Automated Reflective Particle Tag System for Physical Authentication

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Introduction

The Reflective Particle Tag (RPT) was developed during the late 20th century for identifying items accountable under bilateral nuclear weapons treaties.[1, 2] The RPT is a field-applied tag and seal composed of specular hematite particles in an adhesive polymer matrix. When illuminated from different angles, each RPT presents complex patterns of millimeter-scale light reflections unique to the tag. These patterns are suitable as a means of physically authenticating the tagged item. Subsequent advances in imaging and computing technology enable automation of the RPT procedure, enhancing inspection efficiency for wider adoption. In prior work, we discussed the performance of the maximally stable extremal region (MSER) and wide baseline matching (WBM) algorithm approach for tag validation.[3] We report in this paper on the design considerations, development, and testing performance of two new RPT prototype systems, and describe physical and chemical properties of the polymer and particle components. The new RPT system includes automated light control, sample collection, and an image database.

Tag Description

The adhesive polymer is mixed with the specular hematite particles to create a unique pattern of reflections under varying illumination angles. The formula for the historical RPT system used a UV-cured polymer, a 50:50 mix by weight of the commercial resins Ebecryl® 3700-20T[1] and Gafgard ® 233[2]. The resin is only partially cured by the UV exposure since it is self-shading by virtue of the particle filling and the film thickness. The cured polymer is not transparent to UV radiation. The cured resin mixture has an elastic modulus of 20 MPa and glass transition temperature (T_g) of 50˚C, with 0.6% weight loss to 325˚C, and thermal decomposition above 400˚C. The specular hematite particles were derived from a particular source of raw iron ore.[3] To replace the historical supply, new ore was obtained from the same deposit and precision grinding was

[1] Cytec Industries, Smyrna, GA USA
[2] International Specialty Products, Wayne, NJ USA
[3] Ward's Natural Science, Rochester, NY USA

performed to match closely the historical size distribution and reflective properties[4] (Figure 1). The elemental composition was typical of hematite ore. (Table 1). The historical RPT used a polymer to particle ratio of 28:72 by weight.

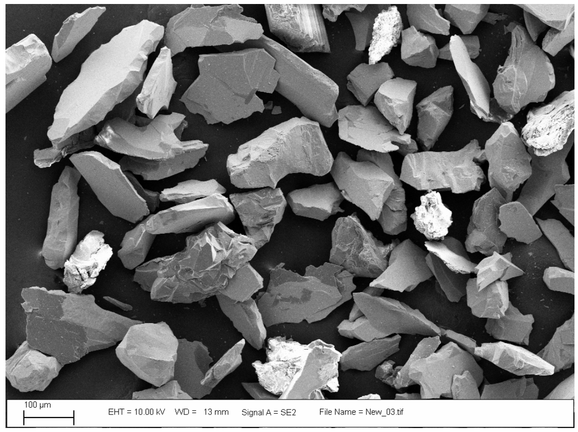

Figure 1. Specular hematite, mean diameter = 177 μm, s.d. = 88 μm, 4.93 g cm^{-3}

OXIDE (CALCULATED)	**WEIGHT PER CENT (95% CONFIDENCE LEVEL)**
Fe_2O_3	90.3 (± 2.5%)
SiO_2	4.3 (± 0.8%)
Na_2O	0.29
K_2O	0.22
MgO	0.21
Al_2O_3	2.33
MnO	0.06
TiO_2	0.75

Table 1. Composition of specular hematite powder produced in this work.

The UV curing used a battery powered bulb lamp. For the current system, we employ a compact battery powered UV LED curing tool.[5] This provides an intense UV source for field use, curing a tag to hardness within a few minutes. A new two-component epoxy resin system[6] was selected for evaluation as a potential polymer replacement, since eliminating the UV cure step and hardware would simplify RPT field application further. The UV cured polymer system underwent extensive testing and security evaluation in the historical RPT development effort; thus, replacing it with a chemically cured epoxy system requires significant study of mechanical, environmental, and security characteristics as part of formal system vulnerability assessments.

