MODERN THERMAL ELECTRON BEAM PROCESSES – RESEARCH RESULTS AND INDUSTRIAL APPLICATION

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Thermal electron beam (EB) technologies are becoming more and more attractive especially because they are ecologically friendly and energy saving on the one hand and highly precise, excellently controllable and highly productive on the other hand.
Using three-dimensional energy transfer fields, the interaction conditions between the EB and the surface of the material, the conditions of the heat conduction in the material, the geometry of the part, and the load conditions of the component can be taken into account. High flexibility, precision, and reproducibility are typical characteristics of EB technologies and facilities. High productivity is achieved by new technological solutions like simultaneous interaction of the EB in several processing areas (spots) or by carrying out several processes simultaneously in modern EB facilities and systems (such as multi-chamber, lock-type and other concepts). The influence of beam parameters and energy transfer conditions on the microstructure of the materials and its properties will be discussed for different EB technologies. Information on ideal treatment conditions will be given. The paper deals with the current development state regarding beam deflection techniques, technological processes and some facility concepts, and with the state of industrial application.

KEYWORDS: electron beam processes, surface treatment, combined technologies, welding, engraving, profiling, beam deflection techniques, materials (structure-property relation), applications

INTRODUCTION

By using the advantages of EB, modern EB technologies differ from other technologies in their advantageous characteristics (Tab. 1).
These characteristics are typical for all EB technologies, i.e. welding, surface treatment, surface ablation or perforation, which are carried out as one-spot techniques. If a multi-spot technique or multi-process technology is applied, the effects of these characteristics are much more effectively.
The present paper will exemplarily demonstrate the state of the art of development and application of EB technologies.

MULTI-TOOL ELECTRON BEAM

Beam deflection techniques

The development of the two-dimensional high-frequency beam deflection technique was the beginning of a new area of thermal electron beam (EB) technologies. The high speed scanning (HSS) technique has been available since 1986 [1]-[3]. In 2000 a high frequency 3D beam deflection technique was created with new possibilities for load and couture specific EB technologies, not only for surface treatment [4]-[10] but also for welding [7][10]-[13] and engraving [14]-[15]. These beam deflection techniques are based on the fact that the EB can act simultaneously in several spots [10]-[13]. In this case the same task is realised in every spot.
A defined and exact positioning of the (mostly oscillation)

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Electron beam (EB)	EB technologies
excellent formability and deflect ability	*high productivity*
good beam profile	*excellent flexibility*
high efficiency	*good process safety*
large penetration depth	*high reproducibility*
high beam stability	*ecologically friendly*

▲ *Tab. 1* ***Characteristics of EB and EB technologies (behind others) .***
Principali caratteristiche del fascio elettronico e delle tecnologie EB.

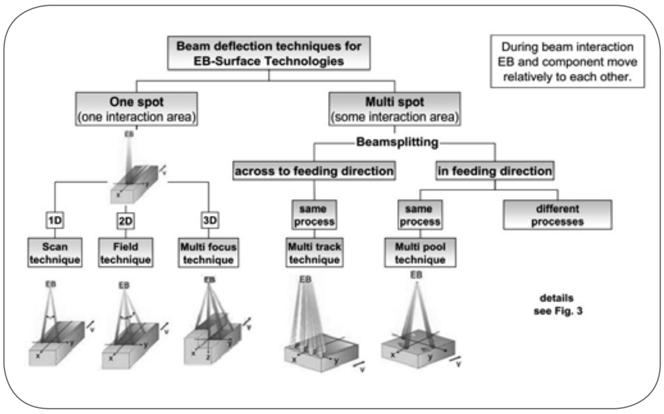

Fig. 1

Beam deflection techniques with movement of EB and/or component [16].

Tecniche di deflessione del fascio di elettroni con movimento del fascio stesso e/o del componente [16].

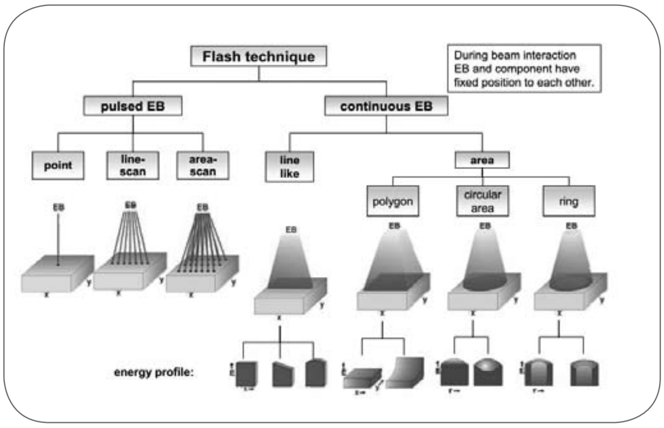

Fig. 2

GD-OES depth profile of a nickel-boron coating on Steel after 1 hour heat treatment at 400°C under neutral atmosphere.

