Large Area Isothermic Plasma for Large Diameter and Specialty Fiber Splicing

Robert Wiley and Brett Clark
3SAE Technologies, Inc. 318 Seaboard lane, Suite 212, Franklin TN, 37067
rwiley@3sae.com bclark@3sae.com

Abstract: A device is presented that creates a large area plasma for splicing optical fibers. The isothermic thermal properties of the plasma facilitate splicing fibers >1mm in diameter without sacrificing splicing performance of standard fibers.

OCIS code: (000.2170) Equipment and techniques (000.6850) Thermodynamics

1. Introduction

In a standard fusion splicer, the plasma generated by a glow discharge between two electrodes is spatially inadequate to encompass fibers larger than 600 microns. The addition of an orthogonally placed third electrode and a three phase driving circuit expands the relatively single dimensional line of plasma into a triangular two dimensional plane. The area that is largely isothermic in a three phase arc can be as much as 100 times larger than a two electrode system and the power density can be adjusted to achieve fiber temperatures from less than 100ºC to greater than 3000ºC. This paper will disclose the thermal properties of a three phase arc and explore how these properties affect fusion splicing.

2. Three phase arc generation

To create a three phase arc, three electrodes are orientated in a "T" or "Y" configuration so that the tips form an equilateral triangle. The electrode spacing can vary depending on the size of the plasma field required for a given application. Each electrode is independently modulated 120 degrees out of phase relative to the other electrodes with a high voltage high frequency (~30kHz) source. Figure 1 illustrates an idealized drive waveform.

In standard fusion splicing the fibers are placed directly between the two electrodes and are heated by [1-3]:

- Impact from ions accelerated by the applied e-fields
- Hot neutral gas molecules resulting from ion recombination
- Ohmic heating from currents passing though the fiber in molten regions where the conductivity is high
- Dielectric (dipole rotation) heating within the fiber (low for pure silica – dopant dependent)
- Radiant heating from the hot ionization and recombination regions
- Convective heating from neutral gas (air) heated by all of the above

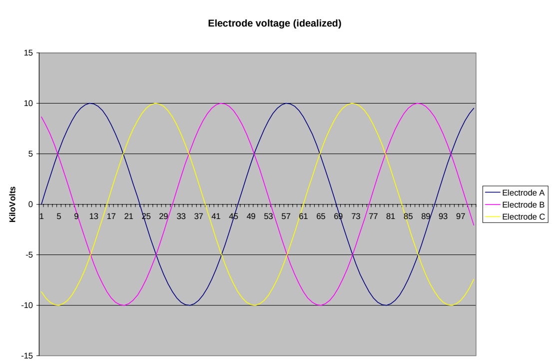


Figure 1: Drive waveform phase relationship

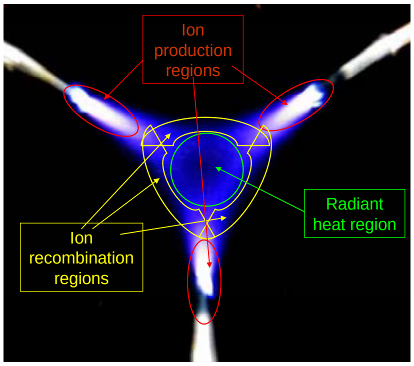


Figure 2: Three phase arc regions

Conversely, only radiation and convection are effective means of heat transfer when using a three phase arc because the fibers are located outside the direct ion pathways (see fig 2). The elimination of the nonlinear heat transfer variables allows for a significantly more stable thermal profile than is otherwise possible.

3. Thermal profile testing

A three-phase "Y" configuration was adjusted to provide a tip-to-tip spacing of 3.8mm. A 2-axis positioning stage provided a movable fixture to accept one end of a standard 62.5/125µm multimode fiber (approximately 2m length) and locate it within the plane of the electrical discharge. The other end of the MM fiber was attached to an IR-sensitive photometer. This arrangement served as a micropositionable pyrometer to determine the fiber temperature reached at different points within the plane of the discharge. The fiber pyrometer was previously calibrated to a K-type thermocouple in a lab oven. Temperatures beyond the limits of the oven/thermocouple were extrapolated.

The arc was discharged in 2 second increments with a total input power of 25.2W. The working end of the fiber was renewed whenever it became visibly deformed. The pyrometer measurement was repeated in a 250µm grid to map the thermal profile of the entire discharge area. Results are shown in Figures 3 and 4.

