BIFOCAL MIRROR TECHNOLOGY FOR LASER CUTTING OF STAINLESS STEEL

TECNOLOGIA DE ESPELHO BIFOCAL PARA CORTE A LASER DE AÇO INOXIDÁVEL

Charles Caristan (Air Liquide Industrial US) & JoseAntonio Cunha (Air Liquide Brazil)

Abstract:

Dual focus technique using Bifocal lenses consumables is being practiced successfully in laser cutting stainless steel fabrication shops throughout the world and yields double digit increase in average production cutting speed. With the market shift towards higher output power lasers and more stainless steel processing, new dual focus solutions using Bifocal mirrors or alternative optics' materials have been developed. Following successful demonstrations with the newest Bifocal mirror technology, metal fabrication shops enjoy spectacular productivity and quality incremental gains in production, from their flat bed laser cutting machines. A case study of a high speed laser blanking project illustrates an example of industrial needs for such solutions.

Resumo:

A técnica de duplo foco usando lentes consumíveis bifocais está sendo praticada com sucesso em locais onde se executa a fabricação de estruturas de aço inoxidável por corte a laser. Esta prática tem sido utilizada em todo o mundo e leva a aumentos de rendimentos de dois dígitos na produção média de velocidade de corte. Com a mudança do mercado para lasers de maior potência e processamento de mais de aço inoxidável, novas soluções de foco duplo usando espelhos de ótica bifocal ou materiais alternativos têm sido desenvolvidos. Após as manifestações de sucesso com a tecnologia mais recente de espelho bifocal, os locais de fabricação de estruturas metálicas passam a desfrutar de produtividade e qualidade espetacular, ganhos incrementais na produção, desde o laser de foco simples como equipamento de corte. Um estudo de caso de um laser de alta velocidade para obtenção de "blanks" ilustra um exemplo de necessidades industriais para essas soluções.

Dual Focus Principle

The traditional BIFOCAL technology includes a lens with dual-focusing capabilities, whose ability to increase laser-cutting speed while improving efficiency has peaked the interest of standard focusing lens users. Unlike the single-focal point lens, a dual-focus lens has one focal point that is positioned preferably near the bottom of the material and a second focal point that is focused near the top surface [1]. The second focal point means that a high concentration of laser power density is directed towards the bottom of the workpiece surface, which in effect reduces dross formation and refines the cut, thus reducing the need for edge clean up after laser-cutting (Figure 1). The other focal point generates another high power density concentration near the top surface of the workpiece, thus maintaining high cutting speeds. The inner portion of the laser beam propagate through the focusing optic within a diameter 2h on the lens as if through a lens of focal length $f + df$; meanwhile, the outer portion of the same laser beam propagates outside of diameter 2h as if through a lens of focal length f.