Profilo GD-OES nello spessore di un rivestimento nichel-boro su acciaio dopo 1 ora di trattamento termico a 400°C in atmosfera inerte.

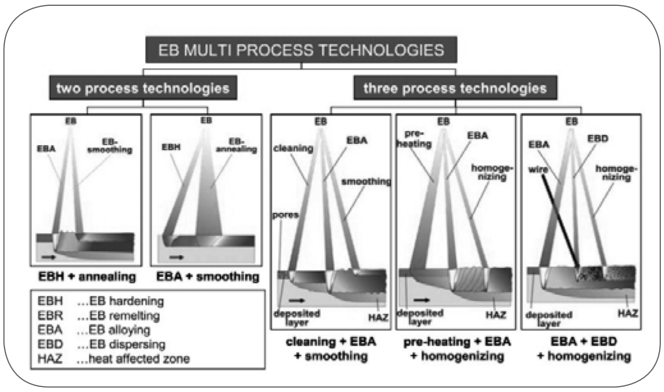

Fig. 3

EB multi-process technologies (examples).

Esempi di tecnologie EB multiprocesso.

EB is the prerequisite for the successful realisation of multi-spot techniques (Fig. 1). The "spot size", i.e. the interaction area of EB depends on the process and is very small in case of engraving (some microns in diameter) and reaches a dimension up to ~ 100 mm2 for surface treatment. The spot size in welding is greater than for engraving but smaller than for surface treatment.

In case of the multi-spot technique, the same task is realised in every spot. It can be differed between two basic beam deflection techniques. During beam interaction

- the beam or/and the component is/are moving relatively one against to the other (Fig. 1).
- the beam and the component are fixed in their positions, so called "flash technique" (Fig. 2).

MULTI PROCESS TECHNOLOGIES

Single treatment often does not fulfil all the demands made on the properties of a component which makes additional treatment necessary. In other cases the material requires special additional treatment (re-heating, subsequent heating) in order to avoid undesired effects (distortion, cracking).

Making comprehensive use of the advantages of EB in this connection means that several EB processes are implemented simultaneously. Now, there are further new and excellent multi-process technologies available, i.e. a combination of different processes in one production run is possible and there is also the possibility of an online process control [9][10][14]-[15].

At present there are two and three-process technologies available (Fig. 3).

The advantages of such technologies are:

- high productivity
- new possibilities for influencing material structure and properties (new very short local thermocycles).

EB SURFACE TREATMENT

Surface hardening and low tempering (controlling component)

EB hardening (EBH) is the most successful EB surface technology used in industry. Lately, more and more multi-process technologies were applied [9][10][14][15].

Fig. 4 exemplarily shows the EBH and tempering of the contour of a controlling camshaft in one process cycle [10]. Two energy transfer fields (hardening and tempering field, Fig. 4b) interact simultaneously with the rotating cam. Because of the stronger load conditions the depth at the radius must be larger (0.65…0.75 mm) than at the flanks (0.55…0.65 mm).This is programmable without any problems.

Another technically and economically very attractive EBH technology is applied in case of a calotte carrier [9][10] (Fig. 4a). The surface contour is programmed as a rotation-symmetric energy transfer field with a surface contour congruent energy distribution (Fig. 4b). The resulting hardening profile is characterised by constant EBH thickness that is independent of the incidence angle of the EB (Fig. 4b).

The energy transfer is realised by flash technique. During the interaction of the EB ($\leq$ 1.0 s) the component is fitted to the beam before crossing the α/γ transformation temperature (processing time $\leq$ 0.2 s). This technology guarantees a high productivity (up to 3.500 parts per hour).

