A Systems Approach to Specifying a High Reliability, High Quality Thick Film Passive Component for Hybrid, Multi-Chip Module and Surface Mount Applications

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Abstract

A quantitative analysis of thick film chip resistors is presented regarding design and construction. Critical reliability and performance data are compared for two techniques used to adjust final resistance tolerance — abrasive trimming and laser trimming. Additional enhanced performance characteristics are discussed for diamond sawing versus laser scribing methods of die separation, and 3-sided versus 5-sided surface mount terminations, including nickel barrier and solderability aspects. This analysis will provide vital information for component engineers working with parts specifications for thick film passive components.
Additionally, specification guidelines are defined based upon each given packaging and electrical application for optimum performance and reliability of a thick film passive component. These guidelines are specified for applications involving epoxy die attach, eutectic die attach, wire bonding, and surface mount reflow soldering. Some typical pitfalls that occur when using an incorrectly specified component for a given application are discussed.

Key Words: Thick film chip resistors, abrasive trimming, laser trimming, reliability, power rating, pulse behavior

Introduction

Passive components continue to play a significant role in the design engineer's parts list. In fact, "The use of passives continues at an astounding rate. In the future, some people have assumed that passives will be 'integrated' away into the integrated circuit. The exact opposite is happening; passive growth continues unabated. The growth of passive components on a PCB from only 25 percent in 1984 to over 90 percent today is arguably the most remarkable change in all of electronics." [1] It remains for the experienced electronic designer to attempt to successfully integrate different types of passive components interconnected by various processing technologies into a reliable circuit. However, there are still daily problems resulting in premature failures of electronic systems. Based upon many documented learning experiences, this paper provides a systems-based selection process derived from generally recognized best practices in today's electronic industry for the thick film passive component.

Passive Component Selection Criteria

A review of the literature indicates consistency in criteria for selecting passive components [2][3]. A summary of important factors, including input from a passives component engineer [4], results in a list of 12 items:

- Value/Tolerance/Stability
- Size
- Power Rating/Dissipation
- Voltage Rating
- Operating Temperature
- Temperature Characteristics
- Pulse Behavior
- RF Performance
- Current Noise (Resistors)
- ESR/Loss (Capacitors/Inductors)
- Robustness of Termination
- Compatibility with Assembly Requirement

Value/Tolerance/Stability

The primary function of a component is to provide its nominal value within a tolerance and to

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remain stable. In the area of thick film chip resistors, there are two fundamental manufacturing methods used to achieve these critical characteristics: abrasive trimming and laser trimming. References in the literature cite differences in the performance and reliability according to which method is used [5][6][7].

Abrasive trimmed resistors are virtually sandblasted to value using a small nozzle cutting into the resistor element. Benefits are outstanding long-term stability, wide and high breakdown voltage kerfs with a minimum of trimming equipment setup. Tradeoffs are slowness and the dust particles of substrate, resistor and sand medium.

Laser trimmed resistors are trimmed to value by a laser beam vaporizing a cut into the resistor element. Benefits are a relatively clean, precise process, capable of high through-put at relatively low cost. Tradeoffs center on the sensitivity of the stability of the resistor, which depends on uniform in-specification resistor film thickness from resistor to resistor and from substrate to substrate, and a 1/2 hour to 2 hour critical setup time of the laser.

Experimental Design

In order to quantify differences between abrasive trimming and laser trimming, an experiment was set up according to Figure 1, "Abrasive vs. Laser Trimming Experimental Outline." Test samples of 2 case sizes were defined: 0303 (Mini-Systems MSR66G) and 0805 (Mini-Systems WA86NS). See Figure 2, "Abrasive Trimming vs. Laser Trimming Test Samples." The 0303 (MSR66G) chip resistor was selected because it represents a smaller, more critical, and challenging requirement due to an effective resistor geometry of only 0.30 mm x 0.51 mm[7]. It also represents the wire bondable or flip chip style with oversized top gold wire bonding pads designed for ease of wire bonding or silver epoxy attachment. This substrate lot had a nominal as-fired average value of 278Kohm requiring a 1.4X trim to reach the target value of 400Kohm. The resistive material was a DuPont Series 17 blend of 70% 100Kohm and 30% 1Megohm material, which is also more difficult to trim to a precise value [8]. Generic construction is also shown in Figure 2, where the resistor is terminated on a bottom conductor on 96% alumina, passivated with laser trimmable glass and then terminated again with a top conductor. In this case, no back conductor or wraparound end cap is utilized since the chip is designed for wire bonding on the top conductor. Specifics of paste composition and processing are shown in the experimental outline in Figure 1.

On the other end of the application and resistive scale, the 0805/WA86NS is a wraparound solder tinned 5-sided terminated chip resistor with a nickel barrier designed for surface mount soldering assembly. The construction again follows Figure 2 where the resistor is terminated on a bottom conductor on 96% alumina, passivated with acid resistant, laser trimmable glass and then terminated again with a top conductor. Next, in this case, a wraparound end cap is fired onto the top and back conductor to facilitate surface mount soldering applications. Samples were made from a substrate lot with a nominal as-fired value of 11.3 ohms which requires a 1.4X trim to reach the target value of 16.3 ohms. This requires resistive material made from a low end blend of 55% 3 ohm and 45% 10 ohm DuPont Series 17G paste, which is more difficult to trim precisely without changing in value than middle decade resistor material, such as 1Kohm or 10Kohm material.

In order to directly compare abrasive trimming and laser trimming, all proper precautions were taken for the initial critical laser setup such as starting with a well maintained laser, balancing low trim speed with laser rep-rate, use of "L" cuts where possible, trims limited to 50%, starting trims off the resistor, optimized X-Y focus, 10µ minimum substrate penetration, back-light inspection, and resistor thickness held to lower end of thickness tolerance [9][10][11][12]. In addition, multiple trial and error cuts were made at different lamp power to determine maximum insulation resistance after exposure to 425°C for 10 minutes. This latter technique has proven itself to laser trim millions of thick film resistors that have successfully passed thermal shock and life testing with no lot failures [8].

