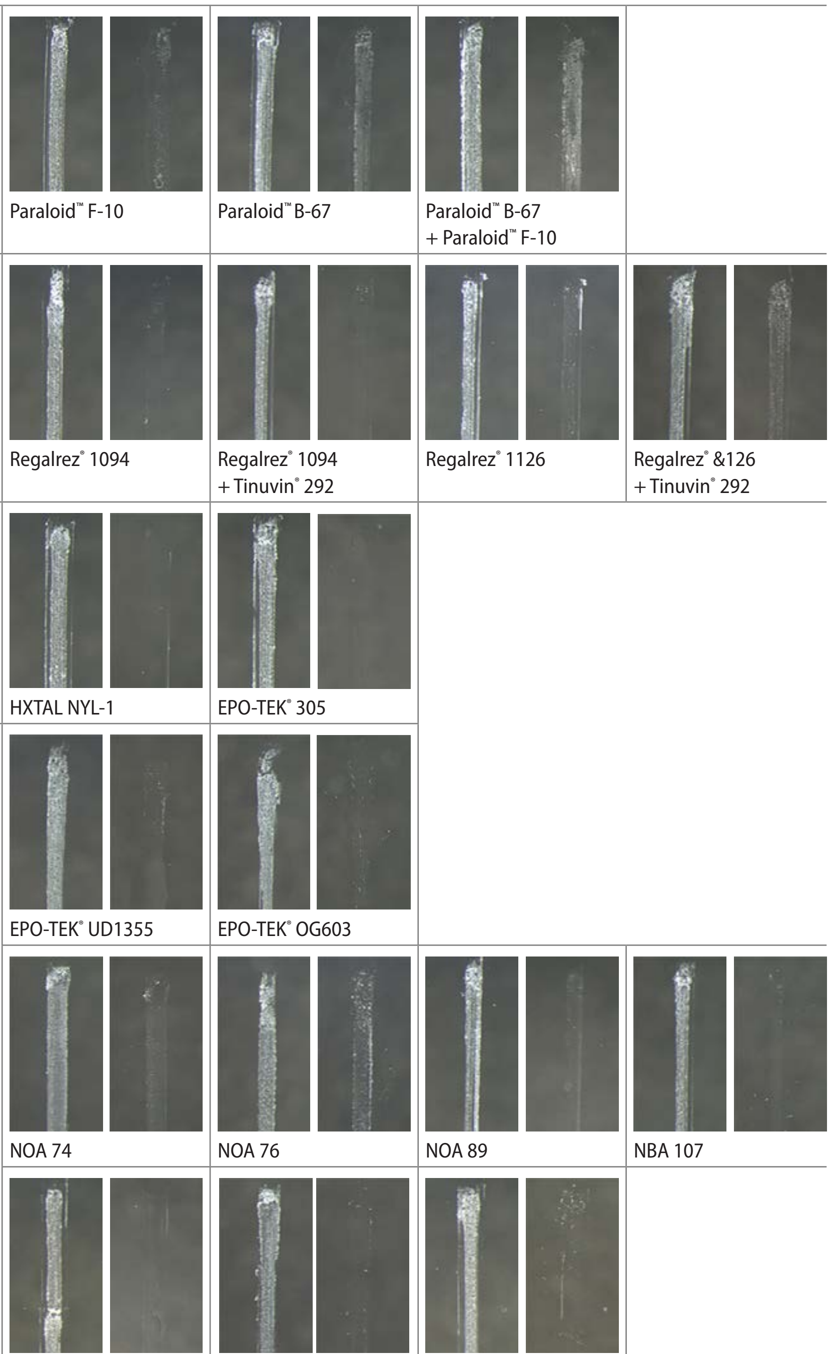
Figure 3. ΔE94 values of fill materials after aging

RESULTS AND DISCUSSION

Evaluation of fill materials and methods

Suitability of fill materials was determined on the basis of their working properties; how successful they were in treating the damaged PMMA test samples, and their performance after accelerated light aging. An overview of the visual results obtained with each material is reported in Table 2. Color measurements performed on fill materials after 400 hours of accelerated aging exhibited primarily alterations in b* and L* values, corresponding to yellowing (positive b*) and darkening (decreasing L*). Changes in ΔE94 values are shown in Figure 3. No color changes were visible to the naked eye on aged films having a ΔE94 value below 2.

