Laser Cutting of Nickel-based Feltmetal

An Honors Thesis

By

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Abstract

Laser cutting of metals has been an important application of high-power lasers for many years because of its advantages over traditional mechanical cutting. In industry today many different types of metals and alloys are being cut with laser beams. However, some materials emerge onto the industrial market that cannot fit into the traditional laser cutting methods, so new research has to be conducted to determine whether or not these materials can be cut effectively by the use of lasers. One of these unique materials being used in industry today is known as feltmetal. This material is constructed out of common alloys; however, it is manufactured to be very porous (20% dense). Feltmetal is used primarily as seal material inside turbine engines because of its abradable and temperature resistant qualities. This porous material is currently being cut by mechanical means. The results of this research demonstrate that the laser cutting of feltmetal can be a feasible and successful way to obtain high quality cuts.

1. Introduction

Feltmetal is a metal fiber material that is useful because of its resistance to extreme temperatures and its abradable qualities. It is constructed by vacuum-pressing a series of metal fibers, with lengths ninety times larger than their diameter, into a larger form. Feltmetal is primarily constructed out of super-alloy material because of their proven resistance to high temperatures. The abradable qualities of feltmetal come from the porous nature of the fibrous material. These two qualities make feltmetal a desirable material for use as seals in diesel turbine engines, because feltmetal seals can be placed on the stationary surface of the engine and the blade of the turbine can abrade away all the material it comes into contact with. Feltmetal seals are low-leakage and high strength seals that minimize wear on the moving blade.

Traditional methods of mechanically cutting are currently being applied to cutting feltmetal, however, the irregular structure of feltmetal results in tool wear and poor cut quality. New processing techniques need to be developed in order to make high quality, low cost cuts.

Laser processing of metals has become a common method to cut metal, and industry has recently started relying on laser technology to cut inhomogeneous materials such as alloys, concrete[1], paper, wood and plastics. Many models have been created to aid in the laser cutting of solid metals[2,3,4] and alloys, however less attention has been given to cutting porous materials.

The purpose of this research is to examine the possibility of cutting 4.2 mm thick feltmetal with the use of a continuous wave Nd:YAG laser. This study consists of many experiments that have been designed to analyze the effects that laser power, scanning velocity, assist gas pressure, gas nozzle distance, spot size, and focal plane location have on cut quality and kerf width. A desired cut must be a through cut with vertical cut walls and an absence of charring or glazing.

2. Experimental Studies

2.1 Analysis of Feltmetal

The feltmetal material used for this experiment is constructed from Hastelloy X fibers. Hastelloy X is a nickel-based super-alloy material. In addition to nickel, the super-alloy fibers also contain large percentages of Fe, Cr, and Mo as seen is Table I. The Hastelloy X fibers have a density of 8.22 g/cm^3 and a length that is 90 times greater than their diameter. When pressed into the porous feltmetal form, the substrate has a percent density of 21% (21% metal, 79% air). These mechanical properties allow the feltmetal to abrade when gouged or rubbed. The melting range of the substrate is 1200°C-1355°C, and can therefore withstand high temperature applications[5]. Feltmetal samples of thickness 4.2 +/- .5mm were used in this study.

2.2 Experimental Setup

Cutting was done with a Nd:YAG laser operating in the CW (continuous wave) mode. The maximum output of the laser at the substrate surface was 60 watts. The beam was reflected off of a 45° mirror to direct it downward to be focused onto the substrate by means of a converging lens. The lens used for this work was a plano-convex aspheric condenser lens constructed from B270 optical crown glass. The lens had a diameter of 25mm, an effective focal length of 17mm, and was oriented so the plane surface was closest to the substrate. The back focal length (plane surface of lens to focal plane) of the lens was 9.8mm. The focal spot had a radius of 84μm.

The rear portion of the substrate was attached to a moving stage, and the area to be cut was hanging over the edge so that bottom gas could be delivered. Because of power limitations from the laser, cuts were never made at velocities greater than 5mm/s.

High purity inert gas (argon) was used to shield the substrate from oxidation. The gas was delivered to both the top and bottom of the substrate from copper tubing (Fig. 1). The gas incident on the bottom surface had a nozzle diameter of 4.5mm and is positioned 15mm from the cut. Gas incident on the top surface is delivered at a distance of 15mm from the cut, however the nozzle shape varies from being circular (during cuts when the focal plan was on the top surface of the substrate) to being oval (when the focal plane was on the bottom surface) because of space limitations between the lens and the substrate.

In normal laser cutting applications, inert assist gas is used at high pressures to remove molten material[6]. However, the substrate used for this work is only 21% dense, so cutting requires melting and removing only 1/5 of the metal material that would be needed to cut solid metal of the same thickness. There is less molten material to remove from the kerf, so assist gas pressure in this application can be less than in normal metal cutting applications. Since removal of molten material can be done at lower pressures, a larger nozzle can be used in order to shield the substrate better from the oxidation that tends to occur in the heat-affected zone (HAZ) of the substrate. Optimal assist gas pressure was found to be 100 Kpa, and all measurements presented were taken under this gas condition.

2.3 Cutting Parameters

Multiple experiments were conducted in order to determine the effects of different process parameters on the cutting of the substrate. The independent process parameters are scanning velocity, spot size on surface, laser power density, and assist gas pressure (constant for all cuts). These parameters were analyzed to obtain a zone of optimal cut quality for the feltmetal. Cut quality is determined by the condition of the cut walls (straight or curved) and the charring effect on the surfaces and cut walls of the material.

The beam waist at the focal length has a constant radius of 84μm. Spot size changes by moving the lens (and the focal plane) on the z axis. All spot sizes will be the radius values of the laser beam taken at the top surface of the substrate and will be give in microns. A spot size of 84μm means the focal plane is coplanar with the top surface of the substrate. Positive spot sizes will represent the focal plane being below the top surface of the metal and negative spot sizes will represent the focal plane is above the top surface of the metal.

Power density (I) is defined as laser power (P) over unit area ($I=P/\pi r^2$), where r is the radius of the laser spot. Two cases for power density have to be examined. (1)Case A occurs when power density is changed by varying laser power while keeping the spot size constant. (2)Case B occurs when power density is changed by varying spot size while keeping the laser power constant. Power density on the substrate surface can be identical in two cuts, but the cutting beam (and therefore the cut quality) can have very different characteristics.