[4] Particle Reduction Service, Elk Grove Village, IL USA
[5] Kinetic Instruments, Bethel, CT USA
[6] Two component epoxy Epoxy 5400 A/B, appli-tec, inc., Haverhill, MA USA

In operation, a field inspector places an RPT on an item. Digital images of the tag illuminated from different directions are recorded as references. During subsequent inspection, new probe images of the tag are taken and quantitatively compared with the references as a tag validation. We have shown that images of different illuminations of a tag are as different as images of different tags taken from the same illumination.[3] Thus, for the current development prototypes, we use two illumination angles for simplicity. In field practice, a larger number of illumination angles will be used in order to increase the difficulty of physical tag compromise by duplication.

The current tag reader design features a digital camera[7] and lighting assembly mounted in fixed relative positions on a rigid body. Thus, during the tag validation inspection, the reader-tag pair must return to the original spatial orientations of the reference data collection step. Achieving the identical reader-tag alignment causes the probe image to return the same pattern of reflections as the reference image. An alignment fiducial was used in the historical RPT system, and has been redesigned for the new system (Figure 2). We employ a laptop computer to display alignment lines on the screen, corresponding to the alignment targets on the tag fiducial located under clear tag resin. For field use, the alignment fiducial will be located within the reflective particle field for security.

Figure 2. RPT fiducial with alignment lines in screen viewer.

Alignment to fiducial is subject to operator error, so mechanical alignment may be preferred for some applications of high confidence tag validation. Also, a tag may be protected from mechanical damage or environmental degradation by a cover. We designed and prototyped a mechanically-aligned tag with integral cover for the new epoxy formulation under evaluation (Figure 3). The frame has an alphanumeric tag label for inspector use; a security barcode will be embedded in the resin for the tag reader database use. Asymmetric alignment pin holes and a frame notch prevent misalignment of the reader. The two components (resin and hardener) are packaged as a pre-mixed

[7] Zarbeco LLC, Randolph, NJ USA

dispersion with the hematite particles, and dispensed from a single use bubble pack. This formula sets to hardness within about 5 minutes.

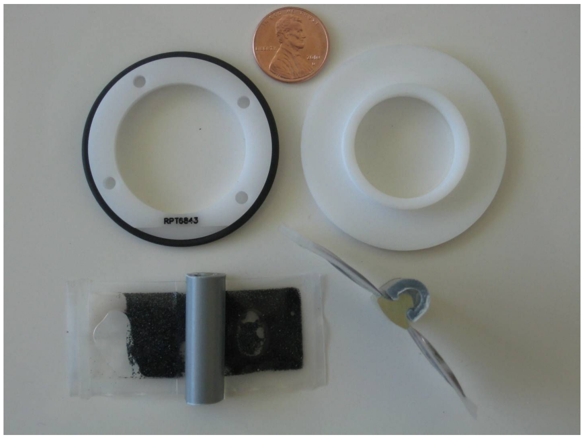

Figure 3. The mechanical alignment tag frame (left, top), with bubble packs (bottom) for dispensing a two component epoxy and particle mixture, and tag stencil (top, right).

Mechanical and environmental testing was performed on both the UV-cured and the two-component epoxy tag matrices as a function of hematite weight loading. Surfaces were cleaned with light abrasion and a propyl alcohol wipe. The UV-cured matrix was tested with a customized fixture, which pulled an embedded plunger out of a thin sample of cured material (Figure 4). This test was performed on a variety of substrates, representing materials likely to be of interest for RPT tagging in authentication work.

