UNRESTRICTED

Ref: ST0012
09 December 1997

Laser Beam Absorption and Mark Depth of Laser Marked Wires

Prepared by:

____

P Cornish
Research Engineer

Authorised by:

____

Dr. P H Dickinson
Managing Director

Spectrum Technologies Limited
Bridgend Science Park, Bridgend, CF31 3NA, UK
Tel: 44 (0) 1656 655437, Fax: 44 (0)1656 655920

UNRESTRICTED

COPYRIGHT DECLARATION

DISCLAIMER

This report is provided by Spectrum Technologies Limited (Spectrum) solely on the following basis.

The contents of this report are intended to provide general advice on the subject matter contained in it. It is for general information purposes only and should not be relied upon in isolation. It should not be regarded as a substitute for utilising your own expert knowledge and/or obtaining other specialist advice. Users of the report must satisfy themselves of the veracity of the information provided. Decisions on process parameters, materials, process systems or other specifications are the responsibility of the relevant technical authority, for which Spectrum cannot be held responsible. This report is provided to you by Spectrum, free of charge, for these limited purposes and on this specific basis. Spectrum excludes all liability in respect of such contents to the fullest extent permitted by law.

CONTENTS

Distribution:

P. H. Dickinson
C. Higgitt
S. Lau
P. Cornish
Report File

External Distribution: Yes

SUMMARY

This report reviews the fundamental physical law governing the absorption of light in material (Lambert's Law) and applies this to the application of ultraviolet (UV) lasers used for marking aerospace wires.

From comparing results from excimer gas lasers and solid state lasers at 308 and 355 nm respectively, it is demonstrated that there is no significant difference between these laser wavelengths, in terms of absorption and marking depth for the two main wire types used in the aerospace industry, namely extruded cross linked ETFE and tape wrapped PTFE wire constructions.

The main factor affecting the absorption of the laser beam, and consequently the depth of the mark, is the absorption coefficient for the materials concerned. Hence, for a given marking fluence (laser energy density at the wire surface) the laser mark depth is essentially independent of both the equipment (vendor) type and the laser type used.

INTRODUCTION

The following analysis is prepared primarily in relation to the application of UV lasers for marking of aerospace wire insulations.

To a first approximation the absorption of a UV laser beam incident on a wire, which results in the marking of the insulation, will follow Lambert's Law[1]:

$$I = I_0 e^{-KX}, \qquad \text{Equation 1}$$

Where,

I_0 = starting or incident light intensity,
I = intensity after the light has passed through a thickness X of a material,
K = the absorption coefficient for the material in question at the relevant wavelength.

This basic universal equation provides an insight into how the depth of the laser mark is likely to change as a function of the controlling parameters (I_0 and K).

DISCUSSION

The intensity of pulsed lasers used in UV wire marking applications can be defined in terms of fluence, measured in J cm^{-2}. That is the averaged laser pulse energy density at the wire surface.

From previous studies [2,3] of UV laser marking of wires, we know that for wires marked at about 1 J cm^{-2}, i.e. to give the optimum contrast, the mark depth is typically in the range of approximately 10 to 20 µm, dependent upon the wire type.

We also know that the contrast varies as a function of the applied laser marking fluence and that there is a threshold for marking of about 0.1 J cm^{-2} above which the mark contrast rises until it saturates, at about 1 J cm^{-2}. Below the threshold fluence no marking of the wire is apparent. Obviously at the threshold fluence the depth of the mark will be infinitesimal. As the applied fluence increases the mark depth will increase. From cross sectioning of wires we can measure mark depth, and as previously noted for systems run at their optimum value this mark depth is typically 10 to 20 µm.

Clearly, the "bottom" of the mark corresponds to the point at which the laser beam, as it passes through the wire insulating material, is attenuated from its initial incident fluence at the surface, equivalent to I_0 in Equation 1, down to the threshold fluence below which no marking occurs. Hence, from measurements of the depth of laser marks, combined with knowledge of the incident fluence and the threshold fluence at which the mark cuts off, which we call here I_c, we can calculate the absorption coefficients for the wire insulations from:

$$I_c = I_0 e^{-KX_c} \qquad \text{Equation 2}$$

Where,

I_0 = the incident laser fluence ,
X_c = the depth of the mark ,
I_c = the fluence at the mark cut off point X_c, (i.e. this is the threshold marking fluence).

