ELECTRON BEAM SOLID FREEFORM FABRICATION
OF METAL PARTS

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ABSTRACT

A novel method for near-net-shape fabrication of large, complex metal parts without the need for specific tooling is described. Parts are built up in a layer-by-layer fashion by feeding raw material in wire form into a melt pool which is maintained with an electron beam. Several different alloys have been successfully deposited using a low-energy electron beam. A model has been developed which permits determination of the melt depth and vaporization-limited power input as functions of beam energy and travel velocity. Processing parameters obtained from experiments with low-energy electron beams can be used to predict melting behavior under the influence of higher energy beams. The process is being investigated as a possible means for manufacturing compositionally-graded components.

INTRODUCTION

There are very substantial military and economic incentives to return naval and commercial ships to service as soon as possible after a failure. Unfortunately, the casting, forging and machining processes currently used to make large replacement drive components such as shafting, couplings, bearings, and propellers, can require lead times of several months. This necessitates maintenance of a large inventory of spares for every vessel in service. The manufacturing costs and warehousing fees for these spares can be a very large portion of the total operating expense for a ship. Manufacture of parts for initial construction can also be costly for short production runs (i.e., if only a single ship of a given design is being built).

One of the most time-consuming and expensive steps in producing components via a conventional route is machining of the part-specific tooling required for casting and forging. Mold patterns, permanent molds, and collapsible cores are required for each casting. Forging demands even more tooling; in some cases, a different die for each reduction step is needed. Moreover, since the dies must withstand high stresses and temperatures, they are generally made from alloys which are very hard at room temperature. This can result in extremely low machining productivity. The inherent limitations of the casting and forging processes in producing certain geometric contours can also result in considerable machining of the final part.

Conventional processing is also somewhat less than optimal from the standpoint of the mechanical properties obtained. The main reason for this is inhomogeneity caused by solute rejection and subsequent convection during solidification. The ensuing macro-segregation will occur over a distance comparable to the dimensions of the casting. It can theoretically be eliminated by a homogenization anneal, but the time required would be excessive due to the long diffusion distance. Forging has little effect on the segregation, and it can also introduce inhomogeneity through non-uniform deformation.

A number of processes have been developed over the past decade which attempt to reduce reliance on part-specific tooling and machining. The most prominent of these Solid Freeform Fabrication (SFF) techniques are: 3-D printing (3DP), Selective Laser Sintering (SLS), and spray forming. All of these processes have certain advantages and disadvantages, and each is superior to the others for certain types of fabrication problems. For example, 3DP and SLS are capable of very high dimensional accuracy for net-shape manufacturing, but productivity suffers due to the need

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for powder spreading and leveling between each layer. On the other hand, spray forming can produce large parts at high deposition rates, but only simple shapes can be created.

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Another approach exists which provides a combination of capabilities uniquely suited to the task of quickly fabricating large components to near-net-shape from metals of engineering significance. In this process, called Electron Beam Solid Freeform Fabrication (EBSFF), parts are built up in a layer-by-layer fashion as in other SFF techniques. However, the similarity ends there; the addition of the metal comprising each layer is accomplished by feeding wire into a melt pool maintained on the surface of the previous layer by an electron beam (shown in Figure 1 for an annular part geometry). A positioning system permits controlled motion of the melt pool, and hence the location where the deposition is taking place. Successive beads of deposited metal are placed adjacent to each other to form a layer. In this respect, the process is somewhat similar to multi-pass welding.

The EBSFF process is very flexible. Nearly any material which can be melted at reasonable power levels and is obtainable in wire form can be used as feedstock. The latter requirement effectively limits consideration to metals, but ceramic powders may be incorporated via cored wire if they can be made to be spontaneously wet by the sheath metal. This approach may be of use for manufacturing cermet cutting tools and other composites. In any event, near term research will focus on alloys of interest for nautical service: stainless steels, rotor steels, bronzes, brasses, and aluminum and titanium alloys.

The versatility of the process is further illustrated by the wide variety of part geometries which can be formed. Parts can be built up on a flat surface by horizontal translation relative to the electron beam, or annular parts can be fashioned by deposition onto a rotating cylindrical substrate. The part can be re-oriented to produce features on virtually any of its surfaces. Prudent choice of the substrate and orientation allows internal channels to be created. Of course, some geometrical constructions cannot be formed, but this is not expected to be a problem for most parts.