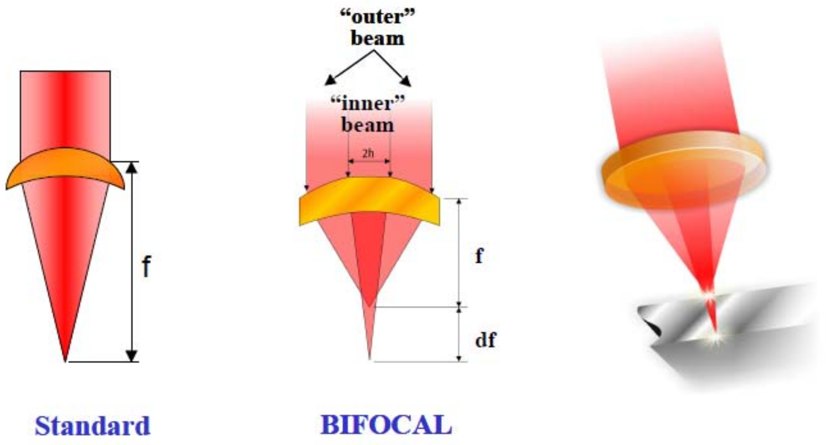
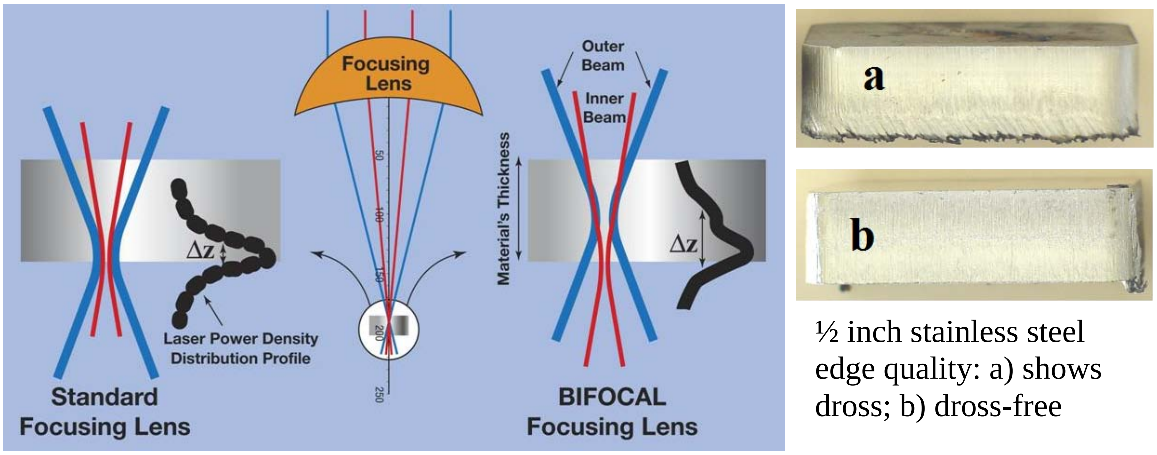


Figure 1. Two focus points are better than one.

When cutting with a standard lens under nitrogen or air assist gas, the focus point is preferably sunk underneath the material's surface (Fig. 2). The deeper it is sunk in thick gage material, the more defocused it is at the top surface of the material, and thus the slower the speed becomes. BIFOCAL technology yields a more efficient distribution of focused beam power density across the thickness of the material. Lower gas consumption rate and higher cutting speed at better or equal or equal edge quality, are a direct result of this property.



½ inch stainless steel edge quality: a) shows dross; b) dross-free

Figure 2. For laser-cutting with high pressure nitrogen assist gas, i.e. cutting of stainless steel and aluminum, the hotter focus point is sunk towards the bottom surface of the sheet, i.e. workpiece, to reduce dross formation. As a consequence, the reduced average power density of the focused beam spot at the top surface of the sheet forces a reduction in cutting speed. With Bifocal technology, the inner beam provides one hot focus point while the focused beam spot at the top surface is much smaller with higher average power density, thus enabling faster cutting speeds. The power density distribution profile along the pointing direction of the laser beam yields much wider focus position tolerance Δz with Bifocal. On the right side, ½ inch stainless steel edge quality: a) shows dross. By adjusting speed and focus position, dross can be eliminated.

The market leads a technology trend towards “extreme power and extreme speed”

The park of high power lasers systems sold is shifting towards higher power lasers; the median output power of CO2 laser systems sold for metal cutting applications is surpassing 3.5kW. Almost all major laser cutting machines builders have developed and launched new commercial products with 4kW, 5kW and 6kW power. The latest developments announce the imminence of commercial 8kW CO2 laser cutting systems. Meanwhile, niche initiatives such as the high speed laser blanking propose to transform automobile sheet metal cutting from the age of press and die blanking tools to the modern and lean age with high speed laser cutting, and also call for higher power and higher speed [2, 6]. This race towards “Extreme Power and Extreme Speed” is not without challenge with the mechanical, electrical and optical design of the laser systems. In response to this challenge, Air Liquide Industrial US has developed a dual focus option utilizing Bifocal mirrors and has demonstrated the dual focus effect at high power with a new zinc sulfide material for focusing lens for fiber laser types applications.

