HIGH ENERGY ELECTRON BEAM (HEEB) PROCESSING OF ADVANCED MATERIALS

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ABSTRACT

High Energy Electron Beams (HEEBs) offer a unique heat source that may be used for a wide variety of materials processing applications. The unique physical characteristics that make HEEB-based processing so attractive are: in-depth energy penetration, very high average power levels, shock generation capabilities, and potential for atmospheric or inert gas environment operations. High energy electrons will penetrate several millimeters into most materials, allowing for subsurface heat treatment. Rapid energy deposition produces moderate to strong shocks in many materials, and many potential applications exist that exploit this phenomenon. The operating parameters of pulsed power accelerators vary, but typical beam energies are a few MeV, beam currents are several hundred amperes, pulse durations are tens of nanoseconds, and repetition rates can be as high as a few kilohertz. The average power levels obtainable with these operating parameters range from a few hundred kilowatts to well into the megawatt range. The surface heat fluxes can be as high as $10^6 - 10^9$ watts/cm$^2$. Such high power levels mean that HEEB processing is ideal for net shape casting applications, and metal melting rates may be as high as 1000 lbs./hr. The fabrication of graded alloy components is discussed as one example of such a net shape manufacturing process. Other applications include heat treatment, surface treatment, shock hardening, powder processing, dynamic powder consolidation, deep penetration brazing, and ceramic component tempering. Many of these applications are being pursued experimentally through a joint effort between Science Research Laboratory, Inc. (SRL) and the Materials Processing Center at MIT, and the SRL/MIT experiment is briefly discussed. Some experimental results on shock hardening of welds in 5086 aluminum are presented.

HEEB ACCELERATORS AND HARDWARE

The HEEB materials processing described in this article uses an electron beam generated by a linear induction accelerator (LIA). Such machines are capable of producing extremely high beam currents over small pulse durations, and they may be fired repeatedly to achieve high average power levels. The first application of the magnetic induction principle to linear electron accelerators was by N. C. Christofilos (Ref. 1) in 1964. Figure 1 shows a schematic of Christofilos' original design, which in modified form is still used today. A Toroidal core is connected to a pulse forming network through a switch. When the switch is activated, the core is energized. The electron beam threads the core, thus acting as the secondary of this pulse transformer. The induced electromotive force accelerates the beam. Many such cores may be energized in sequence by appropriate timing signals to achieve very high overall beam energies. A variant of this principle is to have a solid cathode stalk as the secondary, and the voltage along the stalk is sequentially boosted in precisely the same manner. This latter configuration may be used to create the initial accelerating voltage needed to generate and launch a beam from a cathode surface. Early cores were made of Ni-Fe...
tape wound into toroids, but modern versions use ferrite rings as the cores. Modern drivers for the cores are nonlinear magnetic drives, such as the Mag-I type magnetic compressor developed at Lawrence Livermore National Laboratory (Refs. 2,3).

The accelerator and materials processing chamber used in this work are shown schematically in Figure 2 with operating parameters given in Table I. The accelerator consists of an injection module that generates the beam and an accelerator module that increases the beam energy. The materials processing chamber contains positioners that allow samples to be manipulated while being hit by the beam. The injection module has a stack of cores of the type described above with a cathode stalk threading the center of each one. At the end of the stalk is a thermionic tungsten matrix dispenser cathode and a copper anode. Accelerating modules may be placed in series to achieve very high final beam energies.

The cathode - anode assembly forms a vacuum diode that will usually operate under space-charge current limited conditions. This implies that the emission from the cathode is not the rate-limiting step as far as the flow of current is concerned. Under such conditions, the I-V characteristic for the diode is given by the Child - Langmuir law. For the cathode and anode combination used by the SRL accelerator, this expression is:

\[ I(\text{amps}) = K \cdot V^{3/2} (\text{volts}) \]  
\[ K = 2.0 \times 10^{-6} \]  

Where I is the beam current, V is the voltage across the diode, and K is known as the perveance.

After being generated at the cathode, the electron beam is injected into the second module where it is accelerated to 1.5 MeV. After this extra energy boost, the beam finally enters a transport region that leads to the materials processing chamber and to the target / workpiece. A differential pumping aperture is used in order to minimize the backstreaming of gases generated during the beam - material interaction. Electrons are easily deflected by magnetic and electrostatic fields, and both of these focusing arrangements can be used to manipulate the beam.