Discussion of Experimental Results

Results were evaluated from the test sequence for the test groups as shown in the outline in Figure 1. The first part of the test compared abrasive trimmed 0303/MSR66G 400Kohm resistors to the laser trimmed equivalent initially after trimming and after thermal shock. See Figure 3, "0303/MSR66G - Before and After Thermal Shock." The results show abrasive trimmed parts have a tighter distribution of values initially (no rejects), whereas the laser trimmed distribution was wider and resulted in 14 rejects out of 100 pieces tested. After thermal shock, the abrasively trimmed resistors had an average change of -.018%. The laser trimmed resistors had approximately 5.8X higher average change at -.105%. (Rejects were pulled out before thermal shock and replaced with new units, however, 2 more rejects occurred after thermal shock.)

The first set of four resistor distributions in Figure 4, “0805/WA86NS - Before Solder Wave Tinning, After Solder Wave Tinning, and After Thermal Shock,” shows the comparison of 0805/WA86NS 16.3 ohm resistors initially after trimming and after solder wave tinning. The distribution benefits of a "L" cut show in the initial laser trimmed resistors as compared to the abrasively trimmed plunge cut (both groups had no rejects). After solder wave tinning, the abrasive trimmed group maintained about the same distribution and continued to be reject-free, while the distribution of the laser trimmed group broadened out and suffered 9 rejects. Wave soldering is a good representation of a critical assembly process since it has the highest heat transfer rate of any soldering process due to using liquid metal over a wide temperature range [13].

The last set of 2 resistor distributions shows the comparison of the same 0805/WA86NS 16.3 ohm resistors after thermal shock. Again, the abrasive trim group had no rejects and changed only -.012%, while the laser trimmed group suffered another reject (now at 10) and had a 15X higher change at 0.185%.

At the core of any reliability data is the burn-in or life testing data. In this case, the 2000 hour MIL-PRF-55342 life testing method of switching power on for 90 minutes and off for 30 minutes is used while maintaining a 70°C ambient temperature. See Figure 5, “0303/MSR66G - Life Testing” for life testing data of untrimmed, abrasive trimmed and laser trimmed resistors. The data shows the best stability to be untrimmed parts. The abrasive trimmed parts (average of -0.022%) changed 2.5X less than the laser trimmed parts (average of -.055%). The accompanying tabular data shows that none of the statistical distribution data significantly changed. Furthermore, none of the groups had any failures using a 1% change as the criteria. Figure 6, “0805/WA86NS - Life Testing,” shows the WA86NS parts follow the same trend with the abrasive trimmed parts (average of -0.010%) changed 3.1X less than the laser trimmed parts (average of .031%). Note that for both sets of life testing data, the abrasive trim parts far exceed the accepted industry standard of less than 0.1% change [11], while laser trimmed parts are not as good as the abrasive trimmed parts but are within industry accepted standards.

Power Rating/Dissipation and Voltage Rating

In many respects, the MIL-PRF-55342 requirement of Short Time Overload Testing combines power rating and voltage rating characteristics if the test is done to failure. Figure 7, “Short Time Overload Testing To Failure,” shows the result of performing the test at 2.5X the rated voltage (equivalent to 6.25X the rated power) and then increasing the voltage incrementally until the resistance value starts to change due to overload. Abrasive trimmed parts maintained tolerance through another 1/2 watt of power over the equivalent laser trimmed parts.

Pulse Behavior

It has been reported that “overload by pulse voltage or current is one of the most frequent causes of failure of film resistors” [3]. Using different pulse widths and powers resulted in different curves but the common denominator was that abrasive trimmed resistors always had less change due to voltage pulses than laser trimmed resistors. Figure 8, “Pulse Testing To Failure,” shows the effect of 10 rectangular pulses at 60 volts (approximately 220 watts) 50 μseconds wide at 1 pulse/second. Figure 9, “Visual Effect of Pulse Testing on Test Samples,” shows no damage on the abrasive trimmed parts, compared to the physical arcing damage of the laser trimmed parts.

Current Noise

Using a Quan-Tech Model 315C Resistor Noise Test Set, samples from the abrasive and laser trimmed resistor groups were tested and resulted in the data shown in Figure 10, “Noise Testing.” The best data was obtained from untrimmed parts. Abrasive trimmed parts showed an improvement of 6 - 19% above laser trimmed parts. This effect is substantiated by other researchers [5][6][14].

Robustness of Termination

Multilayer chip capacitors are traditionally 5-sided components, meaning each termination has 5 sides like an open 6-sided box. This type of termination is particularly robust since it has excellent structural integrity. Among chip resistors, there is a choice of 3-sided or 5-sided terminations. See Figure 11, “5-Sided Terminations vs. 3-Sided Terminations.” Three-sided terminations are easier to fabricate since the wraparound termination is applied at a 1 up array or strip of components still connected before final singlelation. The 5-sided termination requires complete singlelation before the wraparound is applied. In Figure 11, it is seen that the 5-sided termination has the benefit of an extra solder fillet around the corner of the termination. These extra solder fillets allow extra power dissipation due to the extra solder. Furthermore, the extra solder fillets are less prone to crack due to board flex because force is more evenly distributed around the solder fillet.

Appearance of chip resistors may also differ with respect to the use of diamond sawing or laser scribing. The 5-sided chip resistor in Figure 11 has been diamond sawed, whereas the 3-sided chip resistor has been laser scribed. The laser scribing process depends upon a series of partially drilled laser holes that form a score line for singlelation. "Unfortunately, intense heat from the laser produces microcracks, laser slag and perforated edges. The end result is a dimensional tolerance which adversely influences yield." [15] Figure 12, "Diamond Sawing vs. Laser Scribing" shows a comparison of 0705 chip resistor components that have been diamond sawed and laser scribed. Diamond sawing is precise and accurate with 90 degree angles assured. However, laser scribing, which can be precise initially with respect to the score line, can ultimately become imprecise due to irregular breaking resulting in skewed dimensions. These uneven surfaces can result in component failure from pick/place jaws and/or misfeeds in auto equipment.

Compatibility with Assembly Requirement

Chip & wire hybrid and Multi-Chip modules require components with terminations compatible with wire bonding. Gold ball thermosonic wire bonding is the most popular wire bonding technique because it is the fastest. Best results are with gold plated terminations, thin film gold and thick film gold terminations. Aluminum wedge bonding is popular for large wire diameter applications that are used mostly for power applications. Small diameter aluminum wire is still used and both aluminum wire types are usually compatible with the same terminations as used for gold ball thermosonic wire bonding.