3. Results and Discussion

3.1 Cutting Energy

Laser cutting is possible when the optical energy of a beam is transferred into thermal energy that melts the substrate, and the melt is removed by an assist gas. An ideal cutting condition would use all of the laser energy produced (E_s) to aid in cutting, however in practice some energy is not used in the cut but rather lost through heat, light, and conduction. The energy required to make a cut of certain dimensions (E_m) is modeled[7] in Eq. 1.

$$E_m = dw_k l\rho\left[C_p\left(T_f - T_0\right) + L_m\right] \qquad (1)$$

The latent heat of fusion (L_m) of Feltmetal was approximated by a weighted average of the individual elements, and it is assumed that none of the material vaporizes but the material is heated completely to the melting temperature. The total volume of the kerf is given by dwl, and the volume of the metal melted in the cut is given by $dw_k l\rho$ where ρ is the product of the density of Hastelloy X and the percent density of the Feltmetal. C_p is the specific heat, T_o is initial temperature of the substrate, and T_f is the temperature of the material being removed.

A part of the excess energy (E_s-E_m) from the cut is transferred, by conduction, to the metal surrounding the cut to produce the heat-affected zone (HAZ)[8]. The HAZ can be identified by the blackening or charring which is evident on its surface (Fig. 2). During this experiment, multiple cuts were taken at varying cutting speeds and no gas was incident on the bottom surface of the substrate. The output power of the laser was kept constant. Cuts were analyzed to determine the energy utilized to make the cut, and a ratio of E_m/E_s was calculated. These values were plotted with bottom char width, and the results can be seen in Fig 3. If all energy is used by the cut ($Em/Es \rightarrow 1$), none can be transferred to the metal surrounding the cut and charring should not occur even in the absence of shielding gas. The most efficient cutting accomplished in this work was 60% laser energy absorbed by the cut, but the data trend suggests that a 100% efficient laser energy transfer would produce no charring.

3.2 Focal Position

Three different focal positions are examined to evaluate the cut quality. The cutting speed is held constant at 3 mm/s, and the gas parameters remain constant. Three series of cuts are taken at each focal position, and the laser power is varied from 48W to 60 W during each series. The spot radius and focal position parameters of five different cuts are shown in Table 2. The focal position near the bottom of the substrate could not be focused on the exact bottom surface because of the short focal length of the lens.

Examination of the cuts (Fig. 4) shows that the straightest cuts were made when the focal plane was positioned in the middle of the substrate, however, charring was very hard to stop and therefore the cuts made with the focal plane in the middle of the substrate were poor quality. A possible reason for this is that when the beam waist is placed 2.1mm below the top surface of the metal, the large spot size on the top surface transfers a large area of thermal energy into the feltmetal causing charring. Also, in this case there was not enough room below the lens holder to place the entire copper tube to deliver argon gas so the tube had to be flattened at the end. This could cause uneven shielding gas distribution which could promote charring. Using a converging lens with a longer focal length should solve this problem. When the focal plane was on the top surface of the substrate, a majority of the cut was straight, however the kerf width at the very top of the surface was sometimes disproportional to the average kerf when the laser was at high power and a "mouth" was formed at the top of the cut (Fig. 5). The power density at the cutting point is fully incident on the surface causing thermal energy to be transferred quickly in one localized spot. This intense heat at the beam waist could melt and eject large amounts of metal around the waist causing an unusually large kerf width ("mouth") at the top surface of the substrate. When the focal plane is below the top surface of the substrate, the top section of the feltmetal absorbs some energy before the beam reaches its smallest area, so "thermal blowout" does not occur at the beam waist. When the focal position is near the bottom of the material insufficient energy is available at the beam waist, and a cone shaped kerf always causes these cuts to be bad cuts.

3.3 Power Density

Two cases where cuts have identical power densities but different cut quality are examined. Power density is power over unit area, but this equation does not take into account the focal position. Three cuts were made during this experiment with constant cutting speed of 3 mm/s, constant gas pressure, and fixed focal position for each series of cuts. For each cut, data were taken with the output power of the laser at 48W, 54W and 60W. One cut was taken with the focal plane incident on the top surface of the substrate, one was taken with the focal plane at +.2mm, and one was taken at -.2mm. The latter two series of cuts had identical power densities and spot sizes for the three different power settings, however the cut quality and kerf width varied greatly between the two series of cuts. It can be seen in Fig. 6 that the cut taken with a spot size of radius 112μm and a focal plane (beam waist) located 0.2mm below the surface had much larger kerf width at the top surface than the cuts taken with a spot radius of 112μm and a focal plane 0.2mm above the surface. A possible explanation of this can be arrived at when considering the composition of the substrate. The fibrous nature of the substrate suggests that a focused beam of only 200μm in diameter will see little metal before it travels down into the top 200μm of the feltmetal. The energy incident at the beam waist of many sections of the cut will not have been dissipated by other metal fibers, so near the full energy of the beam waist is incident on the metal fiber at the focal plane even though it is below the top surface. The high energy density found just below the surface will transfer large amounts of heat energy, and will eject molten material from the top of the cut. By considering the geometry of the beam waist, it can be observed that the entire focal zone of the laser beam is incident on the substrate when the focal position is just below the top surface.

Much more heat can be transferred when the beam waist is below the surface than when the beam waist is incident on the top surface. In the latter situation, half of the focal zone of the beam (the most focused light) is occurring above the substrate. It has been shown in previous studies that deeper cuts can be made when the focal plane is just below the top surface of the material[9], however, data suggests that this intense thermal situation creates a large top kerf width in porous materials such as feltmetal.

3.3 Threshold Cutting Parameters

Experiments conducted with many different parameters were analyzed in order to find the optimal cutting parameters for use on the Hastelloy X feltmetal substrate used in this work. All of the data points were separated according to the cut quality. The three classifications are good cut, no cut (not a through cut), and charred cut. All of the data points were taken with constant argon gas pressure at the top and bottom surfaces of the substrate at fixed distances from the cut. The results of scanning velocity versus power density graph (with spot radius labeled for each point) are shown at Fig. 7. As the power density decreases from the high quality zone, complete cuts can not occur because there is not enough energy to make the cut, this makes up the left part of the no cut zone. Also, when velocity is increase for any power density, there is a threshold where the interaction time is no longer large enough to transfer enough energy to make a through cut, this condition constructs the top part of the no cut zone. When the power density is increased from the optimal cutting zone along any fixed velocity, a point is reached where the heat transfer in the HAZ becomes too large to be contained with the gas parameters that were used. This causes visible charring inside the cut, on the top surface of the cut, or on the bottom surface, and results in a bad cut. When the power density becomes too large for the cutting speed used, the charred cut zone occurs on the right hand side of the optimal cut zone as seen in Fig. 7. When the cutting speed is low, the laser-metal interaction time is high. This allows heat to propagate both longitudinally (in direction of cut) as well as laterally (perpendicular to cutting direction). Small power densities can cause very wide heat affected zones (HAZ) that cannot be completely covered by the shielding gas. This causes the char zone that is show at low velocities of Fig. 7.