Bifocal Mirror versus Bifocal Lens

Dual Focus effect can be obtained by either combination: [standard mirror + Bifocal lens] or [Bifocal mirror + standard lens] (Figure 3). Bifocal mirrors insure greater stability of higher performance at higher power (Figure 4), as they are much less subject to thermal lensing because they are more efficiently direct water-cooled and cost less to maintain and replace than Bifocal lenses. A mirror can last several years whereas lenses must be replaced at least monthly, let alone cleaned sometimes daily. As a consequence, optics’ cost is more advantageous to end-users with the Bifocal mirror alternative.

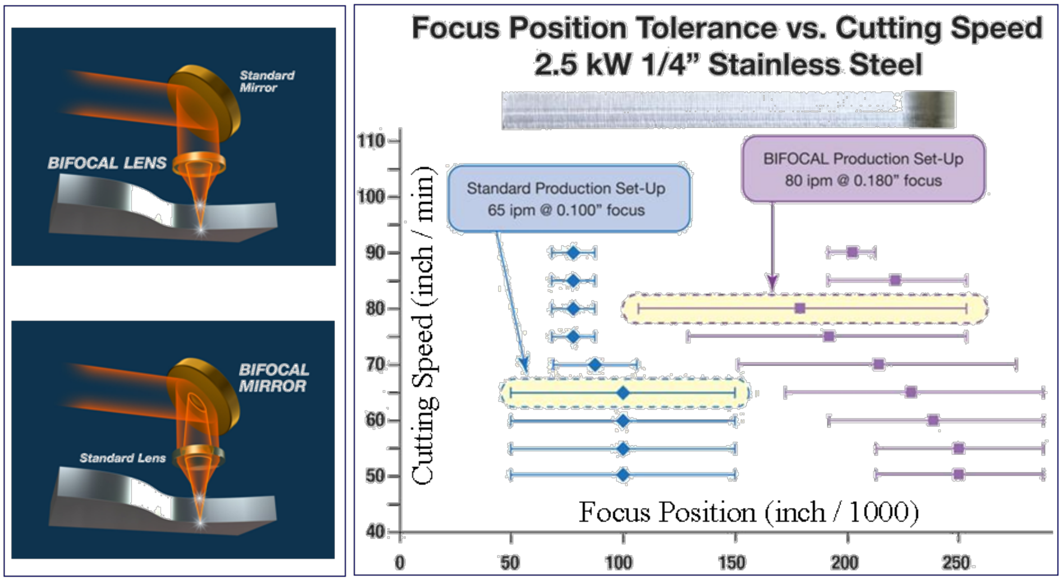


Figure 3 Dual focus effect can be achieved with combination [Bifocal mirror + standard lens] or [standard mirror + Bifocal lens].

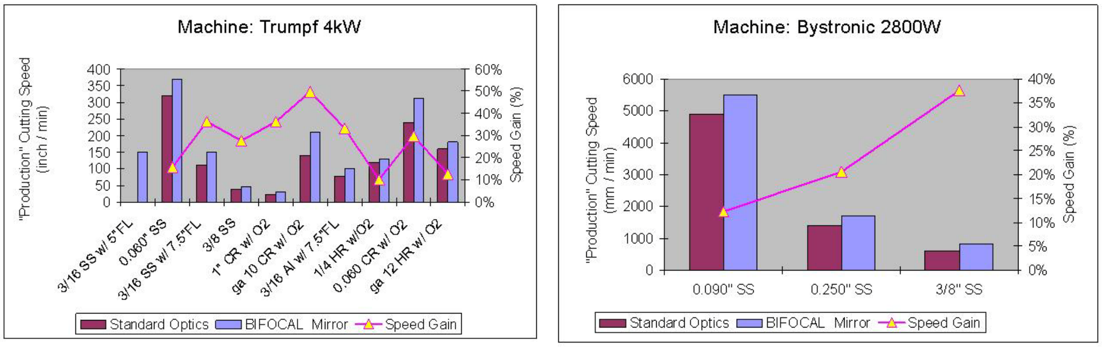


Figure 4. Examples of field results laser-cutting with Bifocal Mirrors: the best results are achieved for any laser-cutting under nitrogen assist gas, i.e. when cutting stainless (SS) steel and aluminum (Al) for the most part. Cutting of cold rolled steel (CR) with O2 assist gas produces the least speed increase.

