Investigations on the Influence of Parameters During Electron Beam Surface Hardening Using the Flash Technique

S Grafe¹, P Hengst¹, A Buchwalder¹ and R Zenker¹,2

¹ Institute of Materials Engineering, TU Bergakademie Freiberg, 09599 Freiberg, Germany
² Zenker Consult, 09648 Mittweida, Germany

Abstract. The electron beam hardening (EBH) process is one of today’s most innovative industrial technologies. Due to the almost inertia-free deflection of the EB (up to 100 kHz), the energy transfer function can be adapted locally to the component geometry and/or loading conditions. The current state-of-the-art technology is that of EBH with continuous workpiece feed. Due to the large range of parameters, the potentials and limitations of EBH using the flash technique (without workpiece feed) have not been investigated sufficiently to date. The aim of this research was to generate surface isothermal energy transfer within the flash field. This paper examines the effects of selected process parameters on the EBH surface layer microstructure and the properties achieved when treating hardened and tempered C45E steel. When using constant point distribution within the flash field and a constant beam current, surface isothermal energy input was not generated. However, by increasing the deflection frequency, point density and beam current, a more homogeneous EBH surface layer microstructure could be achieved, along with higher surface hardness and greater surface hardening depths. Furthermore, using temperature-controlled power regulation, surface isothermal energy transfer could be realised over a larger area in the centre of the sample.

1. Introduction
Numerous mechanical engineering components – such as gears, camshafts and crankshafts – are subject to high levels of stress in terms of wear, impact and vibration. Such conditions require excellent component properties. Hard surface layers are essential in ensuring sufficient wear resistance. Residual compressive stresses in the surface layer increase fatigue strength. At the same time, a tough core material is necessary to avoid component failure due to brittle fracture [1, 2]. Such component properties can be achieved through thermal surface treatment. One of the most innovative thermal surface treatment technologies used today is that of electron beam hardening (EBH), which generates a hard and wear-resistant martensitic surface layer on the base material [3]. The use of electron beam (EB) as an energy source is characterised by high-speed 2D/3D beam deflection (up to 100 kHz), which provides almost inertia-free movement of the EB. The result is that almost any deflection figure can be generated with defined point and line patterns within a predetermined energy transfer field. The intensity of the energy input within the deflection field is determined by the spot interaction time of the EB and the numbers of energy inputs per spot. This means that the energy transfer function can be adapted to the specific component geometry [2, 4, 5].

Depending on the relative movement between the component and the EB during the interaction process, two beam deflection techniques may be applied – the CI (Continuous Interacting) technique and the flash technique. The CI technique – with the component moving relative to the EB – is mostly used for surface hardening of large components, e.g. camshafts [2, 6]. The flash technique is characterised by a fixed component position under the EB, and is frequently used for components where the treatment area
is not larger than the maximum usable EB energy transfer field. Thus, calottes and the valve seats of cylinders, for example, can be EB hardened using the flash technique [2, 6]. In terms of EBH using the flash technique, the potentials and limitations have not been investigated sufficiently to date. To achieve an optimum result in the hardening process, each point of the energy transfer field must be heated up rapidly to the required austenitising temperature and kept at that temperature over the entire energy impact duration. This process is termed surface isothermal energy transfer. Subsequently, rapid cooling is obtained by self-quenching [5, 7, 8]. Therefore, the goal of these investigations was to generate surface isothermal energy transfer within the energy transfer field applied. To this end, the influence of selected parameters was examined by means of the microstructure and hardness of the EBH layer. The experiments were carried out on the hardened and tempered C45E steel. Surface profile measurements and macroscopic examinations were used to characterise the EBH surface characteristics as a function of the surface hardening depth. Microscopic examinations and hardness-depth measurements were carried out to assess the EBH layer properties. The temperature distribution within the energy transfer field during the process was recorded with a thermographic camera.

2. Experimental details

2.1. Base material and sample preparation

The material used for the investigations was C45E steel in its hardened and tempered pre-heat-treated state, and with the chemical composition given in Table 1.