Note the results found along the 3mm/s velocity axis. The cuts made with a power density of around 300 W/mm^2 could not complete the cut, but as the power density increase to 500 W/mm^2 the cuts were completed and had good quality. As the power density increased to around 1200 W/mm^2 both good and bad cuts were made at identical power densities. This effect happened because some of these cuts had identical laser power and spot radius, but the focal planes were interchanged (i.e. the location of the focal plane on one series of cuts was 0.2mm above the surface, while the focal position on the other series of cuts was 0.2mm below the surface. The cuts made with the focal plane just below the surface of the substrate were bad because the cut walls were not straight. As the power density increases out of the high quality cut zone, no good cuts are able to exist because charring occurs.

3.4 Cut Walls

During the laser cutting of solid metals, the molten material has to be ejected from the kerf, otherwise it will solitify inside the kerf. However, with the laser cutting of

Feltmetal, the porous quality of the substrate also allows molten material to be ejected from the kerf into the pores between fibers in the walls of the cut. This glazing effect can be seen under an optical microscope (Fig. 8). Two suggestions theorize why this occurs. First, glazing occurs when the interaction time between the laser and the metal is too high and enough energy is transferred via conduction to the walls of the substrate that they start to melt and gravity and surface tension pull the molten material into the pores. The second cause of glazing occurs at the focal plane of the laser. Walls of cuts made with the focal plane .2mm beneath the top surface show an area of concentrated glazing occurring around the focal plane. This suggests that the high thermal energy at that point is capable of ejecting material at velocities that cannot be removed by the gas pressure inside the kerf. Many cuts made in this study appear to have no glazing to the naked eye, but optical microscopy reveals slight traces of glazing. Glazing is still a problem in the laser cutting of feltmetal when compared to mechanical cutting, however glazing can be minimized when the laser power is used most efficiently ($E_m/E_s \rightarrow 1$) and the beam waist is placed outside or deep within the volume of the substrate.

4. Conclusions

Hastelloy X feltmetal samples of thickness 4.2 +/- 0.5mm have been successfully cut using a CW Nd:YAG laser of power 35W-60W at the surface of the substrate. The maximum effective cutting speed for the work presented was 5 mm/s. Cuts were made with the use of argon shielding gas, successful cuts had straight cut walls and were free from charring. The results obtained show that it is feasible to make good quality cuts of

Nickel-based feltmetal using a 60 Watt Nd:YAG laser beam. A chart of optimal cutting parameters (power density, spot size, gas pressure and velocity) has been established. This methodology can be applied to pulsed and higher-power lasers to test the cut quality of feltmetal at higher cutting speeds.

5. Acknowledgements

This work was done at the Center for Research and Education in Optics and Lasers (CREOL) in the University of Central Florida. One of the authors (B.B.) would like to thank NSF-sponsored Research Experience for Undergraduates-2001 (REU 2001) Program at CREOL, Dr. Kar, Islam Salama, and Yonggang Li. The authors greatly appreciate Harold Howe's assistance from Technetics Corporation, DeLand, Florida for supplying the feltmetal samples.

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List of Figures and Tables

FIGURE 6 *Kerf width for 3 different focal positions. Velocity (3 mm/s) and gas (100Kpa) are constant. Note different kerf width for same power density because of the different focal plane orientation (above or below surface)*

FIGURE 7 *Quality cutting zone chart. Numerical data in parenthesis refer to spot radius in microns and the plus and minus signs refer to the focal plane (beam waist) location as listed in Table 2. Dark circles are good cuts. Top and bottom boundaries on Quality cutting zone are estimated*

FIGURE 8 *Top (A) laser cut. Wall with glazing just below surface. Focal plane (+.2mm) , spot size (+112μm) laser power (60W). Bottom (B) is traditional cut wall without glazing. (100x Optical Microscope)*

TABLE I. Elemental composition of Hastelloy X.

Alloy Composition – by Weight Percent									
	Ni	Co	Cr	Mo	W	Fe	C	Si	Mn
Hastelloy X	Bal.	1.5	21.75	9.0	0.6	18.5	0.1	1.0	1.0

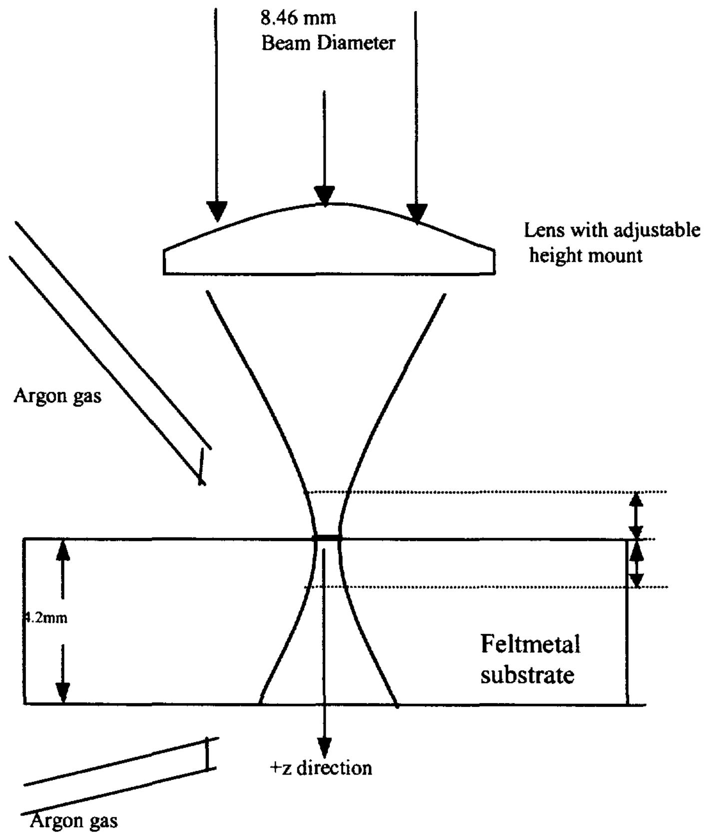

Fig. 1. Diagram of experimental setup. Spot size on surface of feltmetal changed by raising and lowering asphere lens.