The limitations of the process are of great interest for comparison to conventional processing and to other SFF methods. The maximum component size is expected to be limited by cracking caused by tensile residual stresses in the part. Temperature gradients are set up in the part as a consequence of the heat input associated with the deposition process. Differential thermal contraction during cooling after processing leads to the residual stresses. Careful control of the post-processing cooling conditions may mitigate this problem, but a better solution is possible due to a unique feature of electron and other high-energy-density beams. If designed for the purpose, the beams can produce pulses of microsecond duration. The ensuing rapid local thermal expansion leads to shock wave propagation throughout the part. Localized plastic deformation occurs at the shock wave front as it traverses the part and this greatly reduces the elastic stresses. If this is done periodically during processing and while the part is being cooled from the processing temperature, the residual stresses can be reduced to levels below that which will cause cracking. There is no significant macroscopic dimensional change associated with the treatment.

The maximum productivity (deposition rate) attainable in the process is expected to be limited by a combination of vaporization from the surface of the melt pool and heat transfer from the part. Methods for reducing vaporization while maintaining high heat input will be dealt with in the modeling section below. After the heat energy is used for deposition, it must be removed from the part as quickly as possible. If the bulk temperature of the part becomes too high, it may lose its shape or its fine solidification microstructure may coarsen. Active cooling of one or more of the part's surfaces will be necessary to limit this temperature rise. For making large parts from alloys with low thermal conductivity, even this may not be adequate and an atmospheric high-energy electron beam may have to be used in conjunction with convective cooling by a liquid. The extreme

temperature gradients caused by active cooling will make provision for some form of shock stress relief during processing all the more imperative.

It is not expected that the process will be capable of producing true net-shape parts. The spatial resolution of the technique will be limited to a distance approximately equal to the diameter of the feedstock wire. Since relatively large wires can and should be used to attain the high production rates necessary to economically produce large components, dimensional accuracy will be low. Furthermore, the as-produced surface finish is unacceptable for most purposes since there is usually some waviness arising from the one-dimensional nature of the deposition process. This means that some post-machining will always be necessary to achieve the required dimensional accuracy and surface finish. However, it is important to note that this machining will involve the removal of a relatively small volume of material and so will not contribute significantly to the total time required for fabrication. Post-processing of castings (gating system removal, weld repair of defects) and forgings (flash removal) can be far more costly and time-consuming.

The mechanical properties of material produced by this method are expected to be superior to those of cast parts of the same material, but inferior to those of forgings. The improvement over castings arises because only a small volume of metal is solidifying at any one time. This leads to a higher local solidification rate and a finer and more uniform microstructure. Properties are also expected to be more homogeneous since the extent of segregation is limited to less than the size of the bead cross-section. It is feasible to eliminate segregation of this degree via a homogenization treatment. Plastic deformation comparable to that in forging is not intrinsic to the deposition process, so parts produced by this process will not attain the strength levels of forged parts.

Another impediment to commercialization of the EBSFF process is the large capital investment required. For low-energy EBSFF, the electron beam generation equipment is not expensive, but a vacuum chamber large enough to contain the part will be required. For high-energy EBSFF, the electron accelerator itself is costly, and heavy radiation shielding is required to protect personnel and equipment from the hard x-rays produced. On the other hand, a high-energy (>500 keV) beam can propagate in air with minimal attenuation, so vacuum equipment is not necessary.

Trials have been made with several materials using a commercial low-energy (120 keV) electron beam welding apparatus. A layer of 308L stainless steel 0.5 in. thick and 0.75 in. long was successfully deposited onto a 304L stainless steel mandrel with an outside diameter of 4.5 in. Figure 2 is a micrograph of a radial section of the deposit; the individual beads can easily be distinguished due to their different solidification environments. A commercially pure titanium deposit (0.3 in. thick, 1.0 in. long) was made in the same manner. This specimen exhibited some porosity at the interface between the substrate and first layer of weld beads; this was probably caused by inadequate cleaning of the substrate prior to deposition.

The EBSFF process is not only an alternative way of making parts from traditional materials, but can also be used to make materials which are difficult to process conventionally. It is extremely suitable for making parts with composition gradients. By changing the feed wire at appropriate times during deposition of a part, one-dimensional composition variation can easily be achieved. Continuous composition variation is accomplished by using powder-cored wire as feedstock; an appropriate metering device can be used during the fabrication of the cored wire to continuously vary the composition of the powder in the core. The process also provides a very controllable way of reactively forming intermetallic parts, although multiple wire feeders will probably be needed to do this economically.