Table 2. Overview of visual results on scratches



MICROSCOPE IMAGES (25×) OF SCRATCHES BEFORE AND AFTER TREATMENT				
ACRYLIC RESINS	Paraloid™ F-10	Paraloid™ B-67	Paraloid™ B-67 + Paraloid™ F-10	
HYDROCARBON RESINS	Regalrez® 1094	Regalrez® 1094 + Tinuvin® 292	Regalrez® 1126	Regalrez® &126 + Tinuvin® 292
EPOXY RESINS	HXTAL NYL-1	EPO-TEK® 305		
	EPO-TEK® UD1355	EPO-TEK® OG603		
UV CURING MATERIALS	NOA 74	NOA 76	NOA 89	NBA 107
	Dymax® 4-20638	Dymax® 4-20418	Dymax® D 3099	

Acrylic resins

Acrylic resins performed very well during accelerated light aging with ΔE94 values below 1. However, their working properties were not satisfactory, especially for scratch-filling. Low resin concentrations (10–20%) provided lower viscosity solutions that flowed better into the scratches than higher concentration (40%) more suitable for chip; several applications were necessary due to solvent evaporation. However, despite multiple applications, visual results were unsatisfactory. The visibility of scratches was only slightly diminished. Microscopy showed that these solutions formed a "film" that only covered the scratch without filling it in completely. This could be due to rapid solvent evaporation and/or the high molecular weight of these polymers which did not allow the resin to flow in depth. Higher solvent power would be needed to improve performance of the resins; however, PMMA solvent restriction makes it a challenge. Better results were achieved in chip-filling due to the larger size of these damages, allowing for an easier application. Depending on the depth of the damage, repeated applications were necessary after the solvent evaporated to completely fill the loss. The best results were achieved using Paraloid F-10 (40%) which resulted in a repair closely matching the RI of PMMA. However, solvent evaporation leaves the surface uneven, and if too many layers are applied, the clarity of the fill becomes blurred.

Hydrocarbon resins

Hydrocarbon resins also exhibited good aging properties with slightly higher values compared to acrylic resins, yielding 1.6–1.8 ΔE94 after aging. As expected (De la Rie 1993), the addition of Tinuvin improved the stability of both resins upon aging (1.2–1.3 ΔE94). All solutions, with and without Tinuvin, gave very good results during treatment tests. Unlike acrylics, hydrocarbon resins, due to their low molecular weight, flowed easily into small damages. Even a high concentration of resin allowed for very accurate applications, dramatically improving the visual appearance of both scratches and chips. The most satisfactory visual results were obtained with the solution of Regalrez 1094 at 40% in ShellSol D40, especially for filling scratches. This could be due to better penetration of this resin (because it has the lowest molecular weight of all hydrocarbon resins tested). One application was sufficient to successfully saturate scratches, recovering the PMMA's transparency. For chips, multiple applications were needed. Unlike acrylics, despite multiple applications and solvent evaporation, the fills remained clear and the surface smooth.

Epoxy resins

Epoxy resins did not perform homogeneously on aging. As also observed in previous studies, the hydrogenated epoxy HXTAL NYL-1 demonstrated very good results upon light aging (< 1 ΔE94), while EPO-TEK 305 yellowed noticeably. Photo-oxidation was confirmed with FTIR measurements, showing increased carbonyl peaks at 1725 and 1657 cm^{-1}. In addition, EPO-TEK 305 although easy to apply and with a RI close to PMMA, undergoes an exothermic reaction during curing (not mentioned in datasheets), causing a permanent halo on the PMMA surface surrounding the repairs, and is therefore not usable. HXTAL NYL-1, on the other hand, showed very good results overall.

It was easy to apply and restored transparency, substantially improving the appearance of the PMMA. Moreover, one application was sufficient to fill scratches as well as chips, due to its minimal dimensional change upon curing. The fill remained extremely flat and smooth.