**SHOCK HARDENING**

Rapid energy deposition can lead to very large temperature and pressure rises within a material. Figure 3 shows an energy deposition profile in aluminum for a beam with a maximum energy of .4 MeV and a beam current of 400 A. The instantaneous pressure distribution will remain constant for times on the order of the 50 ns pulselength. The pressure profile can only evolve at a rate equal to the wave speed in the material, which is on the order of \(10^3\) m/s. Over a 50 ns pulselength, this distance is tens of microns. The value of the instant pressure rise is given by the Grüneisen coefficient:

\[ \delta P = \Gamma_0 \cdot \delta E, \]
\[ \Gamma_0 = \left( \frac{\partial P}{\partial E} \right)_{V_0} \]  

Where \(\Gamma_0\) is the Grüneisen coefficient. The values of this constant are well-characterized in the literature (Ref. 4). This equation may be integrated to get the pressure rise if \(\Gamma_0\) is known as a function of \(P\) and \(E\) over the range of values of interest. The temperature rise can be found by assuming that the irradiated portion of material experiences adiabatic compression. This temperature distribution will also remain constant over the pulselength, because the characteristic heat conduction distance for a 50 ns pulse is several microns.
Once the pressure wave is generated in the region of beam - material interaction, it propagates through the material resulting in plastic deformation. The shock - relief cycle for planar compression shocks is shown in Figure 4. The cycle ends at point D, where there is a permanent strain induced by the passage of the shock. This plastic deformation can produce substantial hardening, and this is the basis of the shock hardening effect. Once the shock hits the other free surface, there will be reflections. Figure 4 shows the mechanical conditions that a sample would experience if it were subjected to a plane compression wave only; the effects of radial expansion waves are ignored. In the sections below, the metallurgical basis of hardening will be considered, specific dislocation mechanisms will be considered, and results from experiments done using conventional shock hardening techniques will be discussed.

**HARDENING MECHANISMS**

Shock waves propagating in materials will generate substantial new dislocation density in addition to interacting with existing microstructural features. Hardening mechanisms such as formation of dense cellular networks, precipitation hardening, interactions with dispersed oxide particles, and interactions with inclusions all play a role. Twinning is important in BCC metals and alloys, and there have been some reports of shock - induced martensite formation. There have been many experiments that have used conventional shock loading techniques to characterize shock - loaded deformation microstructures. The table below is from a review article by W. C. Leslie (Ref. 5). These established results may be used to predict what microstructures are possible through HEEB-based shock treatment.

| MATERIAL                | OBSERVED EFFECT OF SHOCK LOADING                                                                 |
|-------------------------|------------------------------------------------------------------------------------------------|---|
| pure copper - polycrystalline | Hardness, dislocation density, stored deformation energy, yield stress, and ultimate tensile strength increase with increasing shock pressure, and then reach a maximum. Cellular dislocation structure. | |
| pure nickel - polycrystalline | Very similar to copper. At pressures above 1000 kbar, no cellular structure observed, but dislocation density very high. | |
| pure copper - single crystal | Formation of twins when shocks travel in [001] direction; first ever experimental observation of twinning shear in FCC metal. | |
| aluminum                 | No dislocation cell structure formed up to pressures of 150 kbar, although one is expected. Structure observed was composed of randomly distributed, heavily jogged dislocations, high point defect concentration, and many dislocation loops. | |
| FCC alloys               | As stacking fault energy goes down due to alloying additions, cellular structure gives way to planar dislocation arrays, stacking faults, and twins. | |
**SHOCK HARDENING OF 5086 WELDS**

As a first test of the capabilities of HEEB-based shock hardening, welds in 5086 aluminum were hardened. A welded piece with a fusion zone of approximately 0.2 in thickness was prepared from 5086, 0.375 in thick plate with 5356 filler wire using a standard TIG welding process. The weld bead was machined until the weld was level with the base metal. Hardness profile measurements were made across the width of the weld using the Rockwell F scale. The indents were spaced 2.5 - 3.0 indent diameters apart to avoid adjacent test spots from influencing each other. Figure 5 shows the hardness across the weld before irradiation by the beam. The sample was then irradiated by the pulsed electron beam at ten test points centered on the seam of the weld and separated by a 0.25 in spacing. Each test point received a different number of pulses. Figure 6 shows the increase in hardness as a function of the number of pulses received at the test points. The beam repetition rate was set at 10 Hz to avoid excessive heating that could cause annealing instead of hardening. Annealing was observed when the number of pulses exceeded 500. The hardness between irradiated spots also increased, as shown in Figure 7. For the hardness measurements performed between test points, the number of pulses assigned to these points was chosen to be the average of the pulses received by the two adjacent irradiated test spots. At large numbers of pulses, the region between irradiated spots shows a greater hardness increase than the irradiated test points themselves. This suggests that many pulses (more than several hundred) tend to soften the regions directly affected, but that surrounding regions are hardened by radially expanding pressure waves. Figure 8 shows the hardness profiles at different test points after irradiation. The hardness dip due to the weld is almost eliminated for some test conditions. It was verified that the sample suffered no measurable drop in hardness far away from the weld due to heat generated by the pulsed irradiation. The surface of the test piece was completely unaffected by the beam. This suggests that volumetric penetration is an advantage in the...
shock processing of materials. Laser shock treatment will cause surface damage if protective layers are not used. Electron beam shock treatment requires no such layers.