Transmissive optics for high power fiber-lasers

For metal fabrication, solid state lasers such as fiber lasers emitting at multi-kilowatt power levels compete against the established CO2 laser technology by simplifying the beam delivery system's set-up and maintenance and by delivering quality processing performances with widely superior energy efficiency and smaller footprint. Though one trend is common to all laser technologies: it is the race for extreme-power and extreme-speed. In this high power arena, new comers such as fiber lasers and disk lasers reach 15 kW in industrial applications; sources at 30kW and up to 50kW have even been reported recently [3]. However, when processing with fiber lasers above 2kW of output power, one can observe shifts in focus position of several millimeters between cold mode and hot mode operations. Cold mode operation can be described as the optical elements having been exposed to the laser radiation for less than 3 minutes. During laser exposure, the optics along with their mounts and assembly structure all receive heat input from the laser beam as it gets absorbed and also scatters while propagating through the beam delivery system towards the workpiece (Figure 5). Such heat input needs to be kept under control to the best extent possible, and otherwise managed adequately to minimize consequent heat induced distortions in beam alignment, beam's spot dimensions on the workpiece and positions of focus or foci. This is the reason why most beam delivery systems at high laser power require cooling most often achieved through direct or indirect water cooling.

In order to reduce and control thermal lensing, alternative choice of optic's materials with different properties can be considered. Whereas since early on, fused silica has been the base material substrate of choice for laser processing optics in the 1 µm wavelength region, other materials such as zinc sulfide (ZnS) make a strong case as a substitute. For 1 µm wavelength, Table 1 compares mechanical, thermal and optical properties for boro-silicate glass (BK7), fused silica, multi-spectral zinc sulfide (MS ZnS) and zinc selenide (ZnSe). Because of their lower bulk absorption at the 1 µm wavelength, ZnS and fused silica are preferred materials.

Table 1: Properties of transmissive optics materials for 1µm wavelength laser light [7]. Compared to fused silica, multi spectral zinc sulfide (MS ZnS) has a superior thermal conductivity to avert steep temperature gradients; on the other hand it has significantly more scattering that require efficient cooling of the optics mount and assembly that absorb the scattered light.

		BK7	Fused Silica	MS ZnS	ZnSe
Mechanical Properties	Density (g/cm^3)	2.51	2.203	4.09	5.27
	Poisson's Ratio	0.208	0.17	0.27	0.28
	Hardness (Knoop)	610	500	150-165	105-120
	Rupture Modulus (dyne/cm^2)	1.65E+08	5.00E+09	6.90E+08	5.50E+08
	Young's Modulus (dyne/cm^2)	8.20E+11	7.30E+11	7.45E+11	6.72E+11
Thermal Properties	Linear Expansion Coef (x10^-6/°C)	7.1	0.55	6.5	7.57
	Specific Heat (J/g/°C)	0.858	0.703	0.527	0.356
	Thermal Conductivity (W/cm/°C)	0.0111	0.0138	0.272	0.18
Optical Properties	Scatter Coefficient at 1.06 µm (/cm)	ND	ND	< 3%	< 0.5%
	Scatter Coefficient at 0.6328 µm (/cm)	ND	ND	< 10%	< 3%
	Index of Refraction @ 1.06 µm	1.5066	1.4496	2.287	2.483
	Temp. Change of Refractive Index(x10^-6/°C) @ 1.06	1.2	11	42	70
	Bulk Absorption (/cm) @ 1.07 µm	~ 0.001	~ 0.0001	< 0.0005	< 0.001
	K-Values For Lenses Plano/Convex	0.07112	0.08994	0.02888	0.02849
	Positive Meniscus Lens	0.06573	0.07792	0.02051	0.01758
	Equi-Convex Lens	0.1029	0.11542	0.05494	0.05164

Another significant advantage of ZnS is its low hardness, enabling non-uniform curvature shapes such bifocal curvatures to be machined with diamond-turning machines (Figure 6). Because of its very high hardness, diamond-turning fused silica is not cost effective, making bifocal fused silica lens enormously costly.