PROCESS MODELING

It was mentioned above that vaporization from the surface of the melt pool is expected to be a major factor limiting the productivity achievable by the EBSFF process. Excessive vaporization not

only reduces the amount of thermal energy available in the melt pool for deposition, it also lowers the material yield. Furthermore, if any alloy constituents have very dissimilar vapor pressures, significant differences between the composition of the feedstock material and the part may result. Damage to the equipment for electron beam generation, vacuum production, wire feeding and part positioning may also occur. It is therefore of the utmost importance to be able to accurately predict the amount of vaporization for various operating conditions.

For a given alloy, the quantity of vaporization will be largely determined by the temperature at the surface of the melt pool. This will be determined by the thermal balance between energy added by the beam and heat conducted away into the part. Since electrons are known to dissipate their kinetic energy within a volume of material below the surface instead of at the surface, a heat transfer model which can simulate a volumetric heat source is required. Additionally, the model must be capable of describing the effects of motion of the heat source. Davé [1] has expanded the Green's function model of Eagar and Tsai [2] for moving distributed surface heat sources to also encompass volumetric heat sources.

An effort was made to take into account all factors relating to the energy deposition and heat transfer, but in some cases this could not be done. Electrons in the incident beam were assumed to have a Gaussian distribution of energies. The beam power is of interest for operational reasons, but the power absorbed by the material is the relevant quantity for heat transfer calculations. Consequently, the model results are displayed in terms of the absorbed power; the beam power can be obtained through application of backscattering coefficients appropriate for the material involved. Limitations of the Green's function technique prevent radiation from being taken into account directly, but its contribution was estimated by assuming the surface of the pool to be at the melting temperature. In the interest of simplicity, convection in the melt pool was assumed not to occur, and the physical properties of the liquid and solid were assumed to be the same and constant with temperature. While the numerical accuracy of the results produced by the model will clearly be compromised by these assumptions, qualitative conclusions drawn from the results are still expected to be valid.

Low-energy electrons are expected to have very limited penetration into the interior of a material, and so they will behave as surface heat sources. Comparison of the models for surface and volumetric heat sources confirms that this is true for beam energies below about 200 keV. Increasing the beam energy causes a proportionally greater amount of energy to be deposited below the materials' surface. This enables a greater depth of material to be melted without increasing the surface temperature (and hence, the amount of vaporization), as shown in Figure 3 for Type 304 stainless steel. However, the power input required to obtain a given amount of melting increases with beam energy. This is illustrated in Figure 4, which shows the amount of power required to initiate melting as a function of beam energy. For a given beam energy, absorbed power levels greater than those required to initiate melting, but lower than those which will cause excessive vaporization, can be used for deposition. This defines a processing space as shown for pure iron in Figure 5; the acceptable vapor pressure has been arbitrarily set to one atmosphere (boiling), although the practical limit will probably be much lower.

Another important variable affecting the attainable productivity is the beam travel velocity. Relative to a stationary beam, a moving beam will have to have higher power to cause the same degree of melting or vaporization, since it is always encountering fresh (cooler) material. A processing space can therefore also be defined with respect to the travel velocity (Figure 6).

The plots showing the processing space can be used to obtain the total power available for deposition (i.e., for melting of the feed wire) by subtracting the power required to initiate melting from the actual absorbed power. However, the power required for maintenance of the melt pool must also be subtracted. This can be calculated for a given absorbed power level, beam energy and travel velocity with the additional assumption of a melt pool cross-sectional shape. For a

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rectangular cross-section, the power required to maintain the melt pool is typically about 10-15% of the total power available for melting and deposition. The deposition rate and the deposition energy efficiency can be calculated from the deposition power. The higher absorbed power levels possible with higher energy beams cause an increase in the former quantity (the specific deposition rate is roughly constant at 2.2 lb/hr/kW), but a decrease in the latter one (dropping from 0.41 for 100 keV electron beams to 0.39–0.40 for 1.0 MeV beams). That is, higher productivity can be obtained by going to higher beam energies, but only at the cost of lower energy efficiency.