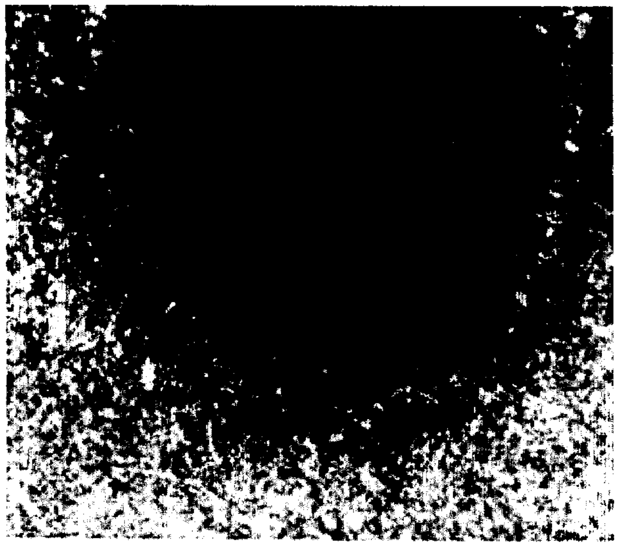

Fig 2. Charring evident at end of cut. Optical Microscope (50x). Focal Plane 2.1mm below top surface of substrate.

Bottom Char Width vs. Efficiency Ratio

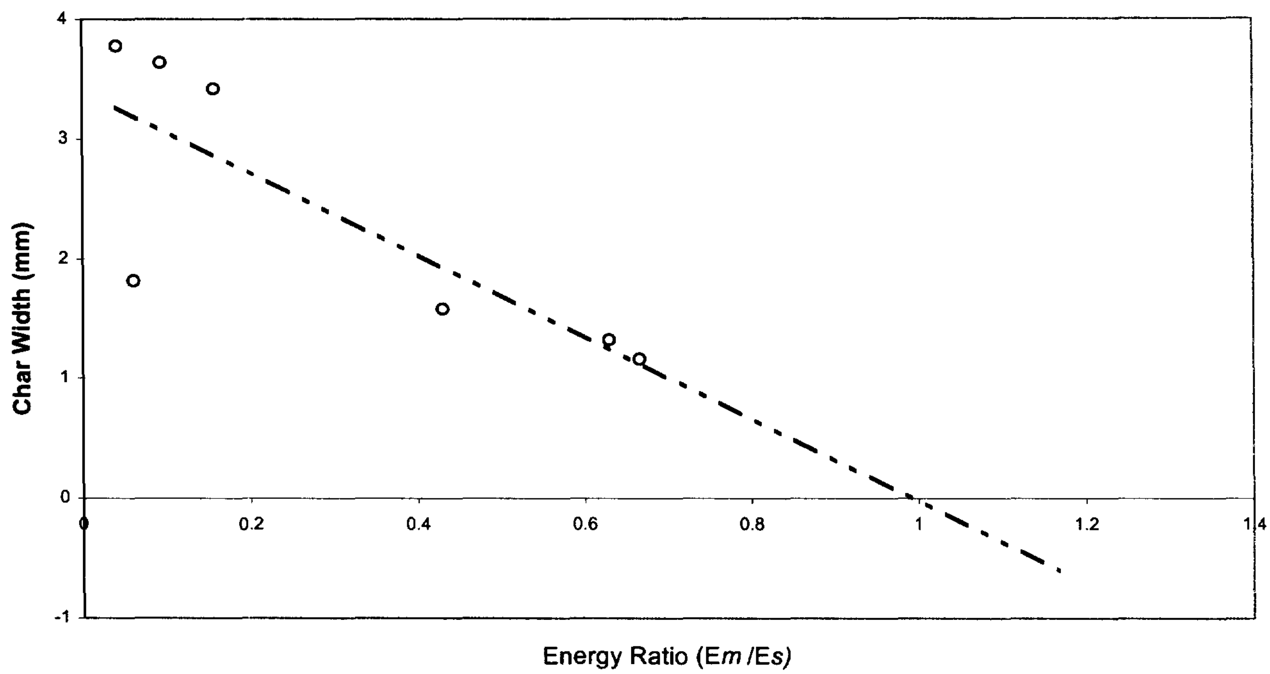

Fig. 3. Laser power on 60W. Velocities vary. Length of cut, Kerf width and depth are measured to determine energy required to cut. Energy ratio is efficiency of laser interacting with substrate. No shielding gas used on bottom surface.

TABLE 2. Spot radius of beam at top surface of substrate.

Focal position	Spot radius on top surface
Top surface	84 μm
Center of thickness (+2.1mm)	+198 μm
Near bottom (+3.2mm)	+327 μm
Just above surface (-.2mm)	-112 μm
Just below surface (+.2mm)	+112 μm

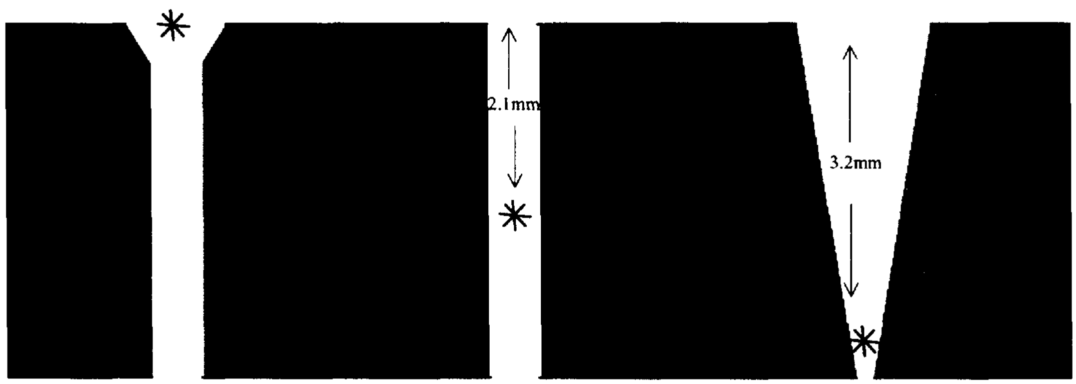

Fig. 4. Cut profile with focal plane at 3 different locations. Left to right; top surface of material, center of material (2.1mm below surface), near bottom surface of material (3.2mm below surface).