Epoxy die attach is traditionally used with silver epoxy on palladium silver terminations. Gold plated terminations and/or thin film/thick film gold are also acceptable although more costly with some tradeoff with less adhesion. Non-conductive epoxy is used on the body of some components for some solder applications to keep the component in place, whereas thermally conductive epoxy is also used on the body of the component for power dissipation issues.

Eutectic die attach is traditionally used with a gold back pad for scrubbing in a component with a high melting point eutectic solder such as 80/20 gold tin for optimum die adhesion and thermal dissipation.

Passive components are usually hot dip, solder tinned for four types of solder assemblies: Hand Soldering, Surface Mount Technology (SMT), Wave Soldering and Vapor Phase Soldering. Hand soldering is typically used for prototypes and low volume production. Palladium silver or platinum gold can be used (platinum gold is preferred for better leach resistance for repeated rework cycles). SMT utilizes pick/place equipment on components with solder paste followed by an IR reflow oven. Generally this process requires solder tinned/nickel plated components. Wave soldering relies upon traditional through-hole soldering for leaded devices and for "mixed" components, which requires leadless devices to be attached with adhesive on the body prior to soldering. This process also requires solder tinned/nickel plated components. Vapor phase soldering relies upon constant temperature, high boiling liquid, condensing on an assembly until components reach the equilibrium soldering temperature. This process requires solder tinned/nickel plated components.

Passive Application Pitfalls

In the process of researching the literature for this paper, it was noted various references cited the same problems reoccurring in industry. Among the most common mistakes:

1. Using silver epoxy on a solder tinned component. (A high resistance interface slowly builds up in time resulting in a reliability issue.)
2. Using vapor phase reflow on assemblies with large mass differences in components. (Small components bathe in molten solder for a long time waiting for large components to slowly heat up along with circuit board, resulting in a severe stress test on the smallest components.)
3. Using non-nickel plated components for Hi-Rel soldering applications. (Barrier layer is necessary to prevent intermetallics of solder and thick film metallization.)
4. Using epoxy silver to die bond chip component resulting in bleed out of clear contaminant. (Surface contamination can result in a separation of the clear resin phase of epoxy but can be remedied by 150C bakeout of substrate prior to die bonding.)
5. Using untinned gold plated components in solder assemblies, resulting in brittle solder joints. (Any gold plated component needs to be hot solder dipped prior to soldering.)

CONCLUSION

Testing has shown abrasive trimmed resistors to have lower noise, better resistance to short time overloads and voltage pulses than laser trimmed resistors. In addition, abrasive trimmed resistors have less change in resistance after thermal shock, wave soldering and life testing than laser trimmed resistors. Furthermore, it appears the requirement of robust terminations is best served by components that are 5-sided and have been diamond sawed. In general, an abrasive trimmed resistor optimizes the performance in most areas and results in better reliability than a comparable laser trimmed resistor.

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FIGURE 1
ABRASIVE vs. LASER TRIMMING EXPERIMENTAL OUTLINE
Thick Film Process & Post Processing

SEQ	OPERATION	0303/MSR66G TOP CONTACT GOLD WIRE BONDABLE CHIP	0805/WA86PGNS WRAPAROUND NI BARRIER SOLDER TINNED CHIP
1	Screen Printer Setup and Alignment	Substrate: 96% Alumina, 0.25 mm x 43.18 mm x 43.18 mm	Substrate: 96% Alumina, 0.38 mm X 43.18 mm X 43.18 mm
2	Print Bottom Conductor	PasteType: Au Wire Bondable Au Conductor	PasteType: Pt/ Pd/Au Conductor
3	Dry & Fire Bottom Conductor	Dry Thickness: 13 μ ±1 μ Fired Thickness: 8μ ±1 μ 10 Min. ±0.5 Min. @ 850C ± 3 C	Dry Thickness: 20 μ ±1 μ Fired Thickness: 11μ ±1 μ 10 Min. ±0.5 Min. @ 850C ± 3 C
4	Print Back Conductor	NOT APPLICABLE	PasteType: Pt/ Pd/Au Conductor
5	Dry & Fire Back Conductor	NOT APPLICABLE	Dry Thickness: 21 μ ±1 μ 10 Min. ±0.5 Min. @ 850C ± 3 C
6	Fire Back Conductor	NOT APPLICABLE	10 Min. ±0.5 Min. @ 850C ± 3 C
7	Screen Print Resistor	Dupont: 70% 1749 & 30% 1759	Dupont: 55% 1703H &45%1708H
8	Dry Resistor	Wet Thickness: 38 μ ±1 μ Dry Thickness: 22μ ±1 μ	Wet Thickness: 37μ ±1 μ Dry Thickness: 22μ±1 μ
9	Fire Resistor	10 Min. ±0.5 Min. @ 850C ± 3 C	10 Min. ±0.5 Min. @ 850C ± 3 C
10	Print, Dry & Fire Glass Layer	Acid Resistant, Laser Trimmable Resistor Glass ,Fired Thickness: 8μ ±1 μ	Acid Resistant, Laser Trimmable Resistor Glass ,Fired Thickness: 8μ ±1 μ
11	Print, Dry & Fire Top Conductor	PasteType: Au Wire Bondable Au Conductor	PasteType: Pt/Pd/Au Conductor
12	Singlelate & End Dip Wraparound Termination	NOT APPLICABLE	PasteType: Low Firing Temp. Pt / Pd / Au Conductor
13	Nickel & Gold Plate	NOT APPLICABLE	Electrolytic Ni / Au Barrel Plate
14	DC Resistance	278KΩ (3σCV =±11.6%)	11.3Ω (3σCV =±21.5%)
15	Trim Resistors	Abrasive & Laser Trim 1.4X to 400KΩ	Abrasive & Laser Trim 1.4X to 16.3Ω