Coil-fed Laser Blanking: Case Study

Whereas in the past century, advances in CO2 laser technology, have enabled nearly all low volume pre-production prototype blanking needs to be done by laser-cutting, when it comes to high volume production of blanks with configured contours directly from coils, almost 100% is to this day manufactured exclusively mechanically with press die-blanking [4,5]. Considering

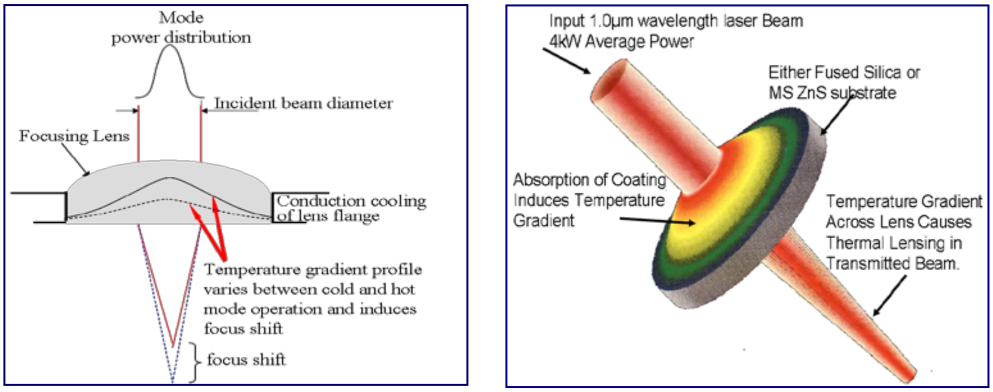


Figure 5: Variations of beam diameter, of mode power distribution and of temperature gradients in the optical element contribute to focus shift. The gradients of temperature with the nature of the substrate and of the coating for the optic. When combining the bulk absorption of coating and base material substrate at 1.07 µm wavelength, ‚typical ¼” thick fused silica and ZnS lenses have almost the same bulk absorptions.