Table 1. Chemical composition (GDOES analysis).

| Element | Concentration [wt.%] |
|---------|----------------------|
| Fe      | Bal.                 |
| C       | 0.51                 |
| Si      | 0.27                 |
| Mn      | 0.76                 |
| P       | 0.01                 |
| S       | 0.01                 |
| Cr      | 0.14                 |
| Mo      | 0.06                 |
| Ni      | 0.22                 |
| V       | 0.02                 |

The C45E steel was delivered as rolled square-section bar and was cut into standard samples with the dimensions 30 x 30 x 20 mm³. The sample surface to be treated was ground with 500 grit sandpaper. The hardened and tempered C45E steel exhibited a banded microstructure due to the rolling process (Figure 1a). The matrix microstructure consisted of tempered martensite and ferrite (Figure 1b). The ferrite indicated incomplete austenitisation during the volume hardening process.

2.2. Experimental setup

Electron beam surface hardening (EBH) tests using the flash technique were carried out in a universal electron beam facility (K26-15/80, pro-beam, Germany) at the Institute of Materials Engineering, TU Bergakademie Freiberg. Figure 2a shows a schematic diagram of the experimental setup. The sample to be treated was positioned centrally under the electron beam in the working chamber. During the energy
input, a flash field (20 x 20 mm²) interacted with the fixed sample. The flash field applied was programmed over several points (spots) (Figure 2b). For recording the temperature distribution within the entire energy transfer field, a PI 1M thermographic camera from Optris (measurement range: 500 °C–1800 °C) was situated at an angle of 61° and at a working distance of 35 mm from the sample (Figure 2a). The emissivity value used for the thermographic camera was set at 0.24, which conformed to the emissivity value exhibited in general by freshly ground steels and ferrous metals at room temperature [9]. For the temperature-controlled power regulation, a Metis HL-22 ratio pyrometer from SensorTherm (measurement range: 550 °C–1400 °C) was placed in a position similar to that of the thermographic camera. The measurement point was located in the centre of the sample surface. The emissivity ratio for the pyrometer was 1.007. This value was determined in a previous work and adopted for the investigations carried out in this study, cf. [10].

Figure 2. Schematic diagrams of the experimental setup and programmed flash field.

The experimental plan was divided into two work sections. Table 2 shows the parameter sets for each work section.

| Work section | Test series | Beam current \( I_B \) (mA) | Deflection frequency \( f \) (Hz) | Point density (points/mm²) | Set temperature \( T_S \) (°C) |
|--------------|-------------|-----------------------------|---------------------------------|-------------------------------|-----------------------------|
| 1            | 1           | 50                          | 100–10000                       | 25                           | 4000                        | 6.25                        |
|              | 2           | 50                          | 1000                           | 25                           | 444                         | 56.25                       |
|              | 3           | 58.4                        | 1000                           | 25                           | –                           | –                           |
| 2            | 1           | 20–90                       | 250–1000                       | 25                           | 1000                        | 1000                        |
|              | 2           | 20–120                      | 1000                           | 25                           | 1000                        | 1000                        |

In the first work section, the experiments were carried out without temperature-controlled power regulation \((I_B = \text{constant})\) and the frequency, point density and beam current were varied. In the second
work section, the tests were performed using temperature-controlled power regulation, while the influence of the deflection frequency and control range of the beam current was investigated (Table 2). As described in [10], the ratio pyrometer with integrated PID controller measured the actual surface temperature and compared it to the set temperature. The manipulated variable was then sent to the CNC of the EB system. The CNC regulated the beam current according to the manipulated variable to achieve the set temperature [10].

For all of the point figures used in these experiments, the deflection frequency was programmed in the software by means of the point delay. A point delay may be defined as the time delay of the electron beam at one point [11]. Therefore, it functions indirectly as the EB spot interaction time. This provided the following correlation: The EB spot interaction time decreased with increasing deflection frequency, whereby the EB plots the deflection figure in a shorter period of time. For all tests, an acceleration voltage of 60 kV was used and the working distance, focus (surface-sharp) and process time \((t_\text{H} = 4 \text{ s})\) were kept constant.