Test Sequence

SEQ	0303/MSR66G TOP CONTACT GOLD WIRE BONDABLE CHIPS (Abrasive / Laser Trimmed)	MIL-PRF-55342 Reference Paragraph	0805/WA86PGNS WRAPAROUND NI BARRIER SOLDER TINNED CHIPS (Abrasive / Laser Trimmed)	MIL-PRF-55342 Reference Paragraph
1	VISUAL INSPECTION	3.1, 3.4, 3.5 - 3.5.3 3.25 4.8.1	VISUAL INSPECTION	3.1, 3.4, 3.5 - 3.5.3 3.25 4.8.1
2	DC RESISTANCE	3.8 4.8.2	DC RESISTANCE	3.8 4.8.2
3	THERMAL SHOCK	3.9.1 4.8.3	SOLDER WAVE	NOT APPLICABLE
4	DC RESISTANCE	3.8 4.8.2	DC RESISTANCE	3.8 4.8.2
5	DIE ATTACH & WIRE BOND on CERAMIC		THERMAL SHOCK	3.9.1 4.8.3
6	DC RESISTANCE	3.8 4.8.2	DC RESISTANCE	3.8 4.8.2
7	LIFE TEST 2000 Hours	3.17.2 4.8.11.1	SOLDER MOUNT on FR4 BOARD	
8	TCR	3.16 4.8.10	DC RESISTANCE	3.8 4.8.2
9	CURRENT NOISE	MIL-STD-202-M308	LIFE TEST 2000 Hours	3.17.2 4.8.11.1
10	MOISTURE RESISTANCE	3.15 4.8.9 MIL-STD-202-M106	SURFACE SOLDER MOUNT on CERAMIC SUBSTRATE	
11	HIGH TEMPERATURE EXP.	3.13 4.8.7	DC RESISTANCE	3.8 4.8.2
12	SHORT TIME OVERLOAD	3.12 4.8.6	TCR	3.16 4.8.10
13			CURRENT NOISE	MIL-STD-202-M308
14			SHORT TIME OVERLOAD	3.12 4.8.6
15			PULSE TESTING	NOT APPLICABLE

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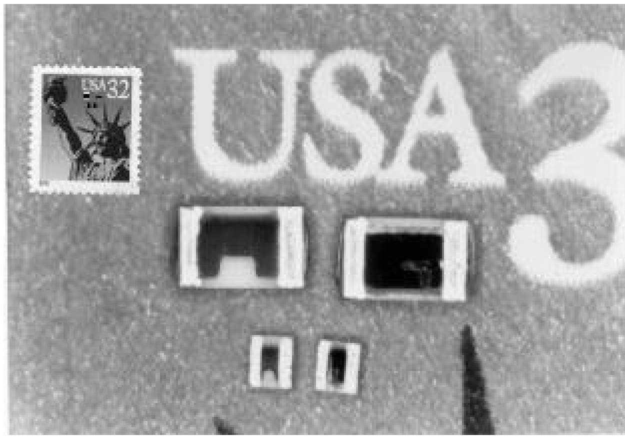
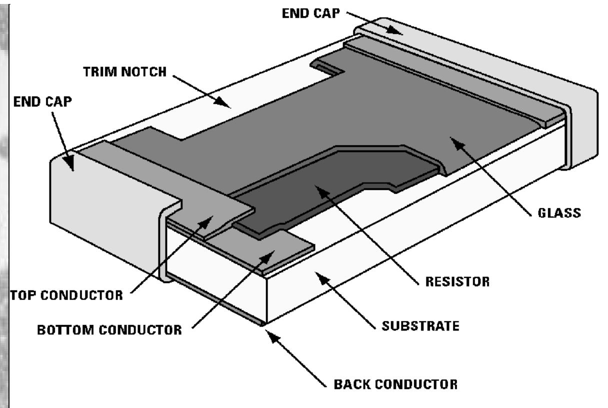
FIGURE 2
ABRASIVE TRIMMING vs. LASER TRIMMING
TEST SAMPLES