A previous Spectrum report [3] undertook detailed studies of the mark depth of UV laser marked wires processed with a frequency tripled Nd:YAG laser (CAPRIS 50) and an excimer laser (CAPRIS 100). Two key wire types were investigated: Boeing BMS 13-48 Revision G, cross linked ETFE solid extruded wire, manufactured by Judd wire; this is equivalent to the type of insulation used on MIL spec' wires to MIL-W-22759/32 through 46. Additionally, Boeing BMS 13-60 Revision D, PTFE tape wrapped hybrid wire, manufactured by Tensolite Company; this is equivalent to MIL-W-22759/80 thro' 92.

Importantly, the depth of the UV laser marks on these wire types was found to be independent of the laser used within the accuracy with which mark depth could be measured. The mark depth for the two wires types were as follows:

BMS 13-48 18.5 $\pm$ 1µm
BMS 13-60 7.5 $\pm$ 1 µm

From this information and knowing the laser marking fluence at the wire surface of 1 J cm^{-2}, and taking the threshold marking fluence as 0.1 J cm^{-2} we can calculate how the marking depth varies as a function of the incident laser marking fluence. Two graphs are attached to illustrate this(see Figures 1 and 2) for Boeing BMS 13-48 and 13-60 wires respectively. In each case the mark depth starts at 0 at the threshold marking fluence, increasing rapidly, following a natural logarithmic curve, passing through the relevant mark depth for each wire type at 1 J cm^{-2}.

It is important to note that these results are not specific to particular equipment, they are a function only of the incident laser fluence and the materials concerned.

A study of these graphs provides some useful pointers as follows:

1. As noted above, the mark depth is essentially the same with the frequency tripled Nd:YAG and excimer lasers, these operate at wavelengths of 355 and 308 nm respectively. Clearly therefore, the

absorption coefficient of these insulating materials does not vary significantly between these two wavelengths.

2. After the initial increase in the depth of the mark, the curves roll over following the logarithmic curve. Two points are relevant:

   Firstly, consideration of the graphs shows that at the standard operating fluence of CAPRIS wire markers a variation of e.g. +/- 10% on the marking fluence causes a very minor variation in the depth of the mark, that is the mark depth is essentially independent of anything other than gross variations in the laser marking fluence.

   Secondly, taking BMS 13-48 as an example, to approximately double the depth of laser marking from e.g. 18 µm to 35 µm would require the laser fluence to be increased at the wire surface from 1 J cm^{-2} to 7.8 J cm^{-2}. In the case of CAPRIS wire markers this is not possible as the maximum theoretical fluence is of the order of 2 J cm^{-2} for CAPRIS 100 and 3 J cm^{-2} for the CAPRIS 50.

   Similarly, one can calculate the fluence required to increase the mark depth on the BMS 13-60 sample to 35 µm; in this case this would require the fluence at the wire surface to increase to 4,640 J cm^{-2} !

   This clearly underlines that the key factor controlling the depth of the laser mark is in fact the absorption coefficient i.e. it is principally material dependent not equipment dependent.

3. Given that it takes a substantial change in the laser marking fluence to achieve any significant change in the depth of the mark, provided the initial fluence is away from the threshold fluence value, we can glean another piece of useful information from the depth of the mark.

   As noted in No. 2 above, minor variations in marking fluence will not cause any significant change in the depth of the mark. Therefore for reasonable beam quality we can expect good uniformity of mark depth. From an inspection of cross-sectioned ETFE wire samples, if there were any gross variation in laser beam intensity, i.e. due to hot spots within the laser beam, these should be apparent as variations in mark depth. This is not the case, indicating that Spectrum wire markers provide good beam uniformity.

Having established that the key parameter that controls the depth of the laser mark in wire insulations is in fact the absorption coefficient of the insulating material, we may now consider how that may vary.

It has been noted that mark contrast varies with the materials being marked. This can be correlated with variation in the absorption of the laser beam by the material. Taking BMS 13-48, again, as an example, absorption of the laser beam here occurs through absorption in the base polymer as well as by pigments incorporated in the polymer. Clearly, different wire manufacturers procure their materials from various sources and formulate their products in different ways and to different compositions. So that, although two wires may be qualified to the same MIL spec., it is highly unlikely that they will have the same formulation and composition. Given that the absorption coefficient depends critically upon the formulation and composition, it is clear that this is likely to vary from one wire vendor to another, and possibly even between batches from one wire vendor.

A tangible result stemming from such variations is in the optical opacity of the wire insulation. It is readily observable that ETFE wires, both cross linked and non-cross linked, from different wire vendors have different opacities; i.e. they contain different pigment content with the net result that to the eye some appear milky and translucent while others appear highly opaque.

Although no tests have been undertaken to ascertain variation in mark depth with similar wire types from different vendors, it is to be expected that such variations will occur.