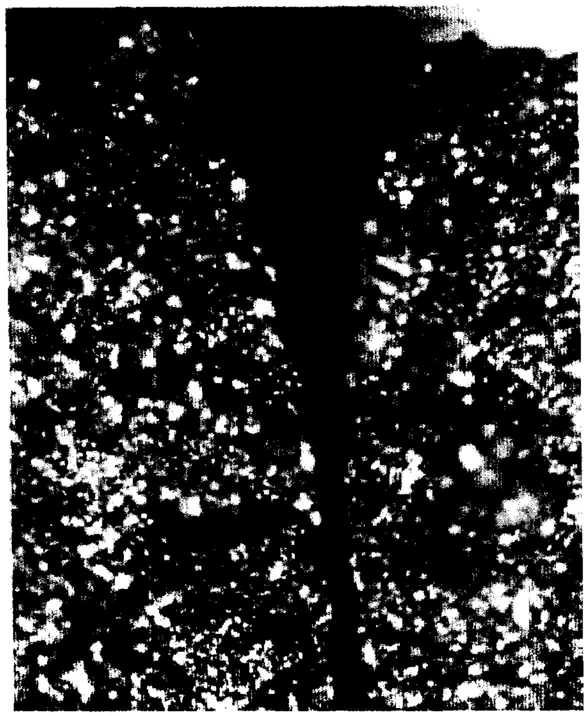

Fig 5. *Focal Length on surface of substrate. Cut mouth is formed, rest of cut is straight. 60W, 3mm/s, 84μm spot radius. (50x Magnification)*

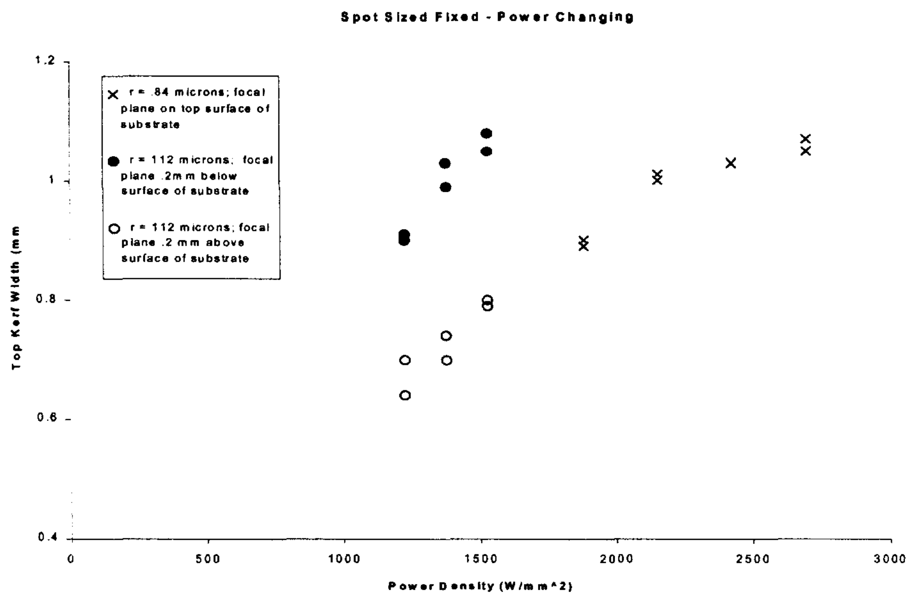

Fig. 6. Kerf width for 3 different focal positions. Velocity (3 mm/s) and gas (100Kpa) are constant. Note different kerf width for same power density because of the different focal plane orientation (above or below surface).