ANATOMY OF A HIGH RELIABILITY THICK FILM CHIP RESISTOR

FIGURE 3
0303/MSR66G - Before and After Thermal Shock

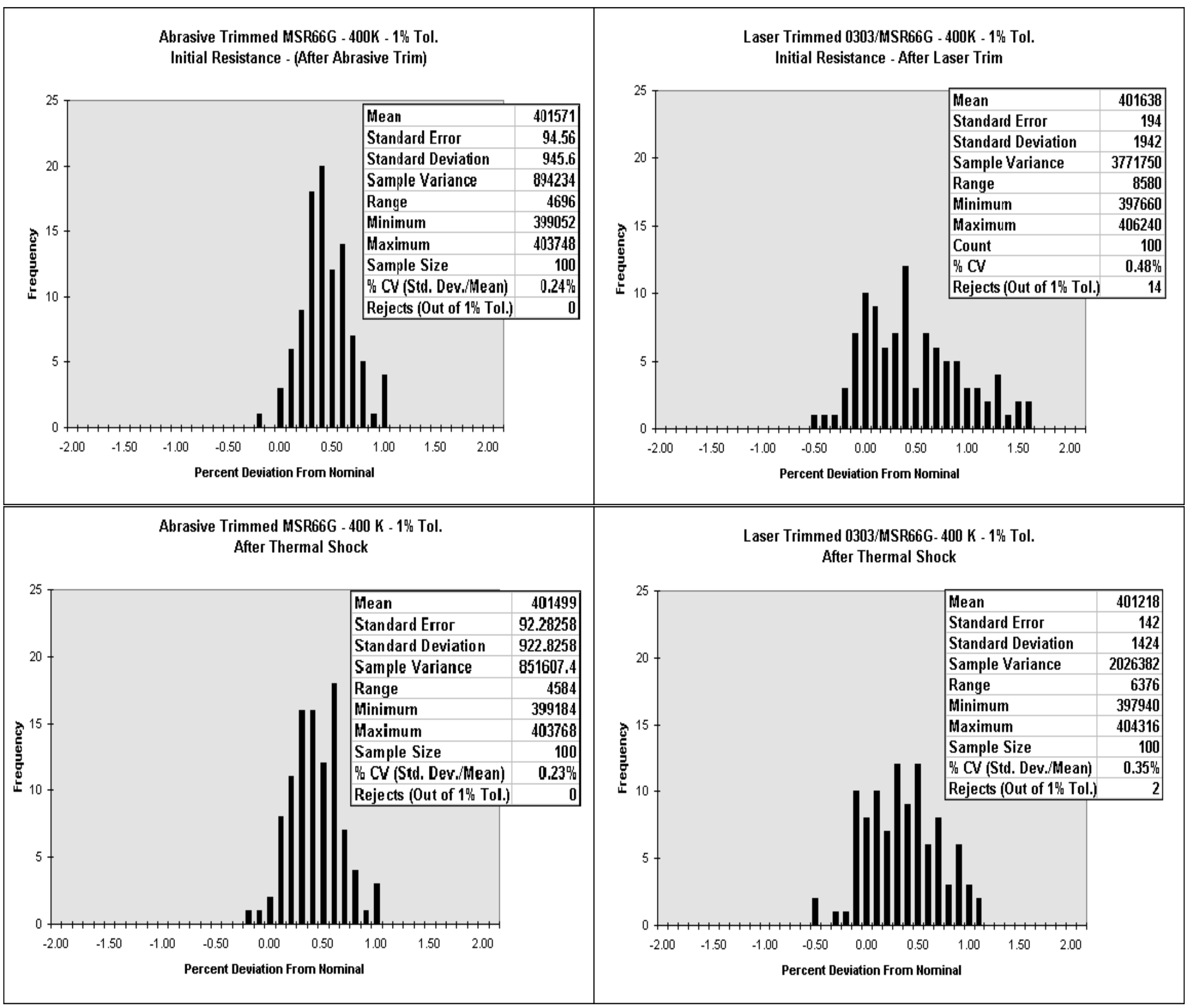


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FIGURE 4

0805/WA86NS - Before Solder Wave Tinning, After Solder Wave tinning, And After Thermal Shock