It is useful to compare these quantities to those obtained with deposition accomplished with a variety of other heat sources. Obviously, lasers, causing only surface heating, will exhibit behavior very similar to that of low energy electron beams. The choice between these two heat sources will largely depend on a comparison of the emissivity of the surface for the laser and the backscattering coefficients of the material for the electron beam. Gas-metal arc welding (GMAW) is another competitive process. Calculations made on the basis of production welding schedules indicate that both deposition rate per unit absorbed power (1.0–1.5 lb/hr/kW) and deposition energy efficiency (0.20–0.26) are approximately half that for electron beams, even low energy ones. This is probably due to the additional power required to produce and maintain the plasma in the arc.

The model's validity was checked by using it to calculate the power required for deposition of the 308L stainless steel sample described in the previous section, and comparing it to the actual power used. The model result was 1141 W and the actual value was 1248 W, a difference of approximately 10%. This is remarkably good agreement, and provides very resounding evidence for the applicability of the model to EBSFF.

SUMMARY

The EBSFF process is a viable way of making large metal components to near-net-shape much more quickly than the established methods (casting, forging, machining). This is confirmed by trial deposits which have been made from several relevant alloys. It may also be useful for making parts from advanced materials which are difficult to make by conventional means, such as particulate-reinforced composites, intermetallic compounds, and materials with composition gradients. However, high capital cost is a significant drawback relative to other SFF processes.

A model for the heat transfer from a moving volumetric heat source has been developed using a Green's function solution for the heat conduction equation. This model is appropriate for modeling the interaction of high energy electron beams with metals. A number of parameters of technological interest relating to deposition with high energy beams can be obtained from the model, such as the vaporization-limited maximum deposition rate and the energy efficiency of the process. Comparison with competitive processes, such as laser and arc-welding-based deposition, indicates that high energy electron beams are expected to be capable of higher production rates and energy efficiency.

ACKNOWLEDGMENTS

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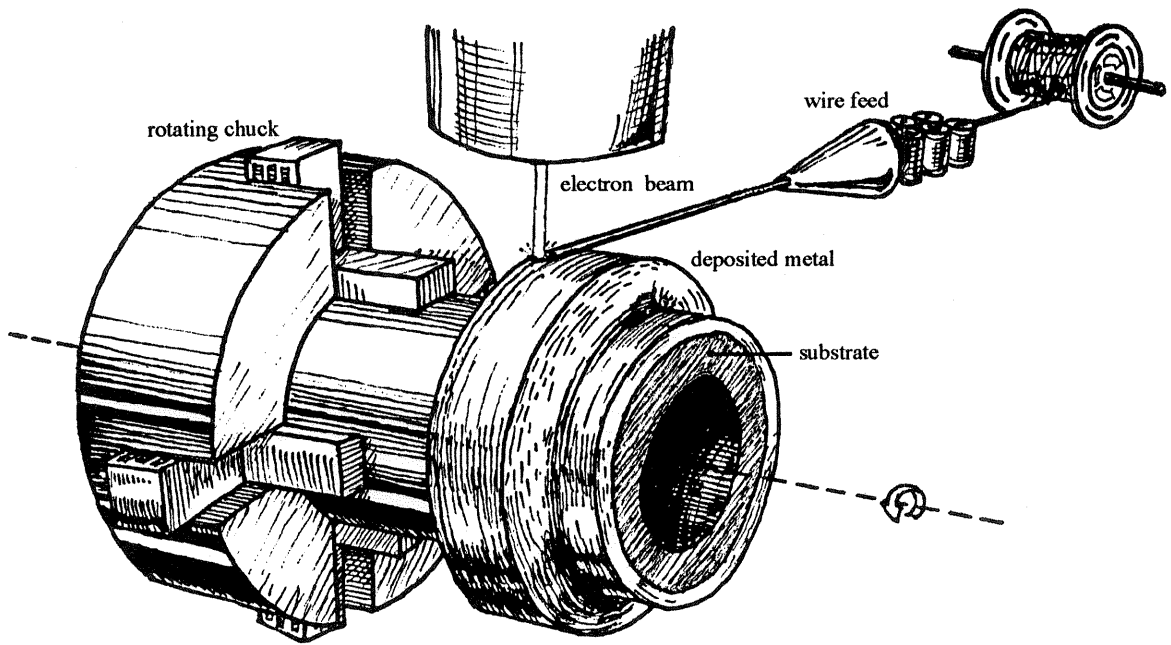
Figure 1. The EBSFF Process