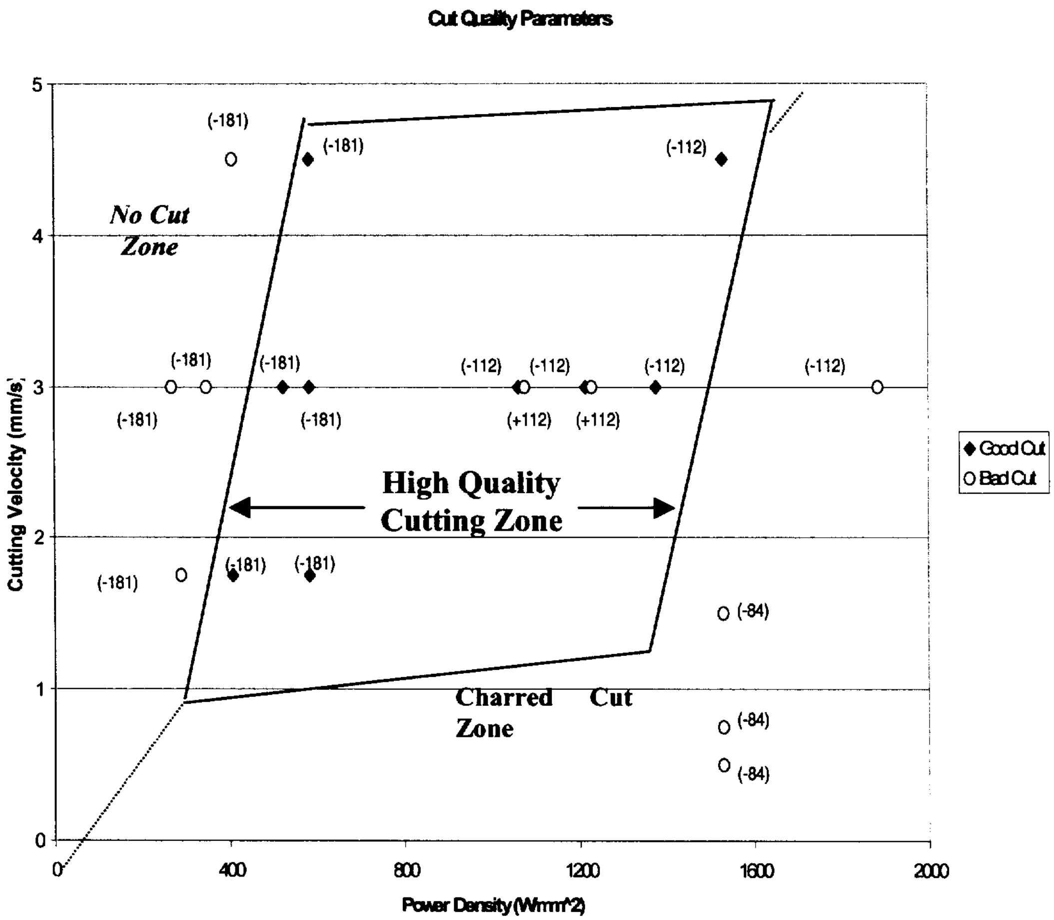

Fig. 7. Quality cutting zone chart. Numerical data in parenthesis refer to spot radius in microns and the plus and minus signs refer to the focal plane (beam waist) location as listed in Table 2. Dark circles are good cuts. Top and bottom boundaries on Quality cutting zone are estimated.

Fig. 8. Top (A) laser cut. Wall with glazing just below surface. Focal plane (+.2mm) , spot size (+112μm) laser power (60W). Bottom (B) is traditional cut wall without glazing. (100x Optical Microscope)

Laser Cutting of Nickel-based Feltmetal

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Little research has be conducted on the laser cutting of porous, inhomogeneous metal materials. The goal of this work is to determine the practicality of cutting 4mm thick Hastelloy X Feltmetal with a Nd:YAG laser while maintaining good cut quality and the integrity of the material.

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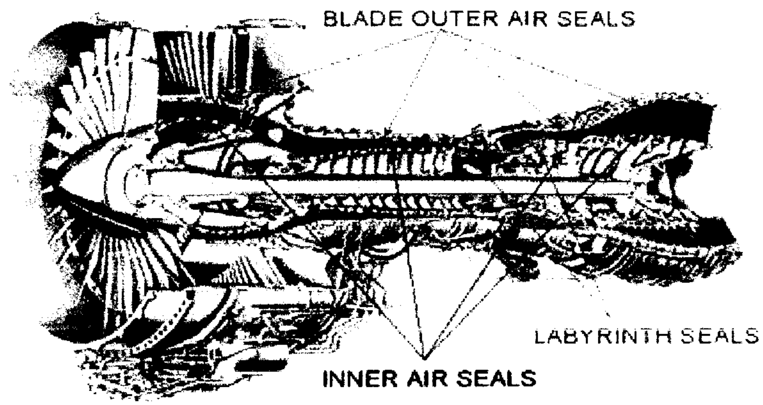
Why Feltmetal?

- Super-alloy base material Hastelloy X provides high temperature tolerance.
- Constructed from fibers pressed together to form material.
- Feltmetal is porous (21% metal, 79% air) -- allows abradability (minimal running clearnaces).
- Uses are primarily in high temperature sealing operations -- diesel turbine engine seals.
- Only traditional cutting methods are being employed to process Feltmetal. Laser cutting may be able to improve speed and quality of cuts.

Elemental Composition of Hastelloy X by Weight Percent.

Alloy Composition – by Weight Percent									
	Ni	Co	Cr	Mo	W	Fe	C	Si	Mn
Hastelloy X	Bal.	1.5	21.75	9.0	0.6	18.5	0.1	1.0	1.0



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Experimental Setup

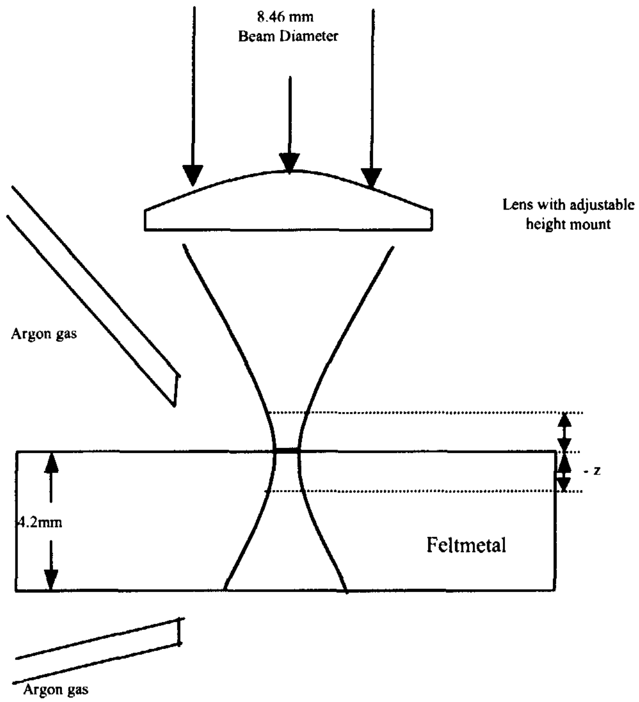


Diagram of experimental setup. Spot size on surface of feltmetal changed by raising and lowering asphere lens.

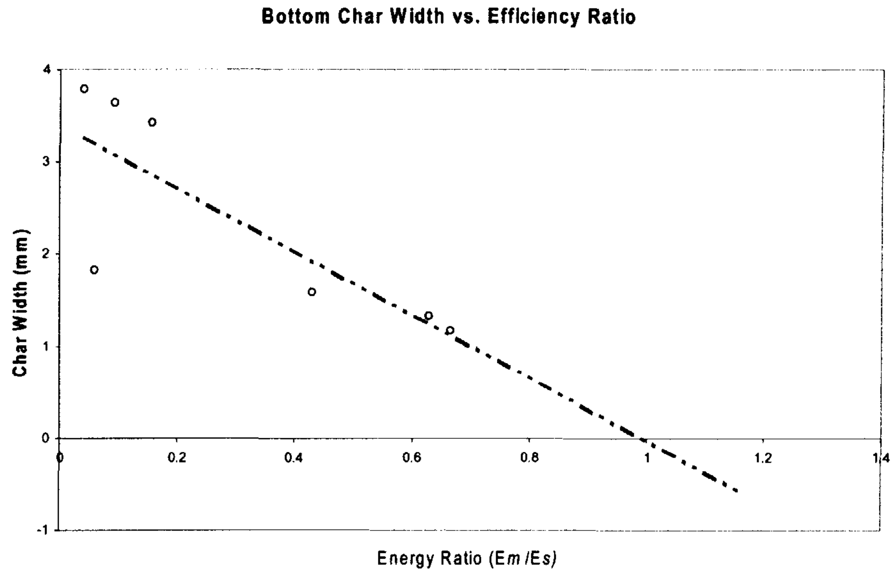
- Nd:YAG laser source - 70W CW mode
- 25mm aspheric condensing lens
- Feltmetal on adjustable speed table
- High purity inert shielding gas (argon) used as assist gas - delivered from copper tubing
- Cutting parameters examined:
  - Scanning Velocity
  - Power Intensity ($I=P/\pi r^2$)
  - Laser spot size (on top surface of FM)
  - Assist gas pressure
- Finding optimal cutting parameters for highest cut quality (straight walls, no charring or glazing of cut)