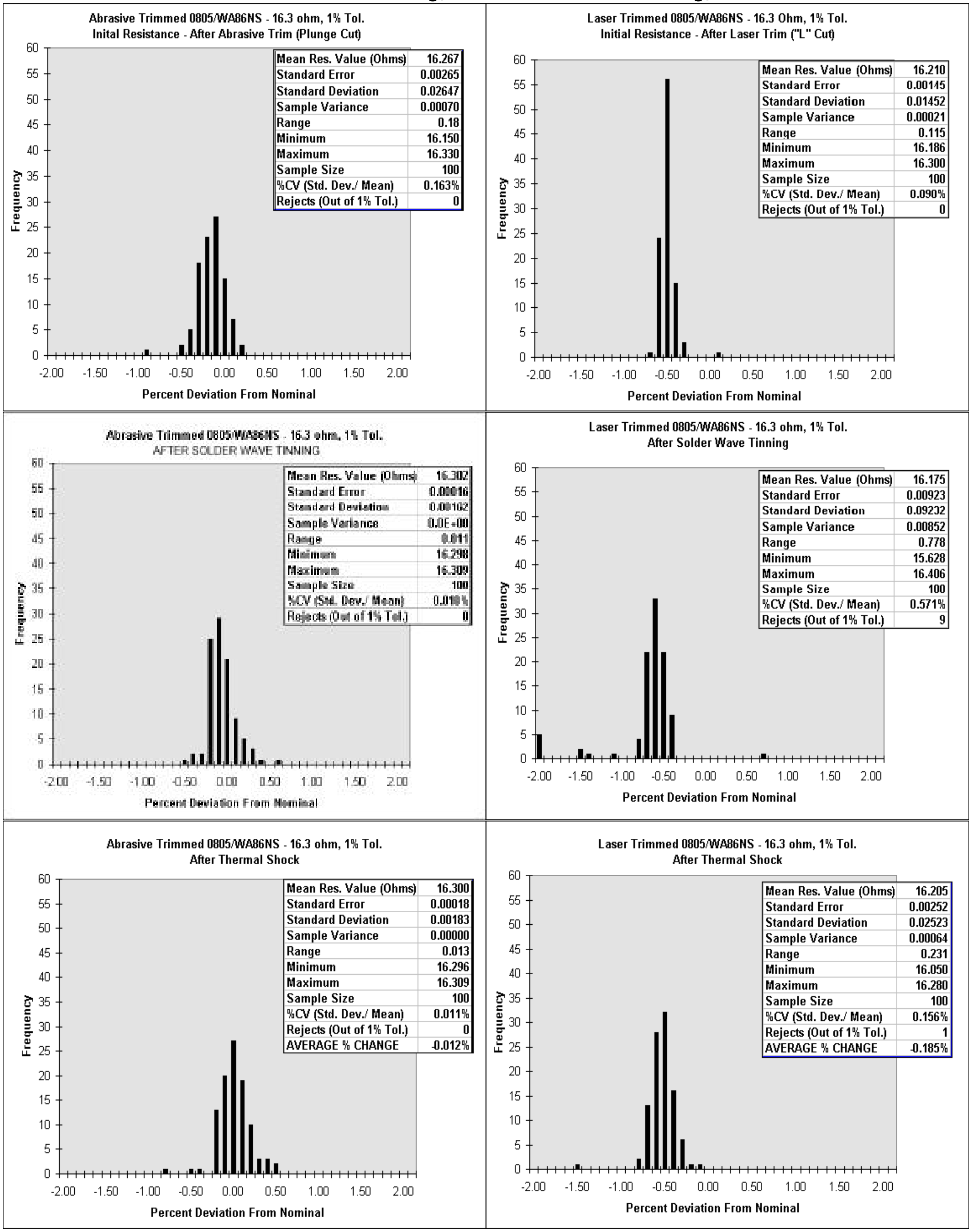
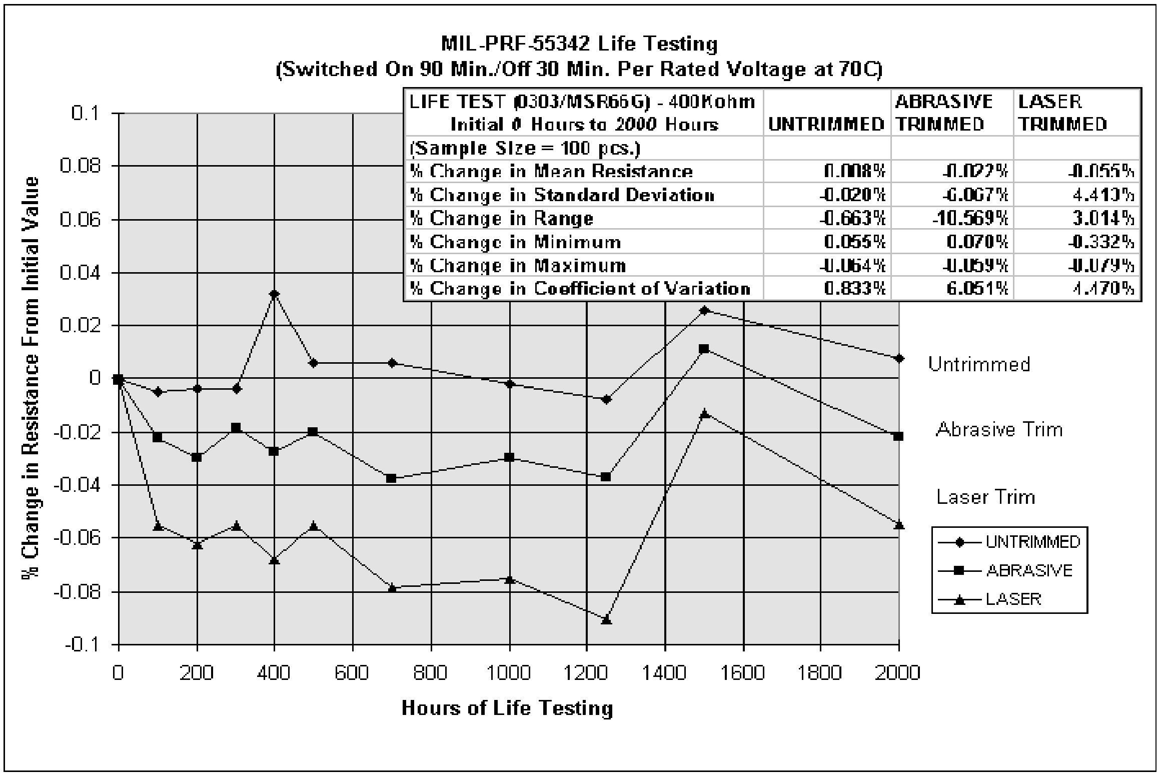
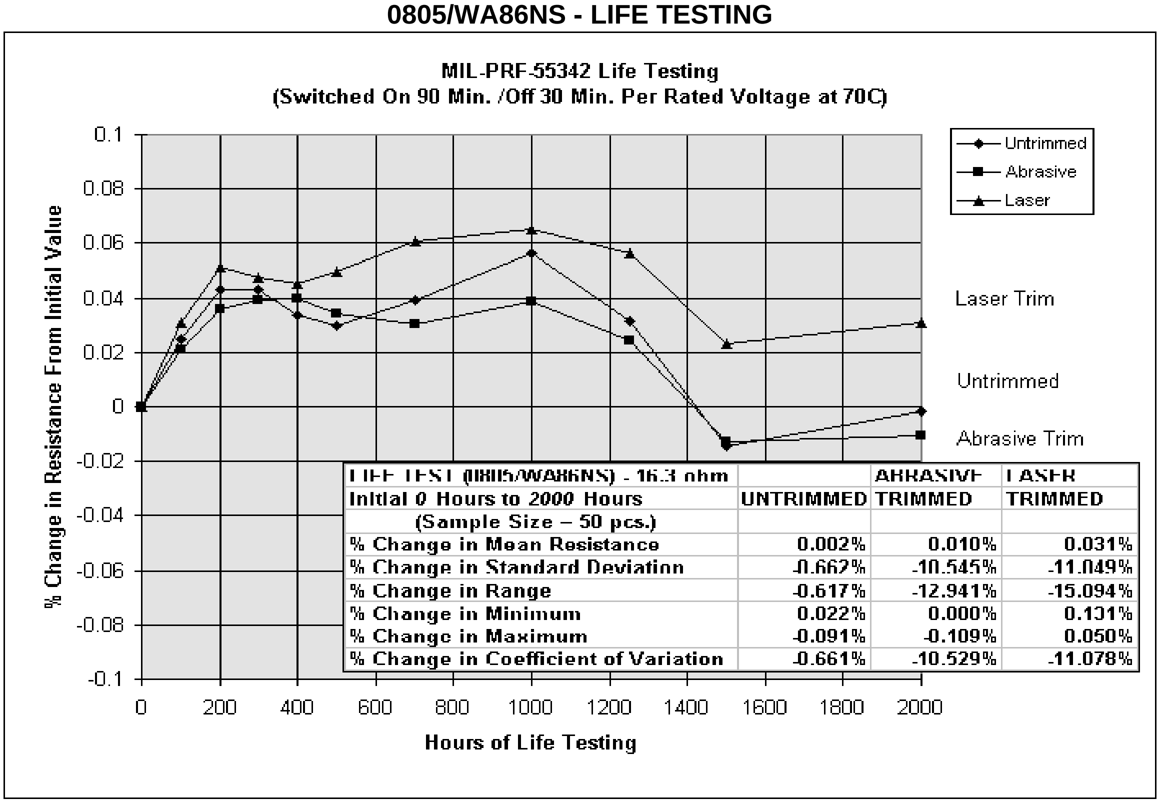


FIGURE 5
0303/MSR66G _ LIFE TESTING



LIFE TEST (0303/MSR66G) - 400Kohm Initial 0 Hours to 2000 Hours	UNTRIMMED	ABRASIVE TRIMMED	LASER TRIMMED
(Sample Size = 100 pcs.)			
% Change in Mean Resistance	0.008%	-0.022%	-0.055%
% Change in Standard Deviation	-0.020%	-6.067%	4.413%
% Change in Range	-0.663%	-10.569%	3.014%
% Change in Minimum	0.055%	0.070%	-0.332%
% Change in Maximum	-0.064%	-0.059%	-0.079%
% Change in Coefficient of Variation	0.833%	6.051%	4.470%

FIGURE 6
0805/WA86NS - LIFE TESTING



LIFE TEST (0805/WA86NS) - 16.3 ohm		ABRASIVE	LASER
Initial 0 Hours to 2000 Hours	UNTRIMMED	TRIMMED	TRIMMED
(Sample Size – 50 pcs.)			
% Change in Mean Resistance	0.002%	0.010%	0.031%
% Change in Standard Deviation	-0.662%	-10.545%	-11.049%
% Change in Range	-0.617%	-12.941%	-15.094%
% Change in Minimum	0.022%	0.000%	0.131%
% Change in Maximum	-0.091%	-0.109%	0.050%
% Change in Coefficient of Variation	-0.661%	-10.529%	-11.078%