UV curing materials

Composition of the UV curing materials varied widely, which was reflected in their aging performance. Dymax 4-20638 showed good stability (ca. 1 ΔE94), unlike Dymax 3099 and 4-20418, which underwent minor discoloration (1.68–2.23 ΔE94). The Norland product NOA 76 exhibited only small alterations, comparable to acrylic and hydrocarbon resins (ΔE94 < 1); ΔE94 for NOA 89 was 2.42; NBA 107, on the other hand, displayed extreme discolorations with ΔE94 values above 16. Mediocre performance was achieved by NOA 74. Both UV curing materials by EPO-TEK exhibited alterations during aging: UD 1355 strongly yellowed after only 100 hours (ΔE94 > 14) reaching after 400 hours ΔE94 values above 17; OG 603 showed some yellowing with a ΔE94 close to 3. Further, UV curing materials posed several issues if used as fill materials. The main problems included: atmospheric oxygen inhibiting the cure on the surface layer (leaving sticky surfaces); shrinkage during polymerization (especially for significantly thicker chip repairs) and in some cases, yellowing during curing process. Covering the resin during the UV curing helped overcome oxygen inhibition, but it can cause an uncontrolled spreading of the resin on the PMMA which could not be safely removed after curing. None of these materials was considered suitable for filling chips on works of art, while Dymax 4-20638 was selected as the best option for scratches.

An overall assessment of the fill materials is reported in Table 3.

Based on this assessment, the following materials were selected for further tests on mock-ups and compared. For filling scratches: HXTAL NYL-1, Regalrez 1094 (40%) and Dymax 4-20638; and for filling chips: HXTAL NYL-1, Regalrez 1094, and Paraloid F-10 (both at 40%). Tests on mock-ups showed that HXTAL NYL-1 and Regalrez 1094 are the best options; they were able to restore the transparency on both objects and face-mounted photographs, proved to be easy to apply and posed no issues during curing (Figure 4).

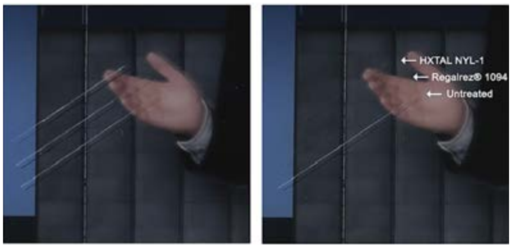


Figure 4. Detail of face-mounted photograph mock-up showing three deep scratches on the PMMA surface interfering with the image underneath (left). The mock-up after scratch-filling (right): upper scratch was treated with HXTAL NYL-1; middle scratch with Regalrez 1094; and lower scratch was left untreated as reference

Regarding the perception of damages and repairs, it was noticed on the mock-ups that damages are significantly more visible on black than on white: on black they appear as white marks, while on white only as shadows. After treatment, the white marks became transparent and the shadows almost completely disappeared. Repairs are not visible from the front; they can only be noticed from certain angles, depending on the size of the damage repaired and the light source angle.

APPLICATION TO CASE STUDIES

An important component of this study was to undergo treatments on case studies representing a range of possible scenarios. The objects consisted of a selection of works from the Cultural Heritage Agency of the Netherlands