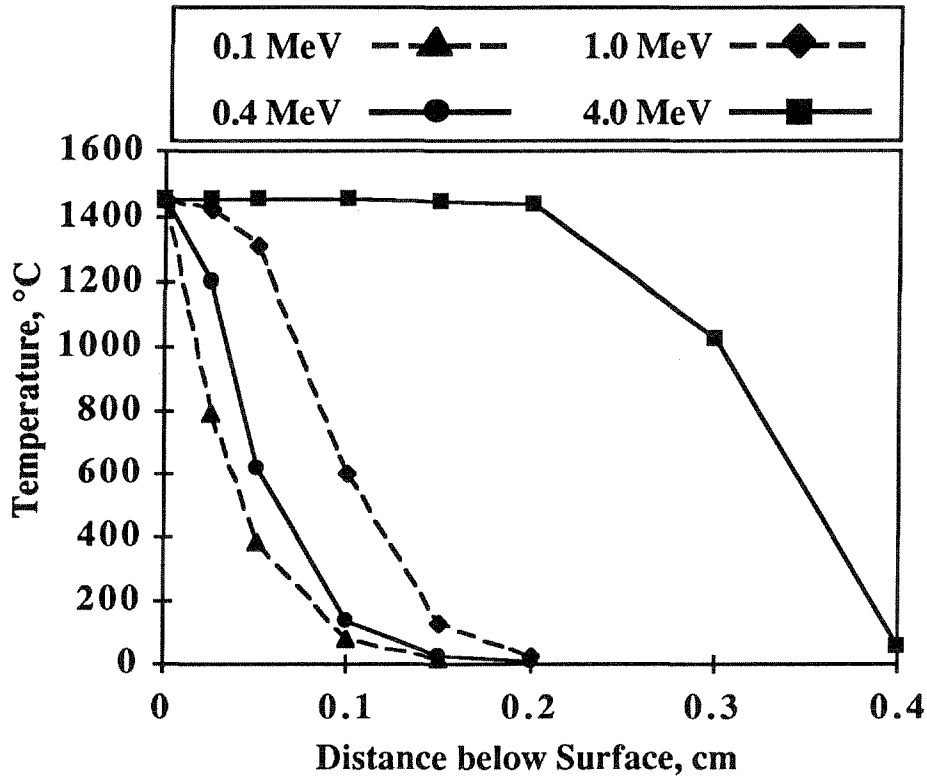Figure 2. Micrograph of radial section of Type 308L stainless steel deposit, 50x

Figure 3. Temperature profiles in Type 304 stainless steel when surface is at 1450 °C (the melting point). The beam radius and travel velocity are taken to be 0.15 cm and 5 cm/s, respectively.
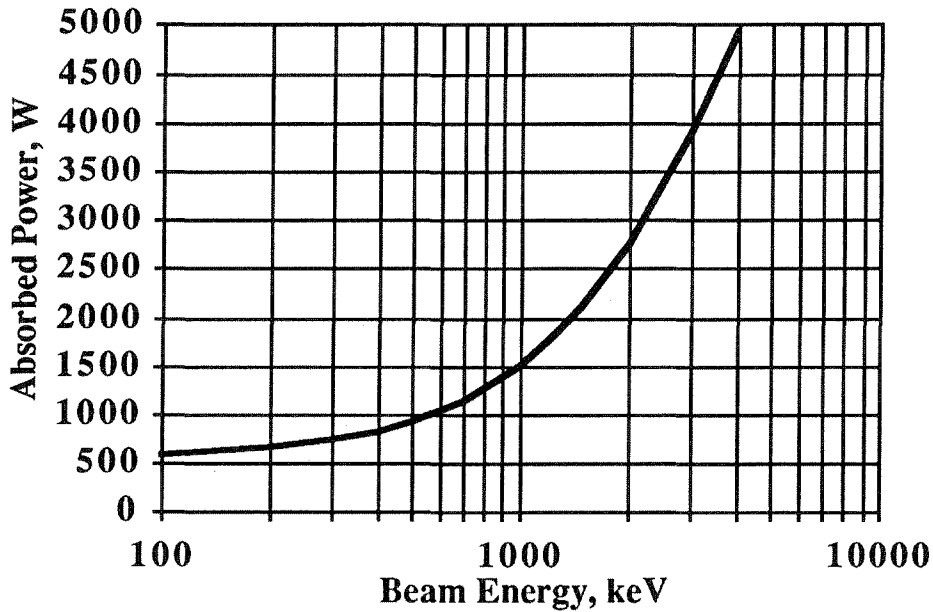