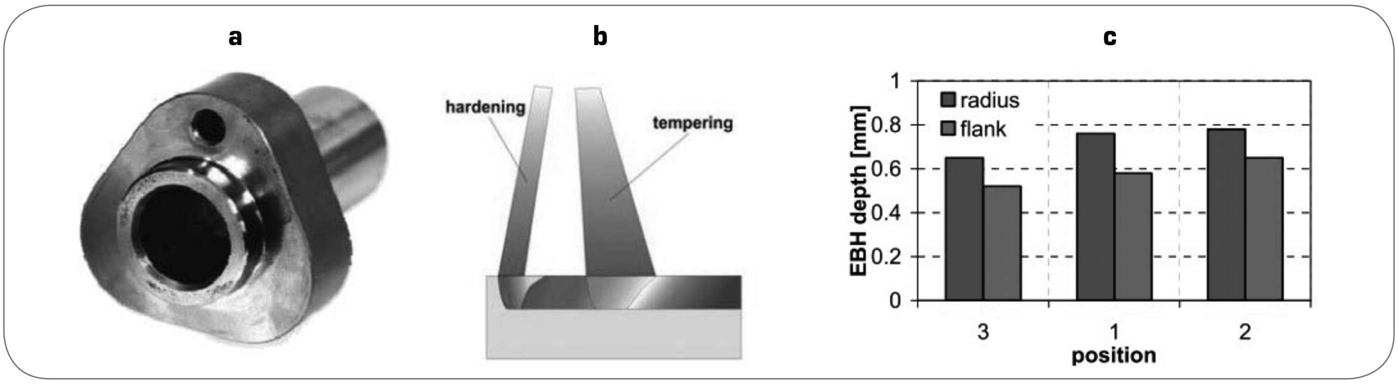

Fig. 4

EB hardening of a power train component (two-process EBH technology) - a) Controlling component; b) Two-process technology; c) EB hardening depths.

Indurimento superficiale mediante EB di un componente di un sistema di potenza (tecnologia EBH).

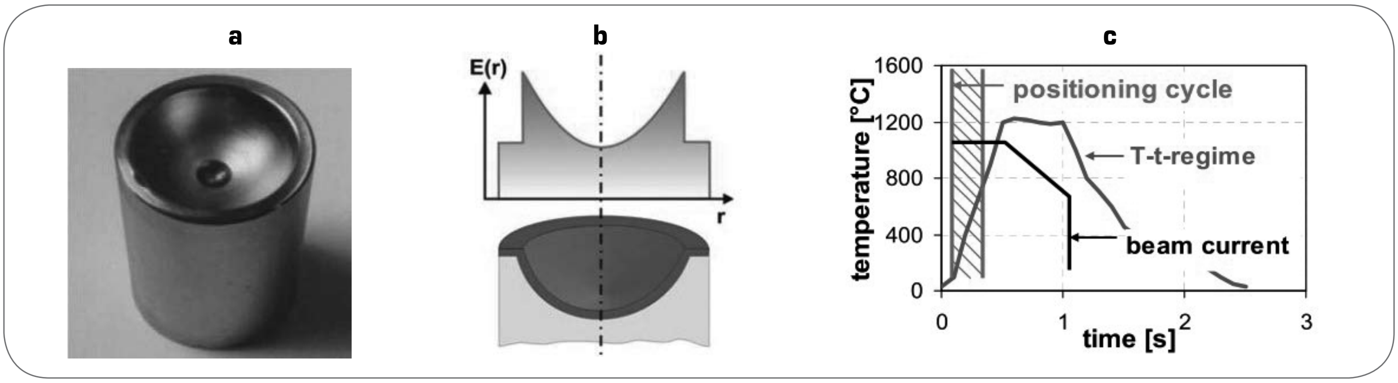

Fig. 5

EB Hardening of a spherical surface (flash technique) - a) Calotte carrier; b) Energy transfer field; c) Process thermocycle.

Indurimento superficiale mediante EBH di una superficie sferica (tecnica flash).

Combined surface treatment (tools, automotive components)

Combination EBH/Nitriding

With regard to complex load conditions for most tools and components, especially close to the surface, the properties attainable by single treatments (mechanical, thermal, thermochemical and coating technologies), in particular, often are insufficient. Therefore, combined processes (duplex or hybrid process) (Fig. 6a) came into the focus of examinations and meanwhile of industrial application [17]-[20].

In case of the sequence of the combined surface treatment combination EBH+nitriding (N) or nitrocarburising (NC) the level of the processing temperature of N or NC in relation to the tempering temperature of the bulk material determines the success of this treatment combination.

The better the tempering stability of the steel the smaller is the hardness reduction in the previously produced EBH layer as a result of the subsequent nitriding process.

It is true that a subsequent EBH after N (NC) transforms the compound layer partially (wider seam of pores), but the hardness of the diffusion layer is higher than after EBH or N (NC) [21]. In case of the component shown in Fig. 6b hardness rises by ~ 200HV0.3 (Fig. 6c).

It has been shown that in the case of optimised process parameters the advantages of this combined treatment complement each other and the disadvantages of the single processes cancel each other out at least partially [20][21].

Combination of EBH and HC

Hard coatings based on titanium, aluminium or chromium carbides are successfully applied as hard wear resistant layers for tools and components. These hard but also brittle coatings are often unable to bring their excellent properties fully to bear on relatively soft base materials. Therefore the base materials are usually subjected to additional heat treatment before or after hard coating [22]-[24]. It is possible to limit the heat treatment to the highest loaded areas and up to the depth where a martensitic transformation is necessary. The thermal loading of the overall component is minimised.