2.3. Test methods

The characterisation of the EBH surface was carried out by means of macroscopic images and surface profile measurements (Figure 3). The macroscopic images were used to evaluate the geometry and to determine the area of the EBH surface \(A_{\text{EBH}}\) (Figure 3a). The surface profiles were recorded with the non-contact surface measurement system SMS from Breitmeier Messtechnik GmbH. The surface profiles facilitated the determination of the volume expansion (Figure 3b) caused by the formation of martensite [12]. To this end, the line measurements were performed at a measurement point density of 100 points/mm and at a sampling frequency of 50 Hz.

![Figure 3](image)

*Figure 3.* Characterisation of the EBH surface.

The line profiles were recorded in the x-direction (Figure 3a). The area integral between the graph and the initial surface represented the volume expansion that resulted from the martensitic transformation (Figure 3b). The light-microscopic microstructural examination of the EBH layer and determination of the hardness-depth profiles were carried out by means of sample cross sections. Hardness-depth profiles were measured at HV0.3 with a Vickers indenter. The hardness indentations were set as a triple row at a distance of 0.05 mm, with the first indentation located 0.05 mm beneath the sample surface. Depending on the surface hardening depth \((\text{SHD})\), 30 to 60 hardness indentation measurements were carried out per hardness-depth profile. Due to the banded microstructure of the C45E steel, three hardness-depth profiles were recorded per sample. The minimum hardness value \((\text{HV}_{\min})\) and the maximum hardness value \((\text{HV}_{\max})\) were determined for each measurement point of the three hardness-depth profiles. The averaging of \(\text{HV}_{\min}\) and \(\text{HV}_{\max}\) per measurement point resulted in an averaged hardness-depth profile, which was used to determine the surface hardening depth \((\text{SHD})\) according to DIN EN 10328. To
determine the limit hardness, the minimum surface hardness value was calculated from the average of the first three hardness values of the mean hardness-depth profile.

3. Results

3.1. Work section 1: Without temperature-controlled power regulation ($I_B = constant$)

3.1.1. Influence of the deflection frequency

Figure 4 shows macroscopic images of the EBH surface generated with different deflection frequencies. It was found that for lower frequencies of up to 250 Hz, surface melting could occur as a result of the relatively long EB spot interaction times (Figure 4a, b). Deflection frequencies higher than 250 Hz did not lead to surface melting due to the shorter EB spot interaction times (Figure 4c–f). In addition, it could be seen that the applied EBH flash field area of $20 \times 20$ mm$^2$ was only achieved at a low deflection frequency of 100 Hz (Figure 4a). The higher the deflection frequency (up to 1000 Hz), the smaller the EBH surface area formed (Figure 4a–d). This could be explained by the shorter EB spot interaction time associated with increased deflection frequency, which meant that the required hardening temperature in the peripheral areas was no longer achieved or that the lateral heat flow was greater.

![Figure 4. Influence of the deflection frequency on the shape and size of the EBH surface.](image-url)

At higher deflection frequencies ($f \geq 5000$ Hz), the applied EBH field length of 20 mm in the x-direction was almost achieved (Figure 4e, f). The higher number of energy inputs at each spot during the process seemed to compensate for the shorter EB spot interaction time. Nevertheless, the EBH surface appeared to be shortened in the y-direction. It was suspected that the electron beam moved over a longer period of time in the x-direction than in the y-direction, which meant that less energy was introduced in the y-direction. Due to the phenomenon of surface melting at $f \leq 250$ Hz, further test results are presented for deflection frequencies of $f \geq 500$ Hz.

The EBH layer cross sections (Figure 5) exhibited a lens-shaped geometry due to the more rapid heat dissipation in the near-edge areas of the samples compared to that of the sample centre.