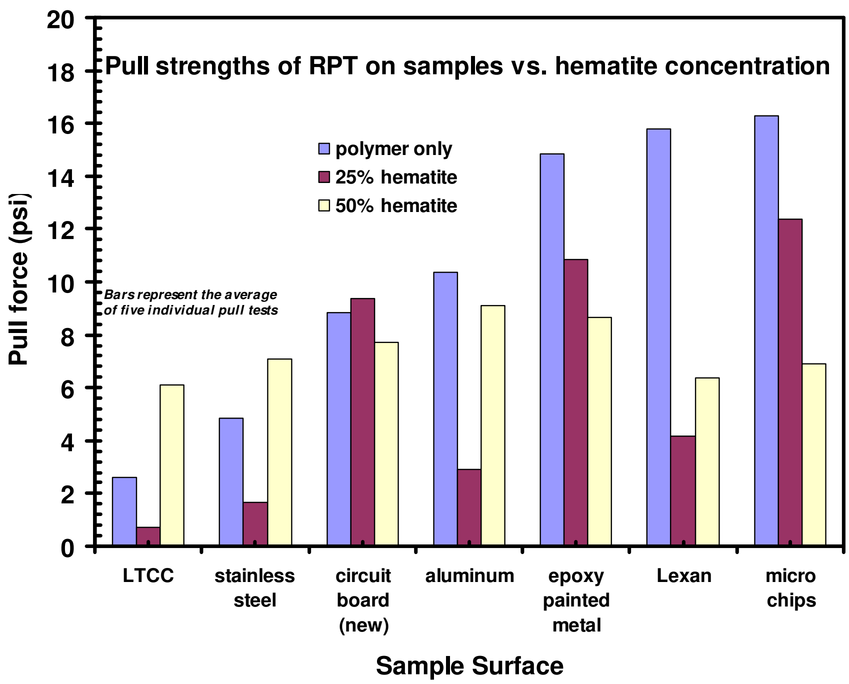

Figure 4. Custom method pull tests of UV-cured tag matrices at various loadings.

The pull strength tests show a general trend of higher strength for clear and filled polymer adhesion to organic surfaces, but most test variability is likely due to the properties of the cured matrix. The pull strength for the historical matrix composition (resin 28:72 particles, by weight) as a function of temperature (-41˚C to +71˚C) showed some improvement with higher temperature, but was variable as well (Figure 5). The difficulty in achieving uniform mechanical properties in UV-cured resin is expected due to the intrinsic UV shading effects of a thick and loaded layer. The historical matrix composition had the lowest pull strength but was most consistent at room temperature (Figure 6).