Table 3. Overall assessment of fill materials

Type	Commercial product	Reversibility	Application and setting	Visual results of repairs	Visual assessment after light aging	Overall assessment for scratch-filling	Overall assessment for chip-filling
Acrylic resins	**Paraloid™ F-10**	Reversible	Scratch: easier to apply at 20% Chip: possible to apply at 40% (multiple applications needed due to solvent evaporation)	Scratch: poor Chip: good	No visible change	Poor	Good
	Paraloid™ B-67	Reversible	Scratch: easier to apply at 20% Chip: difficult to apply at 40%, too viscous (multiple applications needed due to solvent evaporation)	Scratch: poor Chip: poor (bubbles)	No visible change	Poor	Poor
	Paraloid™ F-10 + Paraloid™ B-67	Reversible	Scratch: easier to apply at 20% Chip: possible to apply at 40% (multiple applications needed due to solvent evaporation)	Scratch: poor Chip: poor (bubbles - but less than Paraloid™ B-67)	No visible change	Poor	Poor
Hydrocarbon resins	**Regalrez® 1094**	Reversible	Scratch: easy to apply at 40% Chip: easy to apply, good result at 40% (for chip, multiple applications needed due to solvent evaporation)	Scratch: very good Chip: very good	No visible change	Very good	Very good
	Regalrez® 1094 + Tinuvin® 292	Reversible	Scratch: easy to apply, good result at 40% Chip: easy to apply, good result at 40% (for chip, multiple applications needed due to solvent evaporation)	Scratch: good results Chip: very good results	No visible change	Good	Very good
	Regalrez® 1126	Reversible	Scratch: easy to apply, good result at 40% Chip: easy to apply, good result at 40% (for chip, multiple applications needed due to solvent evaporation)	Scratch: good Chip: very good	No visible change	Good	Very good
	Regalrez® 1094 + Tinuvin® 292	Reversible	Scratch: easy to apply, good result at 40% Chip: easy to apply, good result at 40% (for chip, multiple applications needed due to solvent evaporation)	Scratch: good Chip: very good	No visible change	Good	Very good
Epoxy resins	**Hxtal NYL-1**	Non-reversible	Scratch: easy to apply Chip: easy to apply (for chip, one application possible due to its minimum shrinkage -less than 1%)	Scratch: very good Chip: very good	No visible change	Very Good	Very good
	EPO-TEK® 305	Non-reversible	Scratch/Chip: easy to apply but undergoes an exothermic reaction during curing	Scratch: poor (halo on PMMA) Chip: poor (halo on PMMA)	Visible change Yellowed	Poor	Poor
UV curing materials	**Dymax® 4-20638**	Non-reversible	Scratch: easy to apply Chip: easy to apply (for chip, difficult to cure due to oxygen inhibition and thickness of the repair)	Scratch: very good Chip: poor (bubbles, visible shrinkage, uncured sticky surface)	No visible change	Good	Poor
	Dymax® 4-20418	Non-reversible	Scratch/Chip: easy to apply; difficult to cure probably due to oxygen inhibition (for chip, also due to the thickness of repair; yellowing during chip-filling curing process)	Scratch: very good visual results but uncured sticky surface Chip: poor (cloudy, yellowed, sticky)	Barely visible yellowing	Poor	Poor
	Dymax® 3099	Non-reversible	Scratch/Chip: easy to apply. (difficult to cure due to oxygen inhibition; for chip, also due to the thickness of the repair)	Scratch: very good visual results but uncured sticky surface Chip: poor (cloudy, sticky)	No visible change	Poor	Poor
	NOA 74	Reversible (by peeling)	Scratch/Chip: easy to apply (in some tests difficult to cure due to oxygen inhibition)	Scratch: very good visual results but uncured sticky surface Chip: poor (cloudy, visible shrinkage)	Visible change Slightly yellowed	Poor	Poor
	NOA 76	Non-reversible	Scratch/Chip: easy to apply (difficult to cure due to oxygen inhibition; for chip also due to the thickness of repair; yellowing during chip-filling curing process)	Scratch: very good visual results but uncured sticky surface Chip: poor (slightly yellowed, sticky)	No visible change	Poor	Poor
	NOA 89	Non-reversible	Scratch/Chip: easy to apply (easy to cure – fast curing time; yellowing during chip-filling curing process)	Scratch: very good Chip: poor (cloudy, visible shrinkage, slightly yellowed)	Visible change Slightly yellowed	Poor	Poor
	NBA 107	Reversible (by peeling)	Scratch/Chip: easy to apply (easy to cure – fast curing time)	Scratch: very good Chip: poor (visible shrinkage, cloudy)	Visible change Yellowed	Poor	Poor
	EPO-TEK® OG603	Non-reversible	Scratch/Chip: easy to apply (difficult to cure probably due to oxygen inhibition; for chip, also due to the thickness of repair)	Scratch: good visual results but uncured sticky surface Chip: poor (visible shrinkage, partially sticky)	Visible change Slightly yellowed	Poor	Poor
	EPO-TEK® UD1355	Non-reversible	Scratch/Chip: easy to apply. (difficult to cure probably due to oxygen inhibition; for chip, also due to the thickness of repair; yellowing during chip-filling curing process)	Scratch: good visual results but uncured sticky surface Chip: poor results (cloudy, shrunk, yellowed)	Visible change Yellowed	Poor	Poor

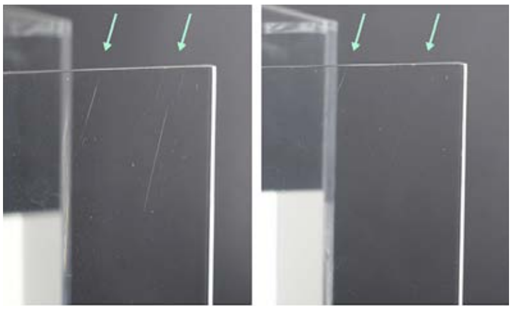


Figure 5. Details of Case 1: the PMMA surface before treatment (left) showing deep scratches interfering with the object's original appearance; after scratch-filling (right) when the transparency was recovered