CONCLUSION

Absorption of laser beams used for marking of aerospace wires should obey Lambert's Law. This indicates that the laser beam will be attenuated exponentially as it passes through the wire insulation. Using Lambert's Law and information derived from measurement of the depth of laser marks and the fluence of the incident laser beam, along with fluence/contrast data, it is possible to derive curves which show the depth of the laser mark as a function of fluence. Consideration of Lambert's Law and these curves indicate that away from the threshold fluence value, the depth of the laser mark will assymptotically approach a maximum value.

Samples of marked aerospace wire have been evaluated. The typical mark depth on BMS 13-48 is 18.5 $\pm$ 1 µm, while for BMS 13-60 it is 7.5 $\pm$ 1µm, for a standard marking fluence of 1 J cm^{-2}. Studies show that the absorption coefficient for the materials involved does not vary significantly between the two main laser wavelengths used for UV wire marking i.e. 308 and 355 nm. The main parameter that controls the attenuation of the laser beam and sets the depth of the mark is the absorption coefficient of the material, and mark depth does not vary strongly with variations in laser marking fluence.

It is concluded that observed variations in laser mark depth are most likely to be connected with variation in material properties, probably related to changes in the absorption coefficient of the specific materials concerned as a result of differences in wire vendors formulations and compositions. It is probable that, within the limits observed, variations in mark depth are unlikely to affect the performance of the wire.

REFERENCES

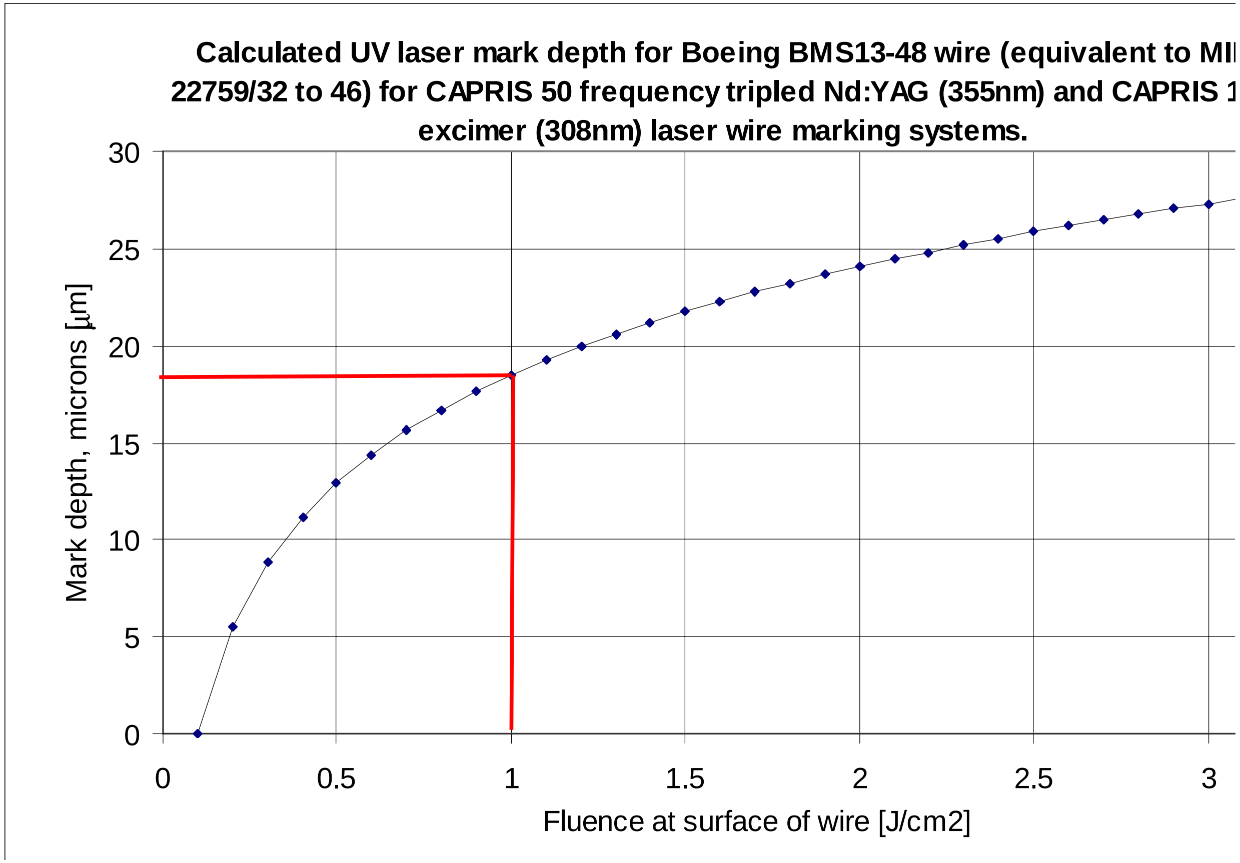
1. See, for instance, Handbook of Chemistry and Physics - definitions and formulas. Published by CRC Press, Cleveland, Ohio.