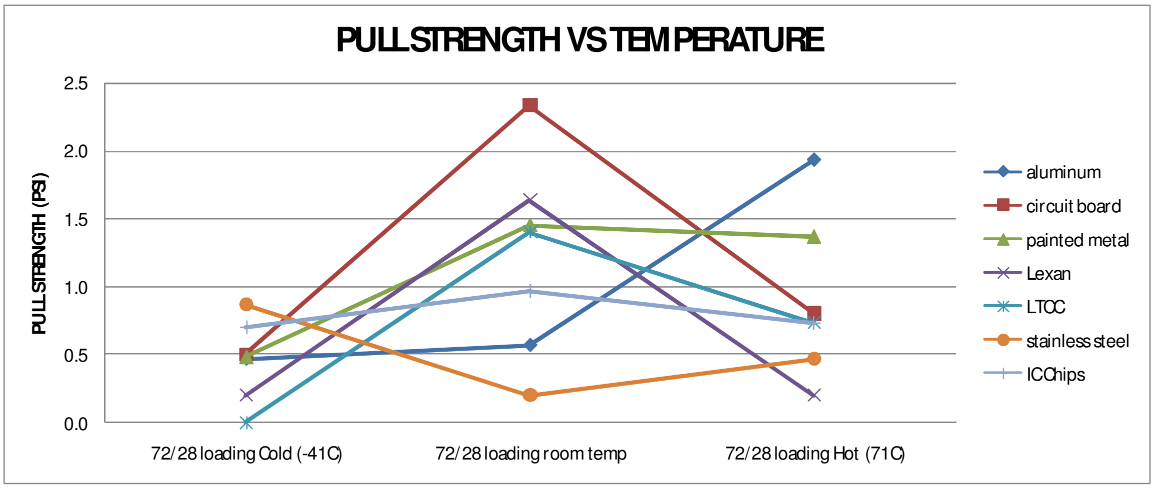

Figure 5. Pull strength as a function of temperature on various substrates

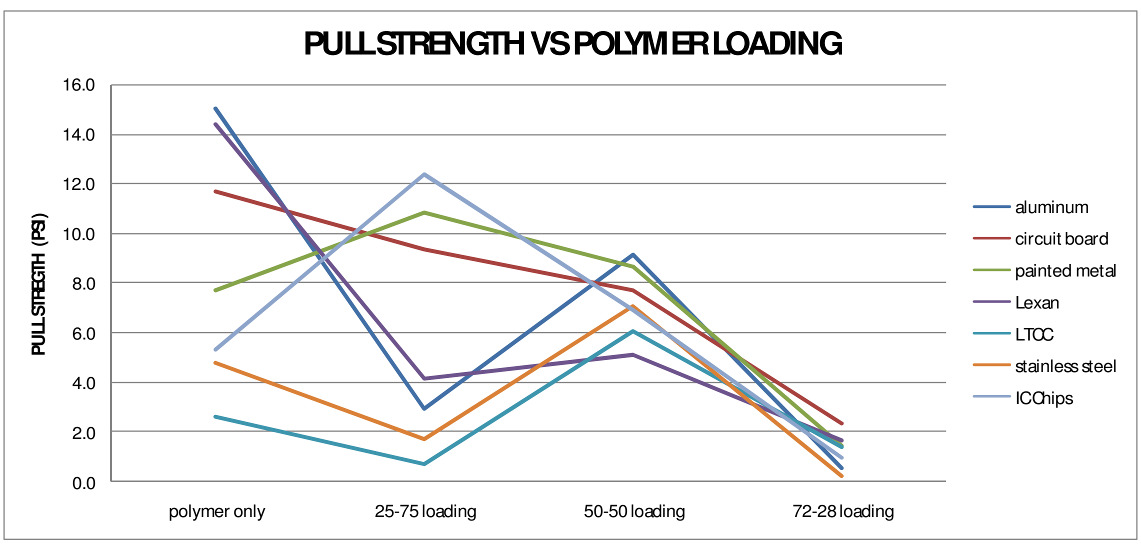

Figure 6. Pull strength as a function of particle loading on various substrates at room temperature

A more conventional tensile strength test was possible with the two-component epoxy matrix candidate, which was evaluated for strength or adhesion to various substrates (Figure 7).

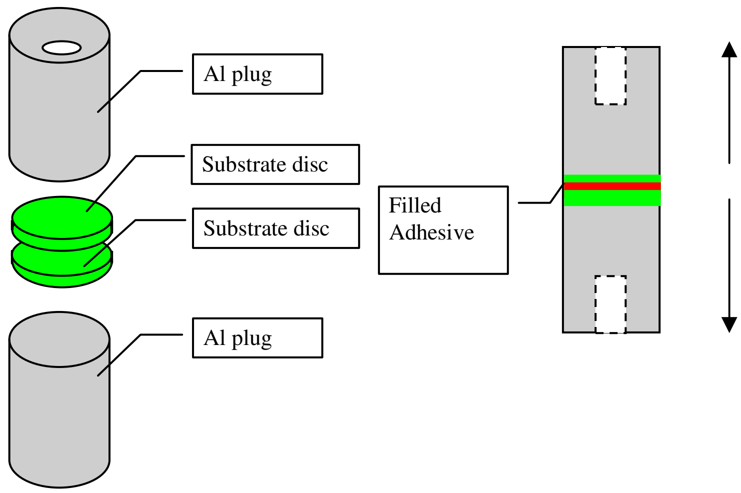

Figure 7. Test apparatus for epoxy matrix strength/adhesion

The tensile samples typically failed within the matrix itself, showing good adhesion to the substrates (Figure 8), except for painted steel at -50˚C (Figure 9). This was due to a failure of the paint coating. The tensile strengths measured by this test are two to three orders of magnitude higher than the custom pull strength tests done for the UV resin, but a direct comparison is not possible until the customs pull test is performed on the epoxy.