With regard to a subsequent heat treatment of hard coated steels it allows for prevention of undesirable changes of composition, structure and properties of the hard coating [25][26]. A very short interaction time and the process-related vacuum support these effects. Moreover, the electron beam hardening technology is well known to cause small changes in size and shape which means that distortion is also reduced in that way also. A combined EBH+HC is successful only if the treating temperature of the hard coating process is lower than the tempering temperature of the bulk material [26].

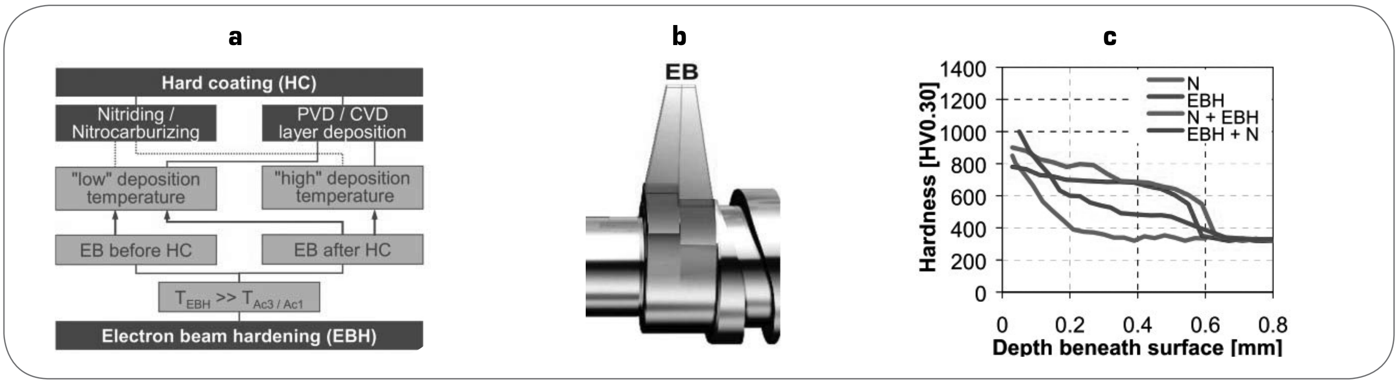

Fig. 6

Combination of EBH with nitriding (N) - a) Technological variants of combined surface treatment; b) Component (detail) steel 54CrV4 (N + EBH); c) Hardness profiles after combined treatment N + EBH (steel 100Cr6).
Applicazione combinata della tecnologia EHB e della nitrurazione (N).

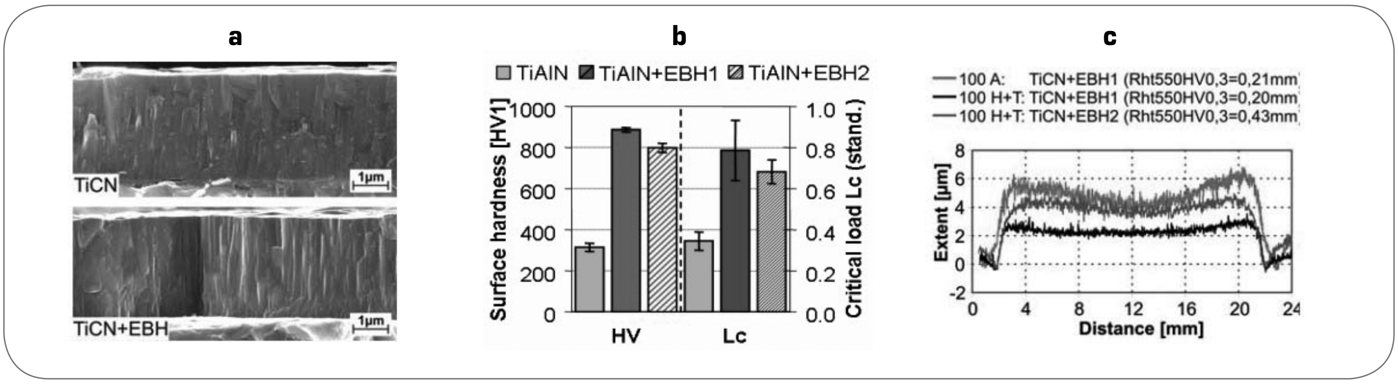

Fig. 7

Combination of EBH and hard coating (HC) - a) Surface layers after HC and HC + EBH (tool steel); b) Surface hardness and critical load of TiAlN coatings on C45 (H+T) (HC + subsequent EBH); c) Surface profiles after TICN + EBH (100Cr6).
Applicazione combinata della tecnologia EHB e del rivestimento duro.