An initial hypothesis held that the edges of the triangular area (in the path of the visible discharge) should be substantially hotter than the center region. It was found however that a roughly triangular area, occupying most of the inter-electrode region, was essentially isothermal, with a sharp drop-off in temperature at the edges. The average fiber temperature reached within the isothermal region was 1660°C (a typical temperature for a fusion splicing operation), with a standard deviation of 34°C**.** By way of comparison, in a typical two-electrode system, an error in fiber placement of only 125µm from the nominal location produces a temperature drop of more than 100°C.

The test was repeated several times at higher and lower levels of input power. Results were comparable to the case for 25.2W. The small distinct irregularity, visible at the upper right of the thermal diagram, was seen at several power levels. Reversing the phase sequence of the drive waveform caused the phenomenon to move to the left upper electrode. The mechanism causing this effect has not been determined.

With an input power of 100W, the test fixture was able to fuse 1mm drawn quartz rod. A 3mm rod could not be fused at this power level, but clearly illustrated the capability of the three-phase device to uniformly surround and heat even very large fibers (see fig 5).

An additional test was performed to determine repeatability of the fiber temperatures reached during repeated arc discharges (see fig 6). The fiber was located 0.5mm off-center, in order to detect any instability on the edge of the isothermal region. The average observed peak temperature was 1850°C, with a standard deviation of only 16°C.

The thermal stability and dynamic range of the plasma can be further improved by eliminating or reducing convection as a heat transfer mechanism. The slight turbulence generated by convection can be reduced or eliminated by generating the plasma field in a partial or complete vacuum, leaving radiation (a highly linear component) as the primary thermal driver.

Figure 3: Three phase arc thermal profile A

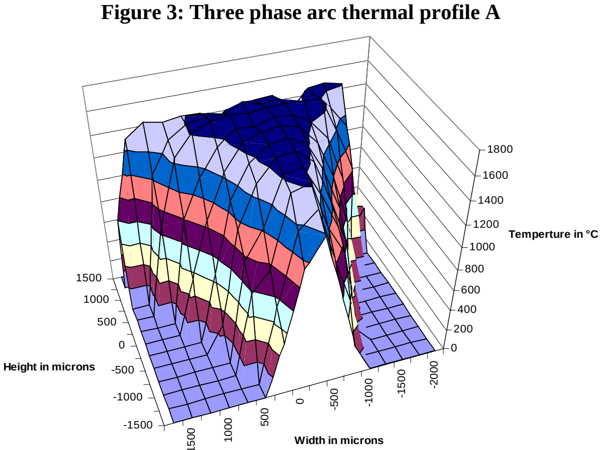
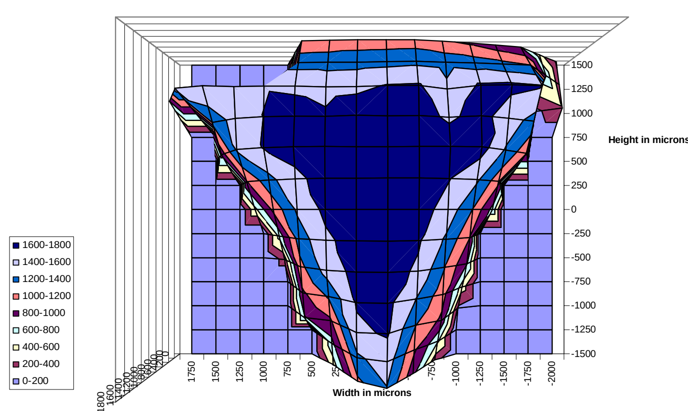