**DEEP - PENETRATION BRAZING**

The application of HEEBs to brazing is unique because HEEBs can penetrate a layer of lower density to selectively deposit energy into a brazing interlayer. One such application is the joining of carbon-carbon composites with refractory metal interlayers. Figure 9 shows a temperature profile in such a joint for a platinum interlayer. This calculation was part of an exploratory study conducted by the Naval Surface Warfare Center in using HEEB technology to achieve deep - penetration brazing (Refs. 6,7). High energy electrons deposit very little energy to the carbon layer while substantially heating the platinum interlayer. The carbon layers to either side will be heated enough through conduction from the thin interlayer to promote good wetting. The energy is efficiently deposited in this manner. The process does not require long cycle times in a furnace in order to achieve good wetting and mechanically sound bonds. The HEEB process causes the temperature to rise dramatically just at the location where it is most needed, at the interlayer. For large and complex geometries, as are planned for the National Aerospace Plane, it will not be practical to heat treat large components in huge brazing ovens. The HEEB process offers a unique way of rapidly and efficiently joining large areas with short cycle times. The feature that makes this application possible is the in-depth energy penetration of high energy electrons, which is not possible by using lasers or lower energy electron beams.

**HEEB-BASED POWDER PROCESSING**

Two applications in powder processing are particularly promising: net-shape casting and dynamic consolidation. Net shape casting exploits the high power levels and broad area coverage offered by HEEB machines to build up materials layer by layer. In this sense, it may be viewed as a three dimensional printing process. Material composition can also be varied to allow for functionally graded components. Continuously and discontinuously reinforced composites could also be fabricated by this route. The only process limitation is the rate at which heat can be transported away from the melt zone either by conduction through the formed component, conduction through die walls or chills, radiation from the melt zone, and convection that is introduced by blowing cooling gases over the component. HEEBs can operate in inert gas or atmospheric conditions, so that this last cooling mechanism is possible. A high value component which can be fabricated by this process is a graded alloy turbine disk. Figure 10 shows a schematic of this process. Such a component is an extension of the dual alloy disk concept with the added feature that discontinuities in material properties are eliminated. Heat flow simulation has shown that material fabrication rates of 250 lbs. / hr are consistent with electron beam operating parameters. Control over microstructure is achieved by controlling the solidification rate, which in turn depends on the temperature gradients in the liquid and solid. A HEEB-based process offers more control over temperature gradients, and this can be used to better control microstructure.

Dynamic powder consolidation, which has already been demonstrated using other approaches (Refs. 8, 9), is also possible through HEEB/material interaction. Manufacture of bulk amorphous components can be greatly simplified by the absence of flyer plates, explosives, and conventional shock loading equipment. The conventional approach is limited to mostly planar geometries, whereas HEEB shock consolidation can be used on irregular shapes as well. The energy per pulse and the number of pulses per second can be regulated to control the energy input to the powder compact. Wide areas or narrow areas can be treated by simply changing spot size or shape. HEEB-based dynamic powder consolidation offers more control over the processing parameters than the conventional explosive shock technique.
This degree of control could allow the manufacture of components that are difficult to make by any other route.

Dynamic phase transformations represent another area where HEEB-based processing can be effectively used. Previous studies have shown that diamond can be fabricated from metal powder / graphite preforms which are heated and subjected to shock loading (Ref. 10). HEEBs can offer a single-step processing tool to accomplish such processing since the sample can be heated and simultaneously shock treated by the beam.

Alloys of components that are otherwise immiscible may be another area of application for HEEBs. If powders of such alloys are pressed and sintered, or HIPed, the long cycle times prevent the powders from forming an alloy. If they are shock consolidated, however, the outer layers of the powders may weld together and rapidly solidify. This will produce a component that is not possible by other techniques. The rapid processing conditions imposed by HEEBs can thus be used to create materials that have metastable, non-equilibrium structures.