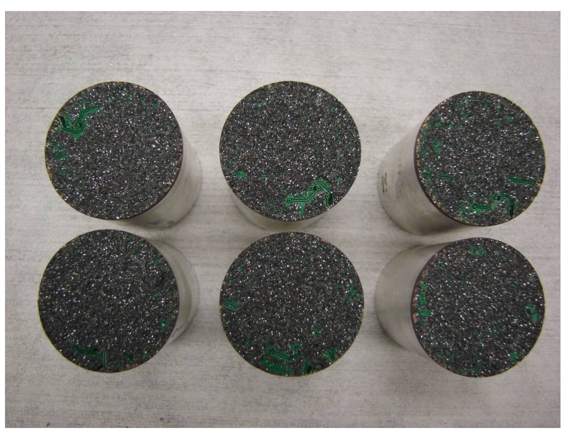

Figure 8. Tensile samples on circuit board failed within the matrix

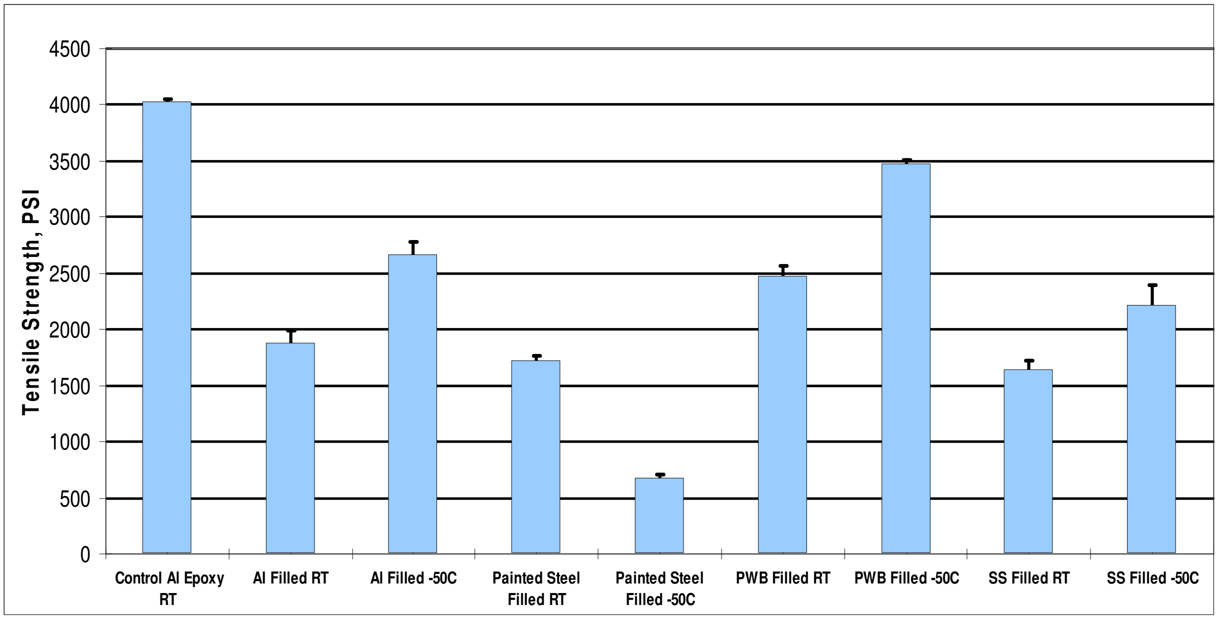

Figure 9. Tensile strength on various substrates at room temperature and at -50˚C

Prototype System Evaluation

The current prototype operates from a battery-powered laptop computer. This controls and powers the automatic operation of the diode lights and the digital camera. A simple inspector interface supports acquisition of reference and probe images. Optical character recognition (OCR) software reads the tag label, with a three-letter descriptor for a facility-area-room code, and a four-digit number for item coding. Database support for image records and algorithm results is automated. No keystrokes are required of the operator, only mouse clicks on the button menu (Figure 10).