Figure 4: Three phase arc thermal profile B



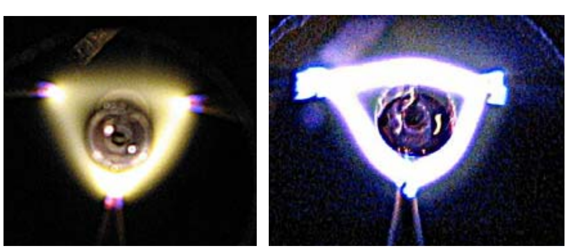


Figure 5: Three phase arc heating 3mm diameter glass rod

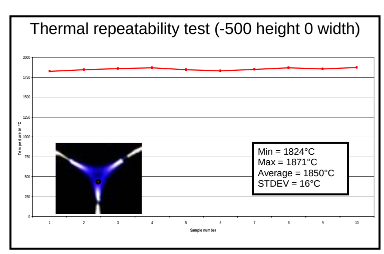


Figure 6: Three phase arc repeatability

4. Splicing and fiber processing

When a three phase arc is utilized in the arena of fiber splicing or other types of thermal fiber processing, the two most prevalent properties that need to be studied are mechanical tensile strength and induced optical loss. In fusion splicing the post splice mechanical tensile strength (assuming virgin pre-arc mechanical integrity) of the fiber is primarily dictated by the concentration of thermal, elastic and viscous stresses causing surface irregularities in the microstructure of the glass. These surface irregularities are also known as micro-cracks. Figure 7 is a table of the primary stress contributors and the effects of utilizing a three phase arc.

Figure 7: Splice tensile strength analysis

Stress contributor	Underlying cause	Effect of three phase arc
Circumferential thermal uniformity	Dictated by the centering of the fiber within the plasma and the size of the plasma field.	Circumferential thermal uniformity is substantially improved since the plasma is at least 1 order of magnitude larger and largely isothermal.
Slope and stability of the axial plasma thermal profile	Dictated by the power density of the plasma, electrode condition, and air flow due to convection and other means.	The electrode condition is less relevant because the fiber is not located directly between the electrodes in the primary ion pathways. The plasma stability and electrode condition effects can be further reduced by removing most or all of the gases present (vacuum) which also reduces electrode degradation.
Plasma and/or fiber contamination	Negatively affected by contamination projected from the electrodes by electromagnetic fields during arc ignition [3].	The fiber and plasma are less affected by contamination since the fiber is not located directly between the electrodes in the primary ion pathways.
Rate of heating	Primarily dictated by the plasma power density and the number and effectiveness of all of the thermal transfer mechanisms.	The rate of heating is slowed due to a reduction in thermal transfer mechanisms and can be further reduced by leveraging the extended dynamic range and slowly increasing the power density of the plasma at the beginning of the splice.
Rate of cooling	Typically dictated only by the thermal mass of the fiber.	The rate of cooling can be reduced by decreasing the power density of the plasma at the end of the splice.
Mechanical stability of fiber	Negatively affected by contamination projected from the electrodes by electromagnetic fields during arc ignition and convection [3].	Mechanical stability is less affected by contamination impacts since the fiber is not located directly between the electrodes in the primary ion pathways.

Although testing is ongoing, preliminary data shows that moderate mechanical splice strength gains are achievable by leveraging the three phase plasma attributes listed above in fig 7. Additional splice strength gains are possible since the three phase plasma can also serve as a highly stable heat source to perform a post splice annealing (flame polish) of the splice region.

The second splice property being studied is optical loss. Preliminary data shows that the three phase system produces splice loss comparable with standard fusion splicing for most fiber types. Some fiber splice combinations can leverage the improved stability and extended dynamic range to produce core diffusion pre or post splice. Achieving proper diffusion of the cores can often significantly lower the optical loss of fibers with mismatched mode field diameters. By altering the phase relationship of the electrodes in a three electrode system from 120 degrees to 180 degrees out of phase, a plasma field is generated that is largely the same as a standard two electrode splicer. Therefore the splicer can be easily switched between two and three electrode splicing depending on the application.

5. Conclusion

Analysis and test data show that a three phase arc provides thermal stability and a dynamic range outside the capabilities of preexisting arc technologies. The large isothermic plasma field allows for production proven arc technology to properly enter the LDF splicing arena with capabilities beyond 2mm. Due to its thermal attributes the three phase plasma is likely to be ideally suited for many other thermal fiber processing applications such as polyimide removal, grating treatment, tapering, annealing, and diffusion [4].

References

1. Walter Frost, Paul Ruffin, and R.E. Turner, "Analytical model of fiber arc fusion splicing" AIAA/ASME (1990)
2. K Binder, J Horbach, H Knoth, and P Pfleiderer, "Computer simulation of molten silica and related glass forming fluids: recent progress" Journal of Physics: Condensed matter (2007)
3. A Krinberg "Electrical conductivity of air in the presence of an impurity" Zhurnal prikladnoi mekhaniki I tekhnicheskoi fiziki No. 1, pp. 76-82, (1965)
4. David Fairbanks "Thermal visco-elastic simulation model for tapering of laser-heated fused silica fiber" SPIE Vol. 1580 Fiber optic components and reliability (1991)