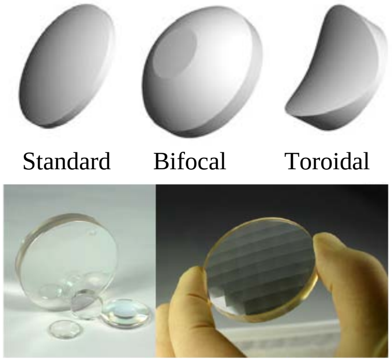
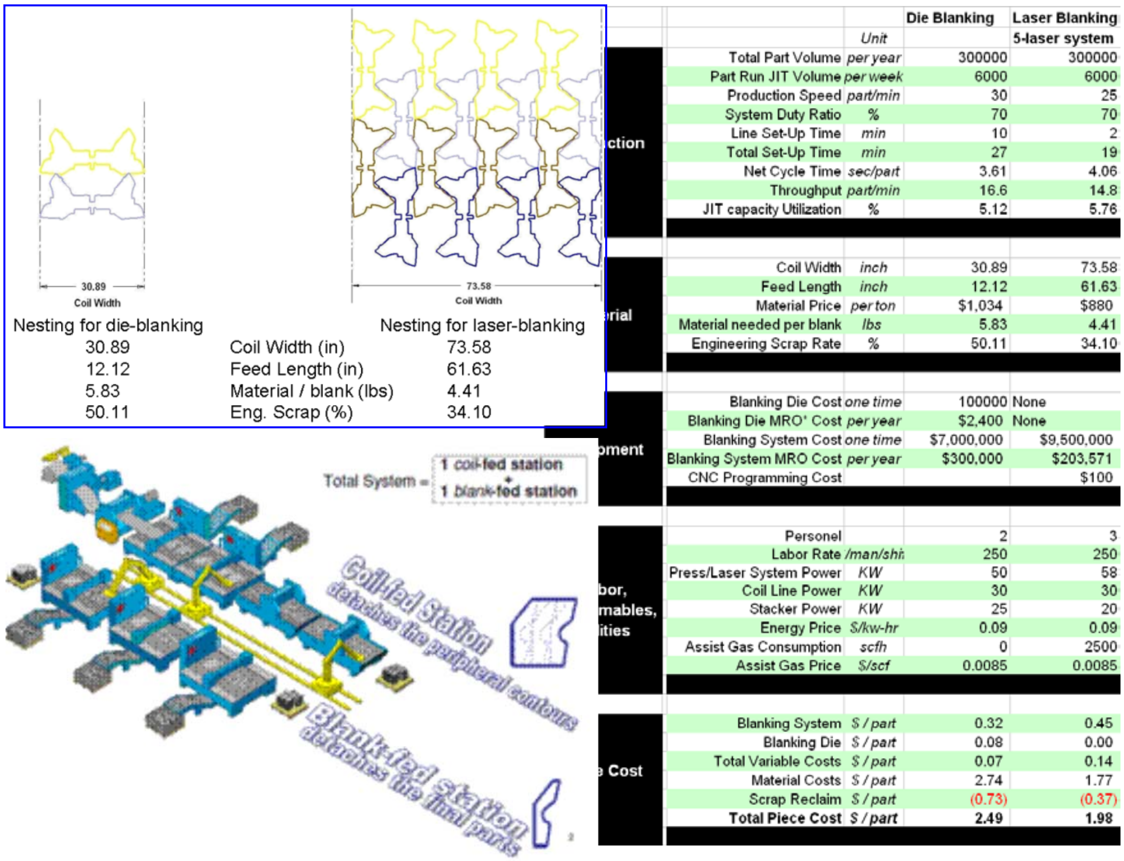


Figure 6: Diamond turning enables machining of surfaces with non-uniform curvatures for bifocal, toroidal, aspheric and even multi-faceted surface shaped optics in materials such as ZnSe for CO2 lasers and, ZnS for solid state lasers that emits at 1 μm wavelength (Photos courtesy of II-VI Inc.)

that mechanical cutting requires a dedicated high capital and maintenance costs blanking die to cut each part, the elimination of blanking dies by using flexible die-less laser cutting reduces capital investment costs. Another direct benefit of laser cutting is its ability to nest parts directly from coil in a way that result in substantially less engineering scrap rate, thus saving in materials. Today, advances with fiber laser cutting systems technologies, have created a long due viable alternative process for high volume production of developed blanks directly out of a coil, in order to address changes in a dynamically evolving market as well as new environmental and energy efficiency rules and requirements [2].

Some of the challenges for such integration of laser cutting in a high volume production environment are the high uptime and high throughput that the blanking industry has been accustomed to with high speed press blankers. Press blankers serving the automotive industry can have uptime above 95% availability and throughput surpassing 60 hits per minutes if the demand calls for it. The solution for this niche application is to use a low maintenance and set-up downtimes system such as fiber lasers which in contrast to CO2 lasers, require much fewer downtimes for beam delivery optics alignment and cleaning.

Moreover, fiber laser beams with their low wavelength and good focusability have cutting speeds that almost double those of CO2 lasers of comparable output power. Therefore when in the past, in order to rival the throughput of a press blanker, one might have needed 10 CO2 laser cutting machines, today only 5 fiber laser cutting machines suffice (Fig 7). As a point of reference, a rectilinear cut in 1mm thick galvanized steel can be performed at 60 m / min with a 5kW fiber laser, compared with 30 m/min with a 5kW CO2 laser. Figure 7 illustrates a comparison of nesting between die-blanking and laser blanking. The corresponding table below showcases the favorable impacts on manufacturing, the environment and profitability of switching from die-blanking to laser blanking.