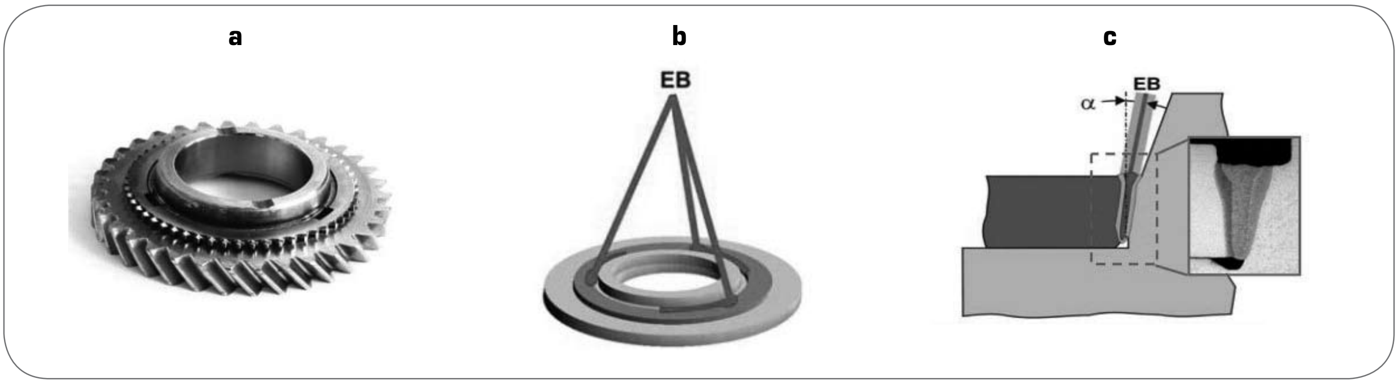

Fig. 8

EB three-spot welding - a) Gear wheel; b) Three-spot welding; c) Detail of welding detail.
Saldatura EB a tre fasci.

A subsequent EB heat treatment after HC has no significant influences on the visual appearance and the structure of the coatings (Fig. 7a). The achievable surface hardness (Fig. 7c) and the hardening depth profile depend on the chemical composition and the pre-heat-treated state of the base material and on the beam hardening conditions. A martensitic layer beneath the hard coating layer is produced, resulting in a significant improvement of the bulk material's load support for the hard coatings. Therefore high surface hardness and high critical loads measured by scratch tests are obtained (Fig. 7b). Additionally, the properties gradient is improved distinctly.

Regarding the application of the HC+EBH combination the surface deformation due to the martensitic transformation must be taken into consideration (Fig. 7c).

EB WELDING

Welding of steel (powertrain components)

A typical powertrain welding unit is shown in Fig. 8a). The conventional procedure used for the EB or laser welding of gear components is a tack welding in a first step and then the joining of the two welding partners by single-pool welding in a second step.

By contrast, in multi-pool welding the components are fixed simultaneously at the time of the first interaction of the EB with the material at several points (Fig. 8b).

It follows in the same processing step a simultaneous movement of several melting pools along one and the same welding seam (Fig. 8b) up to an overlapping zone in the area which has already been welded. The number of welding pools depends on the size and geometry of the part and on the deflection width of the EB. In comparison to the above mentioned two-step technology the welding time is reduced up to one third and also the distortion is minimized because of the lower heating of the parts [7][10][13].

A speciality of multi-pool EB welding is that the welding seam is not perpendicular to the surface (Fig. 8b). The incidence angle of the EB and, consequently, the seam depend on the welding diameter of the welding circle and the distance between beam source and component (Fig. 8c) [10][13].

One important fact for a successful application of multi-pool welding is that the program must be optimized in relation to the jump frequency of the beam from one melting pool to the next and the beam oscillation for an open vapour capillary.

Welding of al alloys (cylinder liner ensembles)

The production of engine blocks as hybrid casting is state of the art. In the automotive industry cast iron cylinder liners are usually applied but there are also cylinder liners made of spray-formed Al materials. The cast engine block either consists of different Al or Mg alloys.

One of the technical difficulties is the precise positioning of each cylinder liner in the mould, one after the other. A technologically more smarter and more profitable technology is the positioning of the liners as so called “liner ensemble” (Fig. 9a). In this case several (2…6) cylinder liners are assembled by EB welding and positioned in the mould as an ensemble in one step. The technical expenditure is much lower [10][15].

Electron beam welding for that application is realised with two-spot techniques using a welding spot and a smoothing spot in one run (Fig. 9c, d).