Energy Efficiency in Material

- Energy modeling

$$E_m = d\omega_k l\rho\left[C_p\left(T_f - T_0\right) + L_m\right]$$

  - E_m = Energy used in making cut
  - E_s = Energy supplied by laser
  - d = depth, of cut; l = length of cut;
  - ω_k = kerf width (cut diameter)
  - ρ = metal density * perecent density
  - C_p = Specific heat of hastelloy X
  - T_f-T_o = Temp. increase during cutting
  - L_m = Latent heat of melting (approx.)
- As E_m/E_s → 1, charring should decrease because all energy being supplied is being used just in cut
- Max efficiency for this work = 60% E_m/E_s
- Charring was eliminated in future cuts with use of shield gas



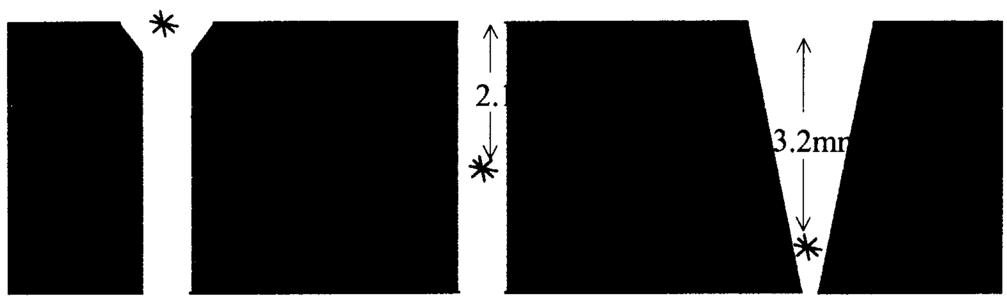
Laser power on 60W. Velocities vary. Length of cut, Kerf width and depth are measured to determine energy required to cut. Energy ratio is efficiency of laser interacting with substrate. No shielding gas used on bottom surface.

Focal Position Inside Feltmetal

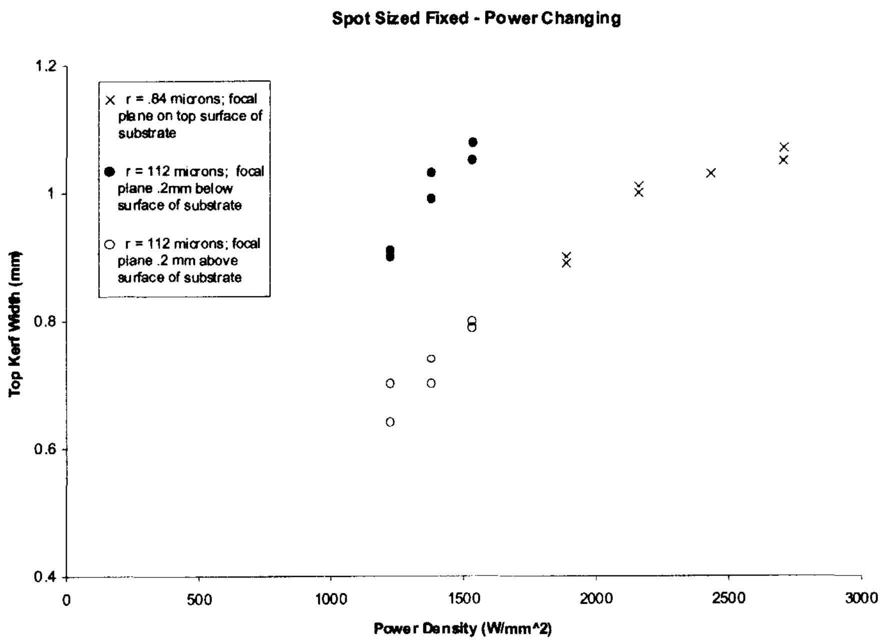
- Cuts taken at three positions:
  - top surface of substrate
  - center of substrate
  - near bottom surface of substrate

Focal position	Spot radius on top surface
Top surface	84 µm
Center of thickness (+2.1mm)	198 µm
Near bottom surface (+3.2mm)	327 µm

- When beam waist is place incident to, or just below, the top surface, a "mouth" sometimes forms making the top of the kerf width very large
- Beam waist incident on center plane of substrate produces straight cuts, but charring is a major problem because larger spot diameter on top surface
- Beam waist incident near bottom surface produces very uneven cut walls and much charring. No good cuts formed.