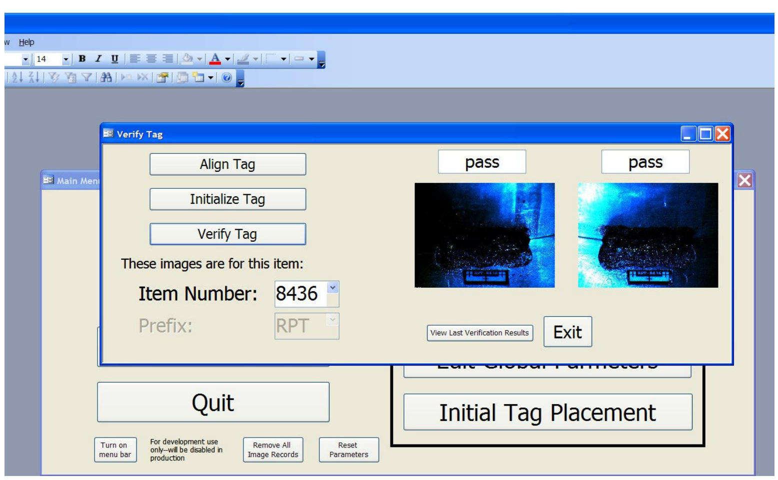

Figure 10. Inspector interface showing right and left illuminations for RPT validation.

We conducted a total of 1,543 trials of this prototype, testing its function and the alignment by fiducial to three unique tags. Two separate aspects of the system function during the test are of note. We test the ability of the operator to reproducibly align to the tag using the fiducial and screen lines (Figure 2). The prototype software to acquire and evaluate data was also tested as a functional component. The imager was removed and repositioned between each verification reading. Results are shown in Table 2.

FUNCTION	SUCCESS RATE IN 1,543 TRIALS
System Success Rate	**86%**
RPT Validation	100% of successful trials
System Failure Rate	**14%**
Label Recognition	73% of failed trials
Image Capture	25% of failed trials
Internal Data Handling	2% of failed trials

Table 2. Prototype system performance over 1,543 trials on three unique RPT

In all tag validation tests, the alignment by the operator to the fiducial was 100% successful in achieving tag validation. These successful tests comprised 86% of the trials. The remaining 14% of the trials were system failures, in which the software failed to acquire or manage image data properly. There were no trials in which the system functioned and failed to verify the tag due to misalignment. Failure analysis suggests that a change to a more reliable barcode identifier and use of more custom software will increase reliability.

Future Work

We continue to explore prototype concepts for RPT reader and tag systems. It is likely that no single RPT system will be compatible with all possible user requirements, and that custom systems will be needed for certain applications. Some objects that may be contacted by a reader may or may not allow the use of a tag frame for mechanical alignment. Some objects may not be contacted at all, and a standoff reader will be needed. Depending on authentication requirements for disarmament use, an RPT system may rely entirely upon commercial components for hardware and software, with minimal custom subsystems. Alternatively, authentication requirements may drive the RPT system to a nearly complete custom configuration. We are developing an understanding of potential RPT applications where the tag functions as both a seal and a unique identifier. The incorporation of additional unobvious security signatures to the tag matrix is under investigation. For all applications, ease of use and high confidence in tag validations are required. Algorithms are being developed to assess incidental damage effects on tag validation characteristics to cope with field conditions. A scratch or dent on an otherwise intact tag must be distinguishable from a compromised tag having a cut or missing portion.

Acknowledgments

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