It has to be taken into account that water jackets are integrated between the cylinder liners which must stay open after welding. Because of the high penetration depth of the EB, the welding takes place only from one side across the water channel up to a depth of 45 mm without closing it (Fig. 9c, d). The diameter of the hole must be ≥ 3.0 mm, but this is normal standard design. The fact that the liners are welded from one side contributes to a very economical production [15].

The application of the two-spot (pool) technique is necessary because most spray formed alloys cannot be welded easily and have a very rough welding bead. The task of the second spot is to smooth the bead.

EB SURFACE ABLATING

Engraving (shaft for force fit with tube)

EB engraving follows the well-known method of producing lateral surface patterns to improve the sliding conditions [27][28], produce reservoirs for colour particles [29], texture the cold rolls to improve sheet quality [30] and - in this present case - to increase the friction in force fits [13].

The principle of these different processes is the same (Fig. 10). At first, the EB with a small diameter remelts the surface in a small pool (Fig. 10a). Then a vapour capillary is produced because of the high beam energy. The vaporised material and some of the liquid material squirt out of the capillary and a molten shell is formed around it (Fig. 10b). Depending on the material and the beam parameters dimples and/or protrusions develop (Fig. 10c).

By applying the EB multi-spot technique, many protrusions can be generated simultaneously around dimples, as spot lines (up to 200 spots per line, Fig. 11a) or as patterns (on a plane surface up to 3.500 spots) during less than 0.15 ms [31].

Large protrusions (Fig. 11b, c) are desired and necessary for force fits of shaft/tube assemblies. The dimples (Fig. 11c) are necessary because they prepare the material for the protrusions.

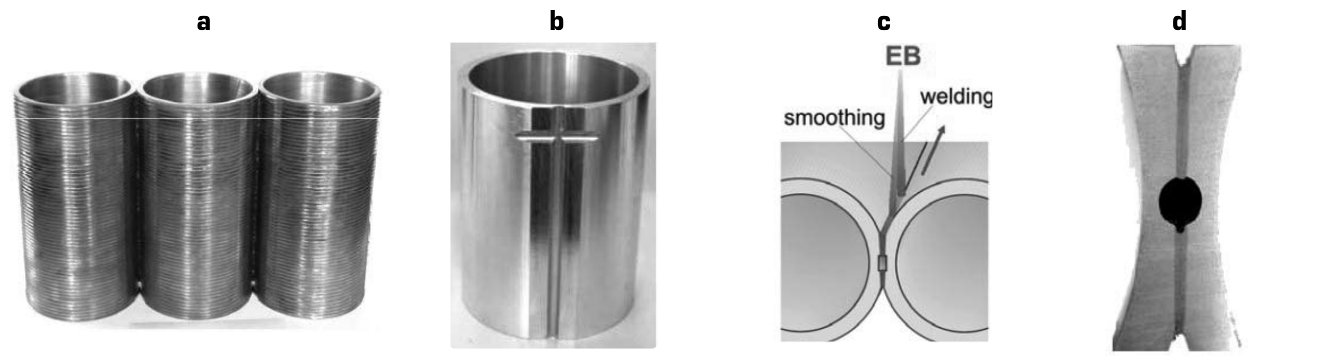

Fig. 9

Two-spot welding of cylinder liner ensembles - a) Cylinder liner ensemble; b) Single cylinder with water channels; c) Welding seam (schematic); d) Welding seam.

Saldatura a due fasci di un complesso di elementi cilindrici allineati.

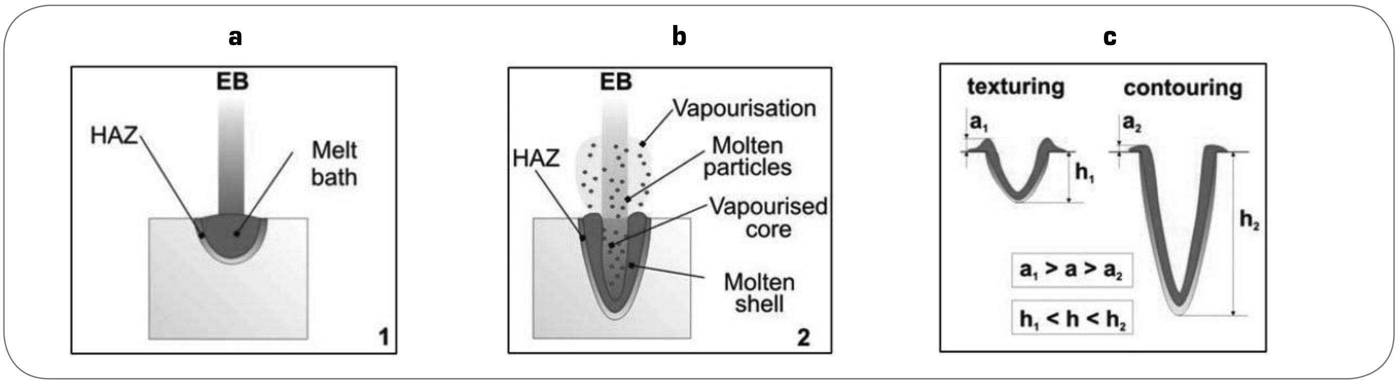

Fig. 10
Principle of engraving.
Schema del processo di incisione.