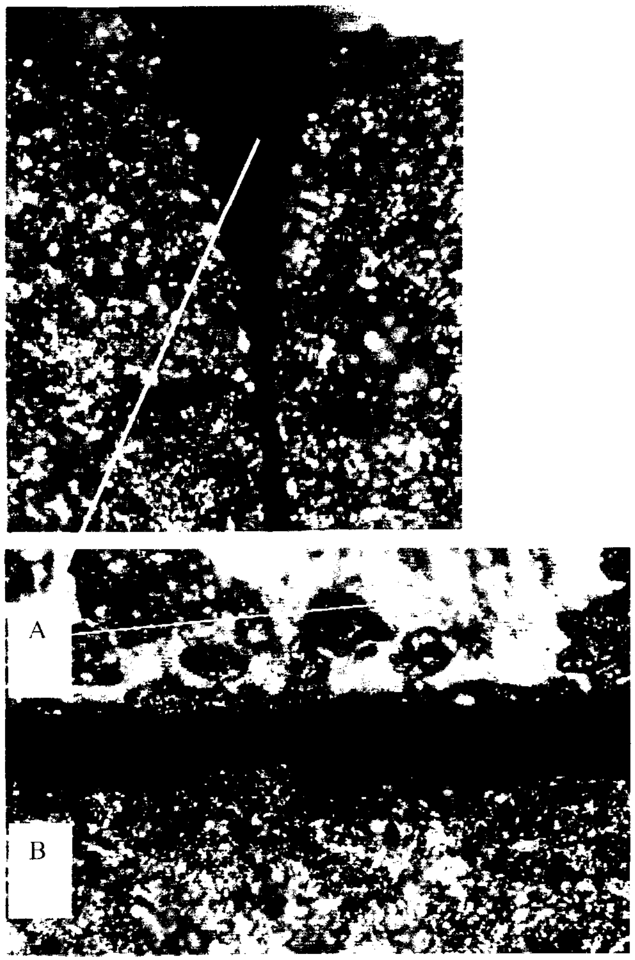
Effects of Power Density



Kerf width for 3 different focal positions. Velocity (3 mm/s) and gas (100Kpa) are constant. Note different kerf width for same power density because of the different focal plane orientation (above or below surface).

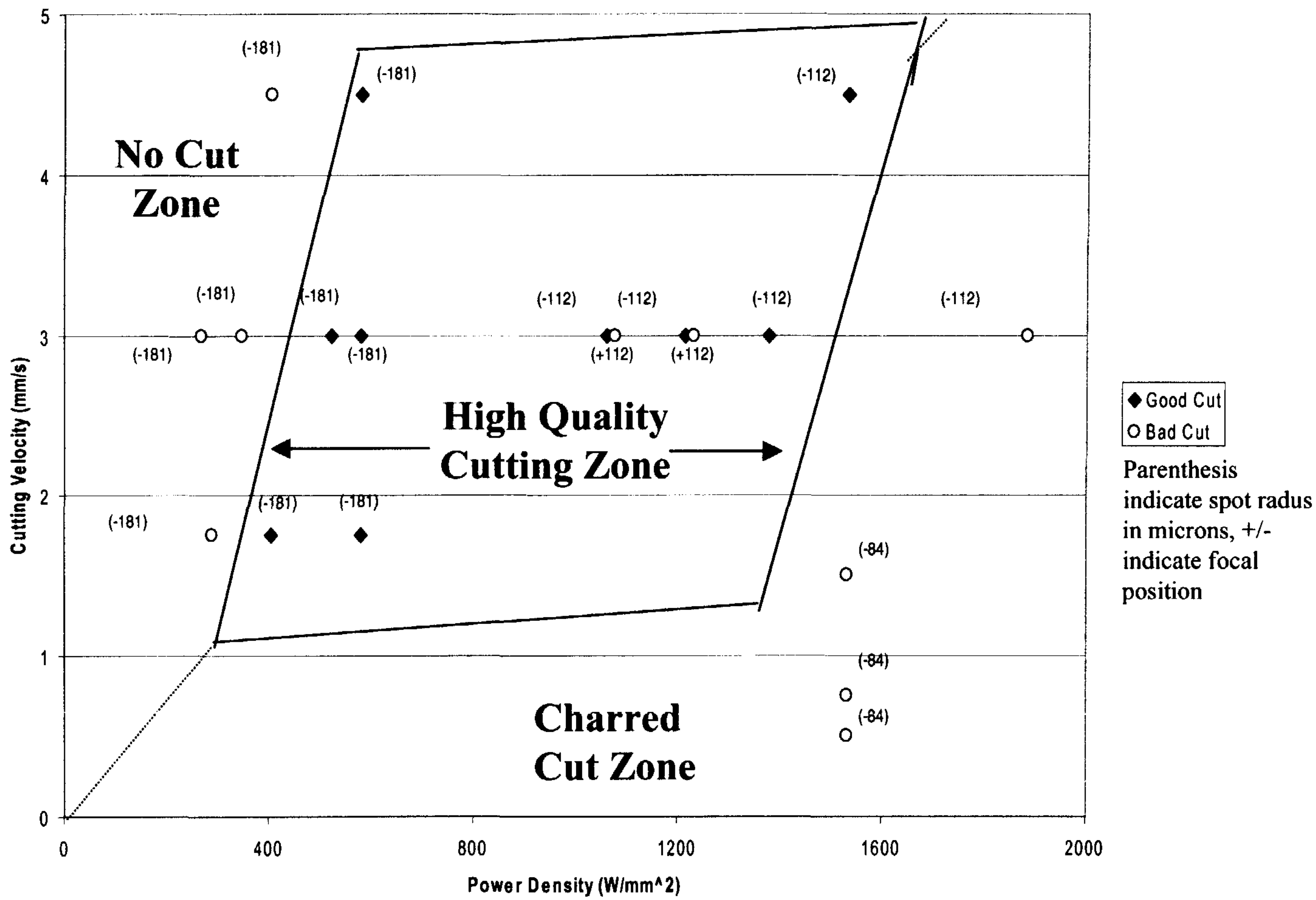
- Power Density defined as $I=P/\pi r_0^2$ where P = laser power and r_0 = spot radius.
- Changing either power or spot radius can change power density, identical power densities can have very different beam characteristics
- Positioning focal plane at equal distances above/below top surface of FM will yield identical power density, but cut quality and kerf width are very diffent
- As power density increases, kerf
  - increases when spot size is constant
  - decreases when power is constant

Glazing and Cut Wall Quality



- Glazing is the resolidification of molten material on the inside of cut walls. Glazing is a common problem with porous materials because the molten metal can travel into the void areas of the porous material altering the material.
- Glazing occurs when the intensity is too high at one point and the molten material gets ejected into the walls, or when excess energy is too high for the scanning velocity and the walls melt, drip, and resolidify.
- Material “A” is laser cut with the focal plane incident on the surface of the material, the intensity is high and charring occurs, “B” is machine cut, no charring visible at 50x optical magnification

Cutting Zones (All Parameters)



Conclusions

- It is feasible to cut 4mm thick Nickel-based Feltmetal with a 70W CW Nd:YAG laser and obtain good cut quality
- Laser power limited cutting velocity in this work(5 mm/s), a higher power laser will increase cutting velocity substantially, however more analysis of cutting this substrate on higher power laser is necessary to examine the effects of charring and glazing under high power densities.
- Inert shielding gas on both surfaces of substrate is necessary to eliminate charring because there is energy lost from cut into material.
- It is possible to cut porous metal materials with a laser beam and maintain the integrity of the material after the cut.