Nesting for die-blanking		Nesting for laser-blanking
30.89	Coil Width (in)	73.58
12.12	Feed Length (in)	61.63
5.83	Material / blank (lbs)	4.41
50.11	Eng. Scrap (%)	34.10

		Unit	Die Blanking	Laser Blanking 5-laser system
ction	Total Part Volume	*per year*	300000	300000
	Part Run JIT Volume	*per week*	6000	6000
	Production Speed	*part/min*	30	25
	System Duty Ratio	%	70	70
	Line Set-Up Time	*min*	10	2
	Total Set-Up Time	*min*	27	19
	Net Cycle Time	*sec/part*	3.61	4.06
	Throughput	*part/min*	16.6	14.8
	JIT capacity Utilization	%	5.12	5.76
rial	Coil Width	*inch*	30.89	73.58
	Feed Length	*inch*	12.12	61.63
	Material Price	*per ton*	$1,034	$880
	Material needed per blank	*lbs*	5.83	4.41
	Engineering Scrap Rate	%	50.11	34.10
pment	Blanking Die Cost	*one time*	100000	None
	Blanking Die MRO' Cost	*per year*	$2,400	None
	Blanking System Cost	*one time*	$7,000,000	$9,500,000
	Blanking System MRO Cost	*per year*	$300,000	$203,571
	CNC Programming Cost			$100
bor, mables, ities	Personel		2	3
	Labor Rate	*/man/shi*	250	250
	Press/Laser System Power	*KW*	50	58
	Coil Line Power	*KW*	30	30
	Stacker Power	*KW*	25	20
	Energy Price	*$/kw-hr*	0.09	0.09
	Assist Gas Consumption	*scfh*	0	2500
	Assist Gas Price	*$/scf*	0.0085	0.0085
e Cost	Blanking System	*$ / part*	0.32	0.45
	Blanking Die	*$ / part*	0.08	0.00
	Total Variable Costs	*$ / part*	0.07	0.14
	Material Costs	*$ / part*	2.74	1.77
	Scrap Reclaim	*$ / part*	(0.73)	(0.37)
	Total Piece Cost	***$ / part***	**2.49**	**1.98**

Figure 7: High speed blanker with 5 laser-cutting machines has throughput comparable to one press line Nesting for laser blanking can be done with large coil that do not need to be slit first and results in less engineering scrap. Laser blanking reduces piece costs, yields superior material utilization. It requires laser-cutting at extreme-speed extreme-power.

Conclusion

In the quest for extreme power extreme speed laser-cutting under high pressure nitrogen assist gas such as for cutting of stainless steel material, Bifocal technology is a method that not only enables higher processing speed, but also increases user-friendliness. This is beneficial for a solid repeatability and reproducibility requirement for acceptance at those extreme regimes to transform new manufacturing applications into true laserfacturing successes.

References

1. Charles Caristan, Viwek Vaidya, “Bifocal Mirror Technology for Laser Cutting”, *Advanced Laser Applications Conference 2007*, Boston, MA

2. Charles Caristan, Jay Finn, “Moving toward laser-blanking: say goodbye to hard tooling”, *The Fabricator Magazine* Nov. 2009

3. Bill Shiner, “Recent progress in high power fiber lasers”, *Automotive Laser Applications Workshop ALAW 2009* , Plymouth, MI May 12-14, 2009

4. Charles Caristan, Taylan Altan, Serhat Kaya, Design for Laserfacturing, *International Automotive Body Congress IABC 2007*, Novi, MI,

5. Charles Caristan, Gulam Mohiuddin, Mariana Forrest, Nasim Uddin, Product Design Guidelines for Manufacturing with Industrial Lasers, *International Automotive Body Congress IABC*, Novi, MI, 2006, pp 24-39

6. Charles L Caristan, “Laser Cutting Guide for Manufacturing”, *Society of Manufacturing Engineers, SME Book Publishing* 2003

7. “Properties of transmissive optics materials at 1µm wavelength, http://www.iiviinfrared.com/pdfs/II-VI_1um_materials.pdf

Corresponding author: José Antônio Cunha (JoseAntonio.Cunha@airliquide.com)