Profiling (bearing inserts)
In this special application (hybrid casting) used to improve the contact between insert and casting the profiles are much deeper (0.1…0.5 mm) than in the above mentioned applications and have a strong melting seam at the side or around the depression [15]. The EB acts on the surface of the component with a high energy density (105…106 Ws/cm²), causing the material to liquefy and/or vaporise locally within an extremely short time without having a significant thermal effect on the surrounding area.
This EB technology is now developed for bearing shell inserts (Fig. 12a) and cylinder liners made of Al materials [15].
It is of importance for the result of the process whether an alloy is present without (pure metals or eutectic alloy) or with a large solid/liquid melting range (hypo-/hypereutectic alloy). In the latter cases (Fig. 12b, c) a relatively wide re-melted border forms on the edge of the profile (fusion shell).
Depending on the casting (Al or Mg alloy) there are differences in the effect of profiling. As a basic principle, a distinction has to be made between:
- mechanical interlocking (Tm, Insert > Tm, Casting) and
- metallurgical connection in combination with mechanical interlocking (Tm, Insert ~ Tm, Casting)
As it is known, further factors such as the casting method and conditions, temperature control, the position in the mould, etc. affect the result with regard to the form fit and connection between insert and casting.
If the insert is made of an Al alloy as well as the casting the contact between insert and casting is generally good (mechanical interlocking and metallurgical connection, Fig. 12c). Ultrasonic measurements support these results. In areas where there is no contact the ultrasonic waves are reflected at the interface. In case of metallurgical connection there is no or a weak signal (Fig. 12e).
To assess the bond strength of castings with profiled inserts, samples were analysed using static tensile tests. The analyses showed that a bond strength which was 3…10 times higher than it was for non-profiled inserts (1…2.5 kN) was achieved by EB profiling [15] (basis: force up to the point where the insert/casting connection is separated). This may be attributed in particular to the fact that the breaking of samples did not occur at the interface between insert and casting, as it was the case in non-profiled reference samples, but predominantly in the casting.

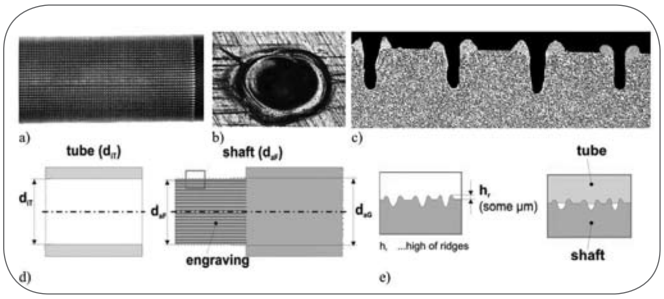

Fig. 11
Multi-spot engraving of shaft for force fits with tubes.
Incisione a più fasci di un albero per accoppiamento forzato con tubi.

The method of EB profiling is a promising alternative to mechanical profiling or coating. The EB method is much faster than the other known technologies of surface "roughening".

SUMMARY AND CONCLUSIONS

- The electron beam can be used effectively in a wide range of surface, joining and removing technologies in all branches of the metalworking industry.
- The availability of new beam guidance techniques is an essential prerequisite for a more and more perfect adaptation of beam handling for technological applications.
- Further progress in EB technologies comes into effect by multi-spot beam deflection techniques and/or multi-process technologies.
- Load, material and component specific technological solutions for EB surface treatment, welding and surface ablation open up new fields for the highly intelligent, flexible and productive EB.
- In the very near future, further new and unconventional design and technical solutions will be available for industrial application.

