Electron Beam Processing of Metals

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Abstract

New technologies in metallurgy and machinery are the main fields of activity at The Centre of Applied Physics & Technology (CAPT INP) at Lipetsk. This report presents a brief review of the present situation in the application of particle accelerators and the first results obtained at CAPT INP. Some peculiarities of electron beam treatment of metals are discussed.

1. INTRODUCTION

The Budker Institute of Nuclear Physics at Novosibirsk has been leading in the field of the application of particle accelerators to industry in the USSR for many years. It was an idea of its founder Prof. G.Budker to use high energy accelerator techniques for practical purposes in industry. In the mid sixties the first special electron accelerators were created, and since then such machines are being used successfully for different practical purposes [1]. Similar activities take place in European countries, USA, Japan, Canada etc.

To intensify the development of such new techniques, INP organized a special department at Lipetsk - Centre of Applied Physics and Technology. This city was chosen because of its proximity to an area where many important industrial activities are located. The main benefitiary of the new technologies that are being developed by CAPT is the Novolipetsk Iron and Steel Works - the leader of the national metallurgical industry. The general direction of CAPT activity is devoted to the development of different methods of treatment of metals and metal machine parts with particle beams.

2. STATUS IN ELECTRON BEAM PROCESSING

First technologies with electron beams involved the treatment of different plastic and polymer materials. Electron beams used here have an energy of about 1 MeV and are extracted into the atmosphere (see part 3). At the same time techniques in metal processing in vacuum have been developed very widely and are under extensive use today. Now new areas of electron beam applications have been discovered. Fig.1 is an attempt to observe the present situation in these technologies.

3. SOME PROBLEMS OF ACCELERATION TECHNIQUES

Many technologies with electron beams require material treatment in the atmosphere, or similar working conditions which are much more preferable. This means that extraction of an electron beam into the atmosphere is the crucial problem of such technologies. Two methods of electron beam extraction are mastered today:

- beam scanning over a foil window;
- focussed beam extracted through system of diaphragms with differential pumping.

The possibility of the "window extraction" method is limited by heating of the metal foil due to energy losses in the foil material. The heating power density dP/dS created by these losses dE/dx is equal to

$$dP/dS = (dE/dx)hJ/e\ , \qquad (1)$$

where h is the foil trickness, j the beam current density, e the electron charge. This means, that dP/dS is proportional to some foil characteristic coefficient and inversely proportional to the square of the electron velocity,

$$dP/dS = k(Z/A)hd/v^2\ , \qquad (2)$$

where Z, A, d are the atomic number, atomic weight and density of the foil material. Because heat transfer across the foil to the air is equal to

$$dQ/dS = q(dT/dx) \sim qT/h\ , \qquad (3)$$

where q is the thermoconductivity coefficient, for stationary conditions together with (1) the maximum foil temperature is

$$T = kGh^2J/v^2 \quad , \quad G = d/qA\ . \qquad (4)$$

This result gives contradictory requirements to the foil material: it should have a high G to be light, with high thermoconductivity and very firm, to have minimal thickness. Table 1 illustrates the present achievements in "window extraction" of stationary beams.

Table 1
Some parameters of foil windows, used for scanned beam extraction

Foil material	Parameter Zd/qA (g*K/W*cm^2)	Foil thickness (microns)	Electron energy (MeV)	Achieved power density (W/cm^2)
Ti	20.6	40	1.5	130
Ti	20.6	10	0.2	5
Al/Be	0.45	40	0.18	13.5

The total power of the extracted beam has a magnitude of 100-200 kW for 1-1.5 MeV electron energy and a few kW for 0.2 MeV.

Extraction of perfectly focussed electron beams has no power limitations in principle, but practically there is usually