FIGURE 7
Short time Overload Testing to Failure

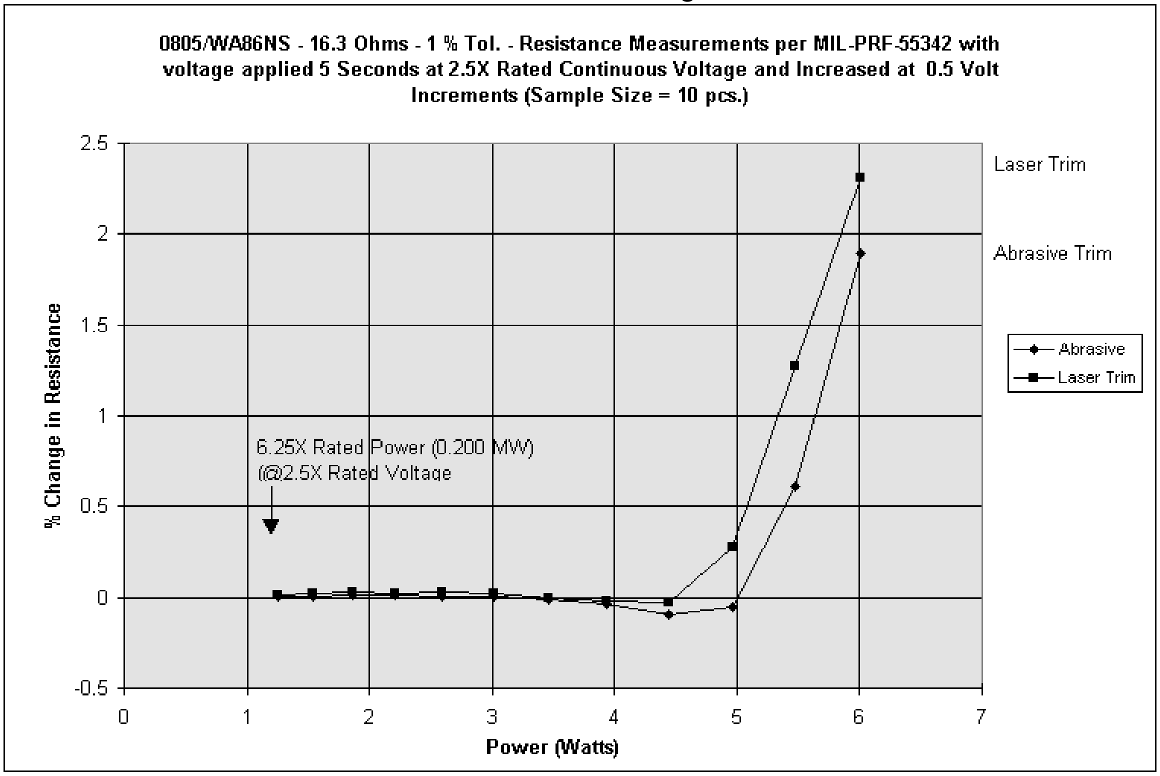


FIGURE 8
Pulse Testing to Failure

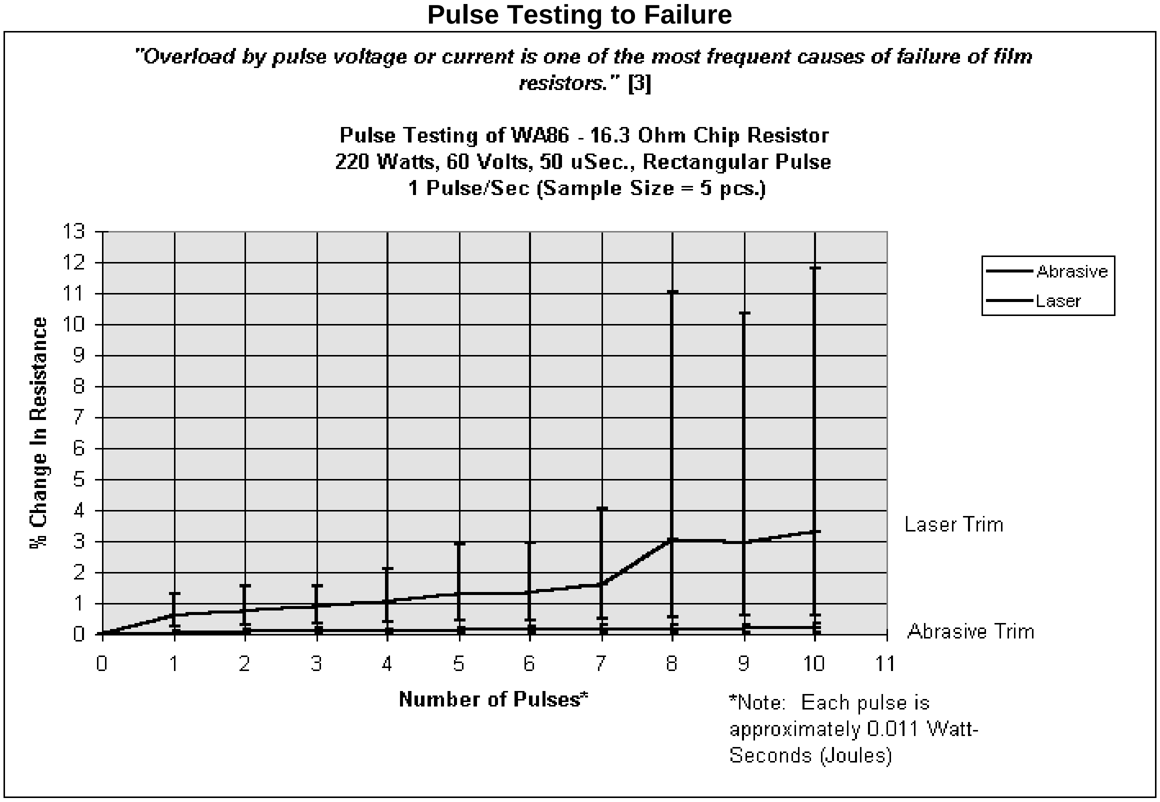
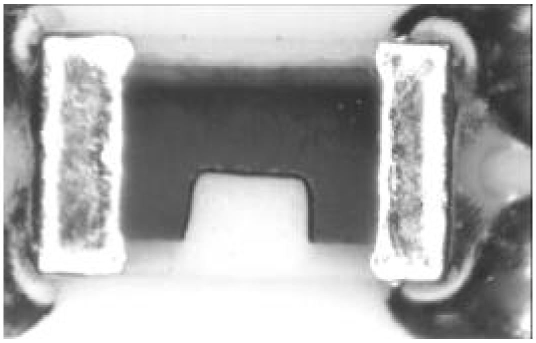