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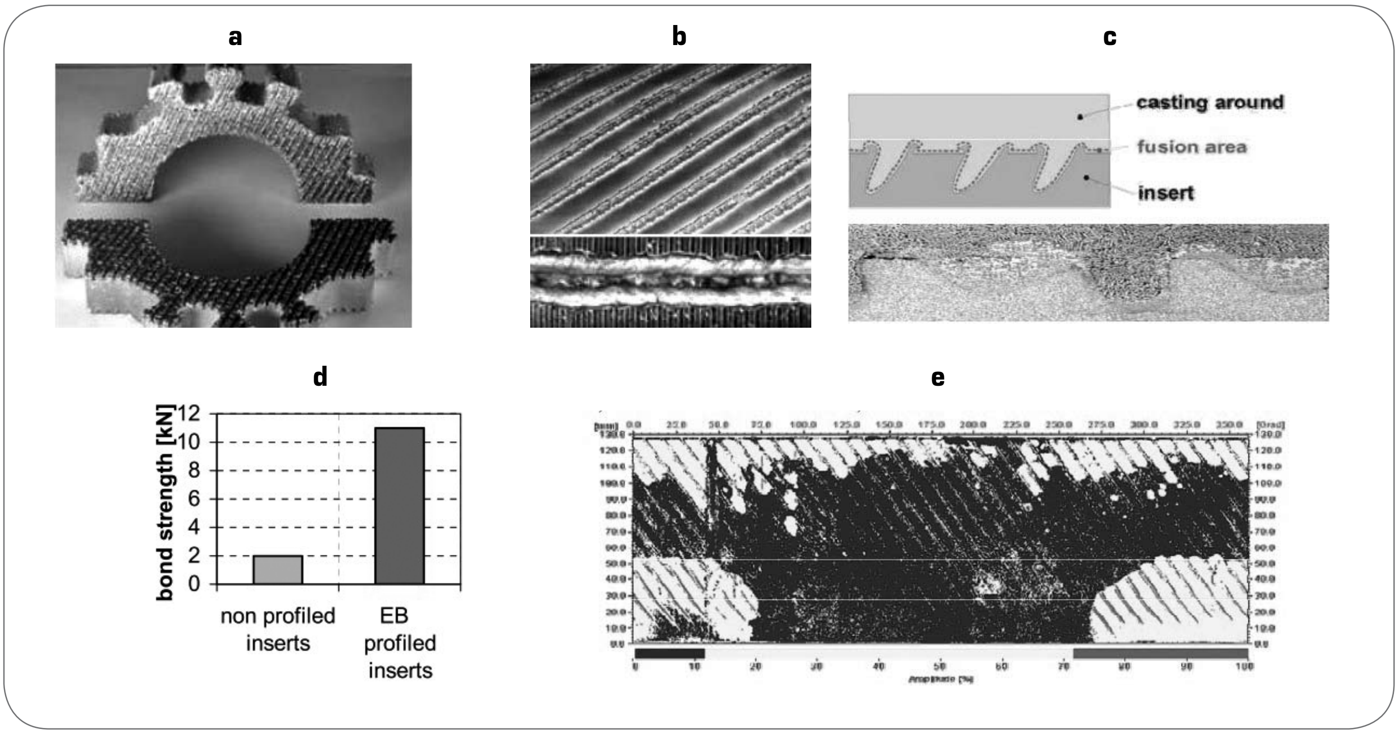

Fig. 12
Multi track profiling of bearing insert.
Profilo a più tracce di un particolare di cuscinetto.

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ABSTRACT

MODERNI PROCESSI TERMICI CON FASCIO ELETTRONICO - RISULTATI DELLA RICERCA E APPLICAZIONI INDUSTRIALI

trattamenti superficiali, proprietà, processi

Parole chiave:

Le tecnologie che sfruttano le caratteristiche termiche dei fasci di elettroni (EB) stanno diventando sempre più attraenti, in particolare perché da un lato sono ecocompatibili e consentono un risparmio energetico, dall'altro danno risultati molto precisi, eccellentemente controllabili e altamente produttivi.

Quando si utilizzano campi tridimensionali di trasferimento di energia, vanno prese in considerazione le condizioni di interazione fra il fascio elettronico e la superficie del materiale, le caratteristiche di conduzione del calore del materiale, la geometria del pezzo e le condizioni di carico del componente. Elevata flessibilità, precisione e riproducibilità sono caratteristiche tipiche delle tecnologie e delle attrezzature EB. L'alta produttività si è ottenuta grazie a nuove soluzioni tecnologiche, come l'interazione simultanea del fascio elettronico con diverse aree di lavoro (spots) o mediante la realizzazione di diversi processi contemporanei nei moderni impianti EB (come il multi-camera, il "lock-type" o altre soluzioni).

Nel presente lavoro si discute l'influenza dei parametri del fascio e delle condizioni di trasferimento di energia sulla microstruttura dei materiali e sulle loro proprietà, per le diverse tecnologie EB. Vengono anche fornite informazioni sulle condizioni ideali di trattamento.

Il documento descrive l'attuale stato di sviluppo delle tecniche di deflessione del fascio, dei processi tecnologici e di alcune soluzioni impiantistiche, oltre a riportare l'attuale stato di applicabilità industriale.