Figure 4. Absorbed power needed to initiate surface melt in Type 304 stainless steel. The beam radius and travel velocity are taken to be 0.15 cm and 5 cm/s, respectively.
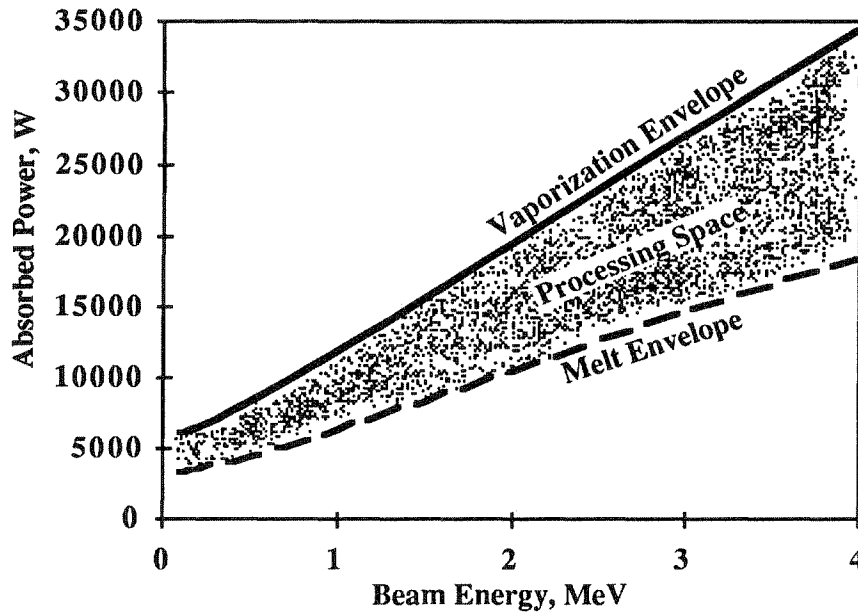
Figure 5. Range of allowable processing power as a function of beam energy for pure iron. The beam radius and travel velocity are taken to be 0.35 cm and 5 cm/s, respectively.
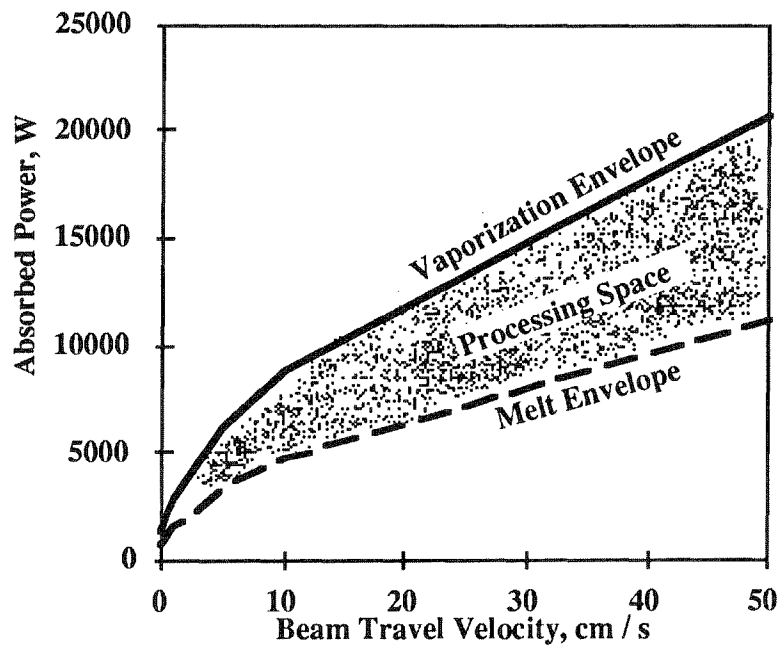

Figure 6. Range of allowable processing power as a function of beam travel velocity for pure iron. The beam energy and radius are taken to be 100 keV and 0.35 cm, respectively.