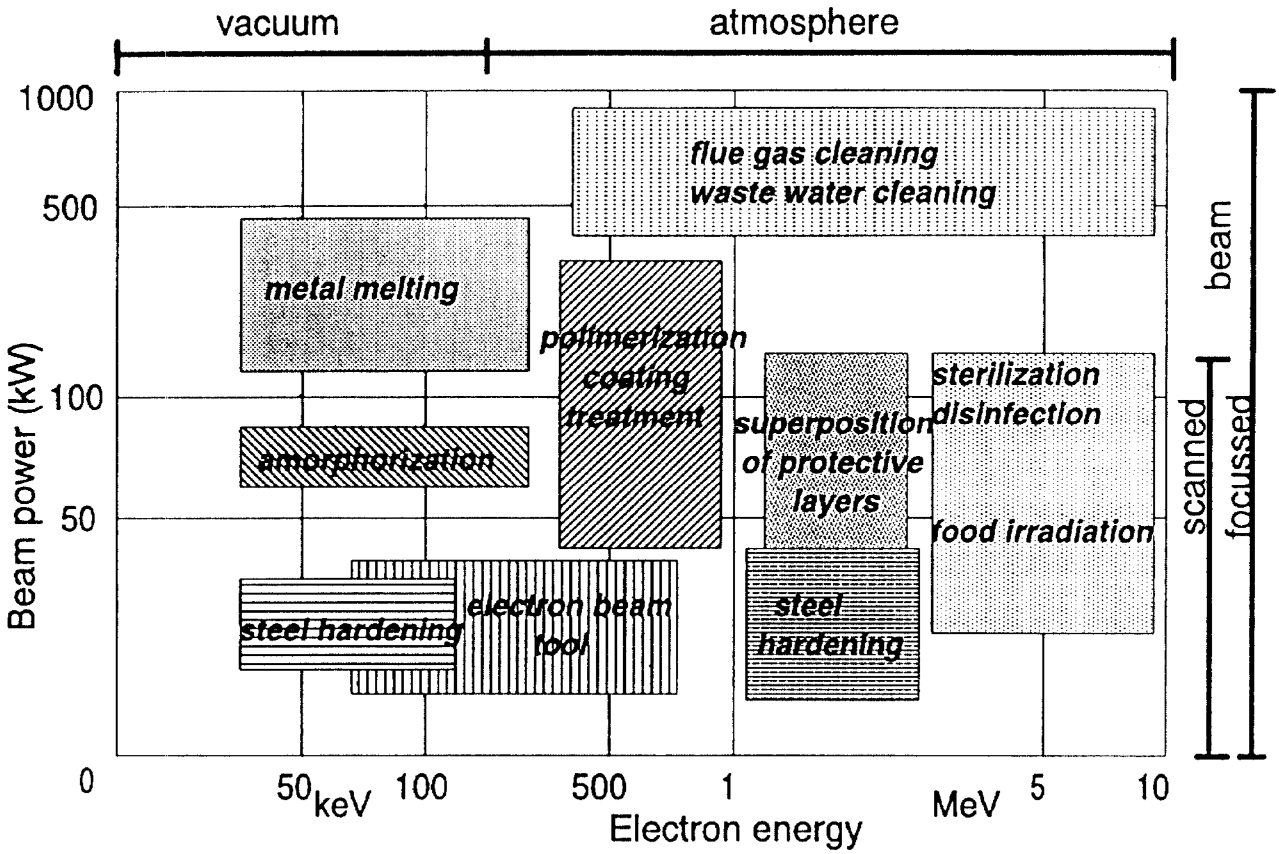

Figure 1 : Status in electron beam processing

some beam halo due to optical aberrations, and it heats the diaphragms of the extraction system. This limits the extracted beam power. The stationary beam power level, mastered today in such systems, is about 50 kW for electron energies of 0.8-1.5 MeV.

4. The Peculiarities of Electron Beam Processing

Electron beams are very specific energy transporters due to the fact that fast electrons are able to penetrate the macroscopic layers of materials. It differs (the material is heated with electron beam) from similar processes with thermosources and laser beams by the fact that, if the electron beam power is high enough, one can reach some temperature of the material in a time duration t_{HEAT}, which is much shorter than the thermoconductivity time interval:

$$t_{HEAT} << t_{cool} = \ell^2 Cd/4q \qquad (5)$$

where ℓ is electron penetration depth, C, d, q the thermocapacity, density and thermoconductivity of the material. Such fast processing, called "adiabatic" [2], implies a very high speed of cooling of the material (temperature T decreasing)

$$dT/dt \sim - T/t_{cool} \qquad (6)$$

So, for steel treated with 1.5 MeV electrons these parameters are equal to: ℓ ~ 0.8 mm, t_{cool} ~ 20 ms, which gives dT/dt ~ $5*10^4$ grad/s for T ~ 1000°. Such high speeds give new possibilities for steel hardening and similar treatments of materials.

Fast heating of thick layers is also a new method of mechanical influence on materials. If t_{HEAT} is comparable with the time of deformation wave propagation, heating with electron beams generates a very powerful strength p inside material:

$$p \sim r\,T E\, \ell/L \qquad (7)$$

where r is the coefficient of thermo-expansion of the material, T the temperature "jump", E the Young's modules, L some characteristic length, depending on the geometry of the sample to be treated. For steel and T ~ 1000° it gives p~10 Pa, which can produce nonelastic deformations inside the metal. It means that the electron beam works as "a hammer", forging the metal.

Such peculiarities bring new quality in metal treatment. Even traditional and "slow" processes, such as melting of metals when superposition of protective layers is being produced, also induces new properties, such as a much better cohesion of cover and basic metal, etc...

The efficiency and productivity of the processes described above are high enough to be practically interesting for industrial applications (see Table 2).

Table 2
Characteristics of thermo-radiation treatment technologies based on the ELV-4 accelerator (beam power of 50 kW)

Technology	Typical productivity rate
Fast adiabatic hardening	$1 m^2$/min
Low temperature treatment	up to $1 m^2$/min at the optimized regime
Superposition of protective layers	60 kg of power/h or 20 m^2/h with a layer thickness of 1 mm
Metal cutting	1 m/min with a sheet thickness of about 30 mm
Metal welding	the same order of magnitude
Metal melting	500 kg/h
Treatment of coatings	0.2-1.0 kg/s or 2-10 m^2/s
Bimetal	10 m^2/h
Treatment of transformer steel	1 m^2/min

5. REFERENCES

[1] V.L. Auslender and R.A. Salimov,"Electron accelerators of Novosibirsk Institute of Nuclear Physics for Industry", Sov. Atomic Energy, vol. 44, pp. 403-408, 1978.
[2] I.N. Meshkov, "Radiation technologies in metallurgy and machinery", Radiat. Phys. Chem., vol.35, Nos 4-6, pp. 483-487, 1990.