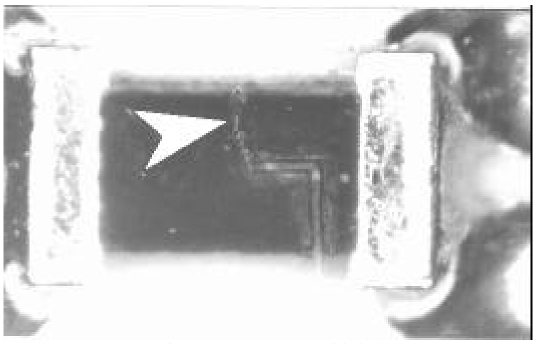
FIGURE 9

VISUAL EFFECT OF PULSE TESTING ON TEST SAMPLES ABRASIVE TRIMMING vs. LASER TRIMMING

WA86-0705 TEST SAMPLES AFTER PULSE TESTING
220 Watts, 60 Volts, 50 μSec. Rectangular pulse
1 Pulse / Sec.. Total of 10 Pulses



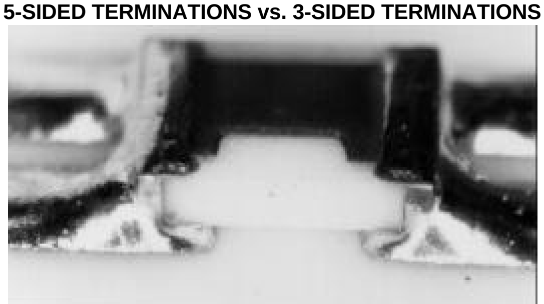
ABRASIVE TRIMMED WA88-0705
NO SURFACE DAMAGE



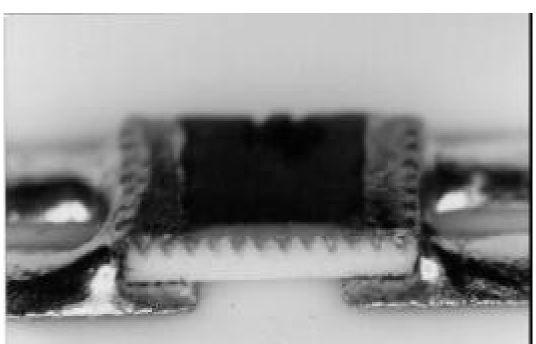
LASER TRIMMED WA86-0705
ARCING DAMAGE

FIGURE 11

5-SIDED TERMINATIONS vs. 3-SIDED TERMINATIONS



5 SIDED TERMINATION



3 SIDED TERMINATION

FIGURE 10
Noise Testing

CURRENT NOISE COMPARISON IN DB
"Sand trimming has lower noise than laser trimming on all three material systems" - RAYTHEON

	MSR66 - .025"x.030" -			WA86 - .080" x .050" - 16.3 Ω		
	UNTRI	ABRASIVE	LASER	UNTRIM'D	ABRASIVE	LASER
	16.3	22.0	25.9	-39.8	-36.8	-36.9
	19.7	19.3	24.3	-38.8	-35.7	-32.9
	15.0	18.4	23.6	-35.3	-35.3	-27.0
	17.7	17.1	21.5	-37.0	-36.9	-34.2
	14.3	17.3	22.6	-39.4	-32.1	-35.9
	14.4	17.0	22.2	-38.7	-37.1	-34.8
	15.7	20.0	20.0	-39.5	-35.3	-32.8
	15.1	16.6	22.9	-39.0	-36.2	-32.2
	17.4	17.0	22.6	-34.8	-37.0	-35.8
	15.8	19.4	22.6	-34.8	-37.0	-35.7
MEAN	16.1	18.4	22.8	-37.7	-35.9	-33.8
RANGE	5.4	5.4	5.9	5	5	9.9
MIN.	14.3	16.6	20.0	-37.7	-35.9	-33.8
MAX.	19.7	22.0	25.9	-34.8	-32.1	-27.0
SAM. SIZE	10	10	10	10	10	10
	UNTRI	ABRASIVE	LASER	UNTRIM'D	ABRASIVE	LASER
%IMPROVEMENT FROM LASER	29.3%	19.3%	BASE	11.5%	6.3%	BASE

The instrument used to perform the above current noise testing (QUAN-TECH MODEL 315C) conforms to the recommendations of the National Bureau of Standards (now called NIST) and to Method 308 of MIL-STD-202 (Test Methods for Electronic and Electrical Component Parts). This instrument measures the noise with no current and the noise with current within a frequency decade geometrically centered at 1000 hertz (Hz). The final result of this measurement is known as the resistor NOISE INDEX.

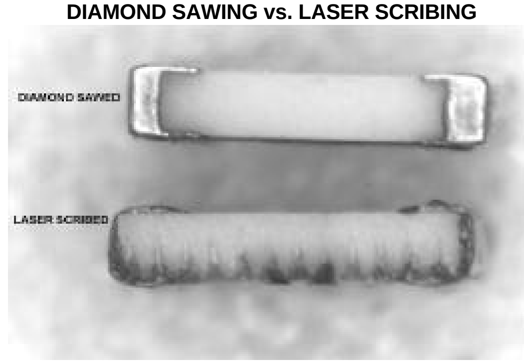
The derived equation for the measurement just described is:

$$N = \frac{\sqrt{Nc^2}}{V}$$

Ec is in microvolts, V is the applied voltage in volts, N is the ratio expressed in dB

FIGURE 12

DIAMOND SAWING vs. LASER SCRIBING



SIDE VIEW WA86-0705