HEAT TREATMENT

The high power levels and shock generation capabilities of HEEBs can be used in heat treatment in several ways. Firstly, the beam may be defocused to cover large areas and heat them uniformly. Temperature profile uniformity in the workpiece may be controlled by varying the rep rate of the beam and its spot size. Uniformity of temperature profiles especially during cooling will insure uniformity of composition in the heat treated component. If however the beam is narrowly focused, shocks are possible. These shocks may be used to directly harden the material or they may serve to create nucleation sites for subsequent phase transformations. This latter possibility is the basis for the third way in which HEEBs may be used for heat treatment, which is a combined mechanical / thermal treatment. This process has two steps. The beam is first narrowly focused to introduce shocked regions in the material. After this mechanical hardening, the beam is defocused to cover large areas. Shocks no longer form, and the material is uniformly heated to promote diffusional phase transformations. The transformed material will preferentially form at the sites which have been subjected to shock treatment. This technique of introducing nucleation sites and then transforming the material can also be applied to recrystallization heat treatments. This would allow greater control over the size of the recrystallized grains, since the grain nucleation sites and their spacing can be chosen.

CERAMIC TEMPERING

Thermal tempering of advanced structural ceramics is an application which takes advantage of the control over temperature profiles possible through HEEB irradiation. The important processing parameters in conventional tempering are the initial temperature from which the component is quenched, and the rate at which heat may be removed from the part (Refs. 11, 12). The rate at which heat is taken away from the surface part is determined by the overall heat transfer coefficient, which includes convection and radiation. HEEB offers an extra control “knob” which can be used to introduce compressive stresses over much larger regions of the part than is possible when surface heat transfer properties alone determine the temperature profile and cooling rate. The HEEB - based process may be used for pure, low creep rate materials which cannot be processed by conventional quenching or glazing. Materials such as high purity alumina, silicon carbide, and silicon nitride could benefit from the ability to maintain inverted temperature gradients at very high temperatures, thus overcoming the problem of fast cooling times that arises during conventional quenching operations. Charge accumulation and electrical breakdown within the material are of some concern. This problem is in part resolved by treating ceramic parts in a background gas. A plasma is created along the HEEB path by
ionization of the background gas. The plasma - ceramic interface provides a current return path for the deposited electrons.

SUMMARY AND CONCLUSION

High Energy Electron Beams offer significant advantages for processing of advanced, highly engineered materials. HEEBs can create useful materials processing conditions by providing high power levels, allowing for shock wave generation, and control over temperature profiles. Shock hardening, dynamic consolidation, net shape casting, deep penetration brazing, and heat treatment are all processing areas that are being actively investigated. Shock hardening has been demonstrated on 5086 aluminum welds with no detectable surface damage. HEEB processing offers a potentially useful means of hardening components fabricated from 5000 series alloys, none of which are heat treatable. Additional experiments at beam energies up to 2.5 MeV are planned for the coming year.

ACKNOWLEDGMENTS

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REFERENCES


FIGURE 1
Schematic of Linear Induction Accelerator (LIA)
FIGURE 2
SNOMAD Linear Induction Accelerator, Science Research Laboratory, Inc.
<table>
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<th>Parameters</th>
<th>Sept. '92</th>
<th>Nov. '92</th>
<th>1993 (MIT)</th>
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<td>Beam Energy (MeV)</td>
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<tr>
<td>Average Power (kW)</td>
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<td>35</td>
<td>200</td>
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TABLE 1
SNOMAD Operating Parameters

FIGURE 3
Energy Deposition Profile in Aluminum
FIGURE 4
Shock - Relief for Planar Compression Shocks

FIGURE 5
Initial Hardness Profile Across 5086 Aluminum

FIGURE 6
Hardness at Irradiated Spots

FIGURE 7
Hardness Between Irradiated Spots
HARDNESS PROFILES ACROSS WELD AFTER SHOCK HARDENING
HARDNESS MEASURED AT TEST POINTS

FIGURE 8
Hardness Profile Across Weld After Irradiation

FIGURE 9
Temperature Profile for HEEB Deep Penetration Brazing

Beam Parameters: 3MeV, 2kA, 1μS pulse, 1.5 cm Gaussian radius
Depasil Nickel-Based Superalloy Powder and Superheat (T = 1650°C)

Surface Heat Mandrel to Melting Temperature (T = 1455°C)

Deposit Nickel-Based Superalloy Powder and Superheat (T = 1650°C)

Change Powder Composition and Shape Turbine Disk

Finished Turbine Disk

FIGURE 10
HEEB Graded Alloy Fabrication Process