2. ‘Excimer Laser Printing of Aircraft Cables’. S. W. Williams and P. C. Morgan. International Congress on Applications of Lasers and Electro-Optics, 1989.

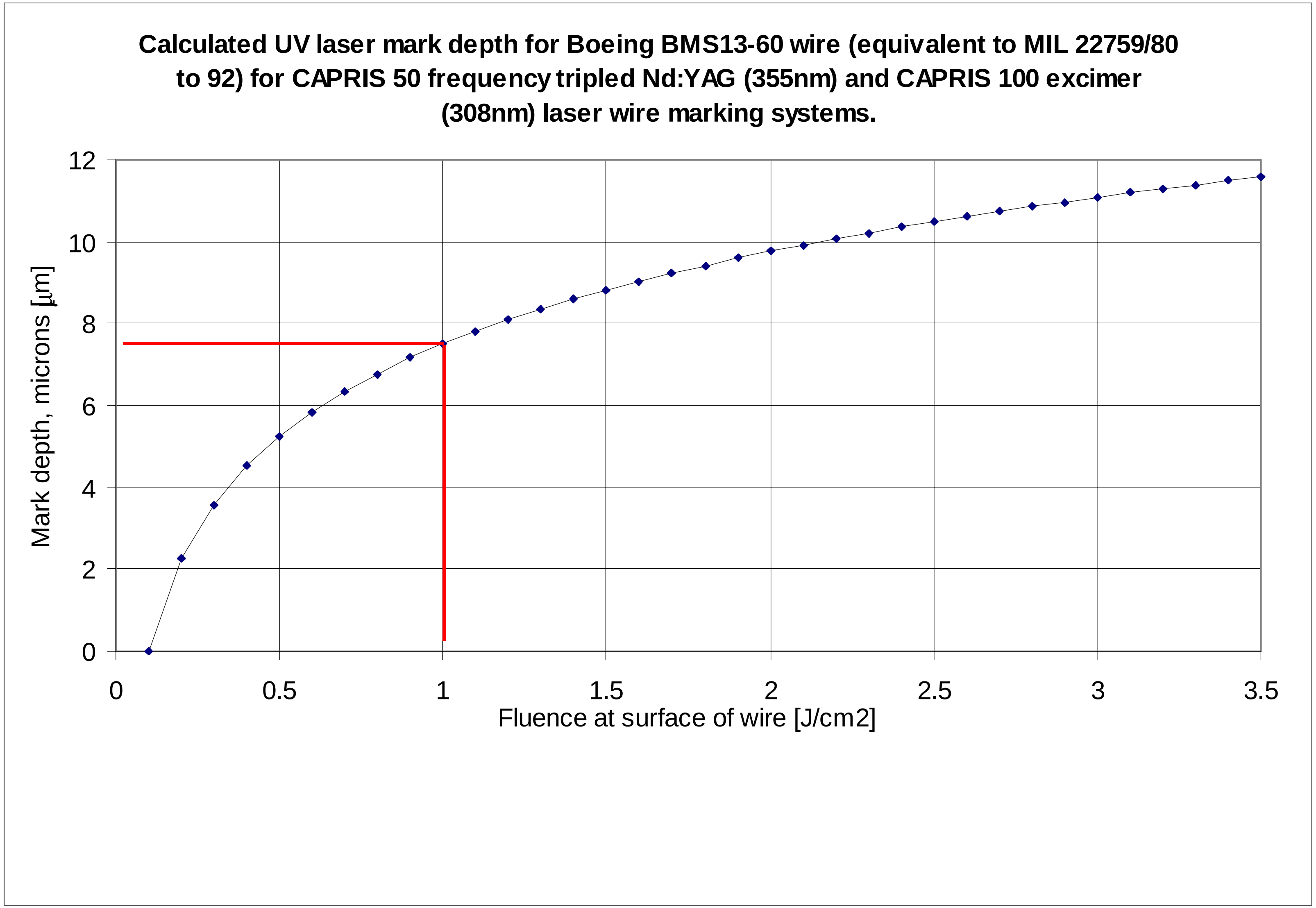
3. ‘Further Studies of UV Laser Marking on Aircraft Wires’. C. Higgitt. Spectrum Technologies report Ref. STL0008, 25th November, 1997.

APPENDIX 1

FIGURES
Sheet 1 Chart A



FIGURES
Sheet 2 Chart B1



UNRESTRICTED