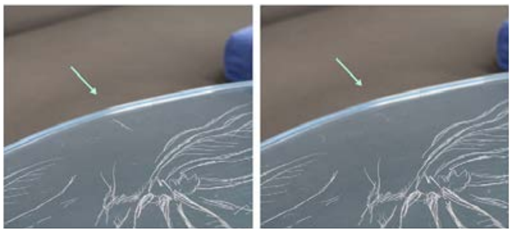


Figure 6. Details of Case 3 showing the ability of the clear resin to re-saturate scratched colored PMMA even without addition of dyes; before scratch-filling (left) and after (right)

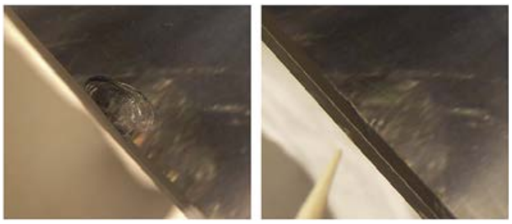


Figure 7. Details of Case 4 before and after chip-filling. © Borzo Gallery

(RCE) collection and a face-mounted photograph from Borzo Gallery Collection in Amsterdam. A brief description of the case studies follows.

1. *Vrijstaande Konstructie K.U.B.1* (1974) by the artist Wilderom, consisting of several pieces of white and transparent PMMA sheets glued together.
2. *Zonder titel* (1971), by Tempelman, consisting of a PMMA cast piece decorated with incised vertical lines and horizontal engravings.
3. *Moeder Libelle* (1976) by A. van den Ijssel is a dragonfly, with metal body and four wings made of colored transparent PMMA. On the light blue wings, small dragonflies are engraved.
4. *Untitled (Vertical Landscape – Windmills* (2007) by the artist Ger van Elk, consisting of a *retouche* with ink on Cibachrome face- and back-mounted with PMMA.

The three RCE objects showed several scratches on their PMMA surfaces. In Tempelman's and van den Ijssel's works, some deep scratches were particularly interfering with the objects' perception and they could also be mistaken for original incisions. In the van den Ijssel, the additional challenge was to saturate a colored transparent PMMA. Treatment strategies were first discussed with the RCE conservation specialist Ron Kievits. It was decided to treat only the most disturbing scratches, identified by placing the objects on a black background, which also helped to improve the visibility of the damages thus facilitating precise applications. Regalrez 1094 was preferred to HXTAL NYL-1 because, with results almost visually equivalent on scratches, it has the added advantage of being highly reversible. The resin was easily applied with the mini-brush as a paint retouch. One application was sufficient to reduce scratches (Figure 5). Scratch-filling was performed with objects lying flat as well as in an upright position. The mini-brush was able to hold the low-viscosity product; however, when treated in an upright position it was necessary to minimize the amount of resin to avoid dripping. Regalrez 1094 treatments successfully "retouched" the damaged PMMA surfaces, recovering the transparency and permitting the reading of all three objects. Treatments showed also the ability of the resin to re-saturate colored clear PMMA without adding dyes (Figure 6).

For van Elk's photograph, the face-mount had suffered a serious chip on its edge. The damage was treated with HXTAL NYL-1 because, due to its minimal shrinkage upon curing, it is easier to use on deep chips. Beeswax was temporarily applied along the broken edge to avoid spreading of resin. Epoxy was carefully dripped within the boundaries of the loss until it was completely filled. After curing, no further applications were required. The repair matched the PMMA surface in level and clarity. The photograph completely recovered the lost transparency and visibility of the image underneath (Figure 7).

CONCLUSION

The results of this extensive investigation showed that excellent alternatives exist to invasive treatments such as polishing or surface modification for the repair of PMMA surfaces. The visual appearance of local scratches and chips can be successfully improved using fill materials. The application methods developed allowed for very precise applications, eliminating the need for finishing treatments. Regalrez 1094 and HXTAL NYL-1 proved to be the most suitable materials for filling scratches and chips. Regalrez has the advantage of being reversible, while HXTAL NYL-1 presents minimal dimensional change upon curing, allowing fewer applications in chip-filling compared to solvent-based adhesives. It is hoped that this research will contribute to assist all conservators in the field dealing with PMMA surface damages in making safe and suitable choices.

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