![Figure 5. Influence of the deflection frequency on the EBH layer geometry in cross section.](image-url)
For a constant point density, the number of energy inputs per spot influenced the results significantly. The higher the deflection frequency, the higher the number of energy inputs per spot. This resulted in both a wider EBH layer and a more homogeneous martensitic EBH microstructure at deflection frequencies of $f \geq 5000$ Hz (Figure 5c, d). Furthermore, higher deflection frequencies ($f \geq 5000$ Hz) had a positive effect on the hardness-depth profiles measured (Figure 6a). In comparison to lower frequencies ($f \leq 1000$ Hz), the average maximum EBH surface hardness was improved from approx. 509 HV0.3 to 582 HV0.3 (Figure 6a), while the average surface hardening depth (SHD) increased from approx. 0.45 mm to 0.5 mm (Figure 6b). The higher the hardening depth, the higher was the volume expansion after the martensitic transformation (Figure 6b). This could be explained by the higher proportion of martensite formed with increasing hardening depth, which also resulted in higher surface hardness values.

3.1.2. Influence of the point density
As illustrated in Figure 7 by means of etched macroscopic images, the higher the point density, the larger the hardness field formed. Compared to the energy transfer field programmed with the dimensions 20 x 20 mm², the hardness field achieved was smaller. Due to heat conduction at the field edges, the process of martensitic transformation was not completed and a heat-affected zone was formed (the white area in Figure 7). It was found that the higher the point density, the smaller the heat-affected zone generated and, conversely, the larger the EBH area (Figure 7).

The EBH layers exhibited a lenticular geometry in their cross sections (Figure 8), which corresponded to the heat conduction described above. Furthermore, the overview images show a slight increase in the EBH layer width for a higher point density of 56.25 points/mm² (Figure 8c). At low point densities of 6.25 points/mm² and 25 points/mm², the EBH layer exhibited a banded microstructure that resulted from
the rolling process of the base material, and which could not be eliminated by EBH due to the short process times (Figure 8a, b). In comparison, the EBH layer microstructure appeared to be more homogeneous for the highest point density of 56.25 points/mm² (Figure 8c). The higher energy input per area suggested higher treatment temperatures, which led to more uniform carbon distribution with a more homogeneous distribution of the transformation products.

![Figure 8. Influence of the point density on the EBH layer geometry in cross section.](image)

In addition, an increase in EBH surface hardness values and surface hardening depths suggested a higher degree of carbon solution in austenite during the austenitisation process. As a result, the highest point density of 56.25 points/mm² led to both the highest EBH layer hardness value of 669 HV0.3 (Figure 9a) and a surface hardening depth of 0.57 mm (Figure 9b). Similar to the influence of the deflection frequency, there was a correlation between the surface hardening depth and the volume expansion (Figure 9b).

![Figure 9. Influence of the point density on the hardness-depth profiles and the characteristic parameters resulting from the martensitic transformation.](image)

### 3.1.3. Influence of the beam current

Figure 10 shows the influence of the beam current on the macroscopic appearance of the EBH surface with respect to the field area.

![Figure 10. Influence of the beam current on the shape and size of the EBH surface.](image)
The hardened field area increased almost symmetrically with increasing beam current (Figure 10a–c). The reason for this was the higher energy input per spot. As a result, the required transformation temperature for EBH was even achieved at the edges of the EB deflection field – despite more rapid heat dissipation in comparison to that at the sample centre. Nevertheless, the surface exhibited local surface melting (SM) in the centre of the hardened field at a beam current of 66.8 mA (Figure 10c). The light microscopy images of the EBH layers show lenticular edge layer geometries for the above-mentioned reasons (Figure 11). In addition, it can be seen that the EBH layer width increased with increasing beam current from 15 mm (50 mA) to 19 mm (58.4 mA), cf. Figure 11a, b.

![Figure 11](image)

**Figure 11.** Influence of the beam current on the EBH layer geometry in cross section (SM: surface melting).

The maximum surface hardness values achieved in the EBH layer increased with increasing beam current from approx. 490 HV0.3 (50 mA) to 734 HV0.3 (58.4 mA) (Figure 12a). For $I_B = 50$ mA, the austenitisation was incomplete, while for $I_B = 58.4$ mA, the austenitising temperature was high enough to ensure complete carbon dissolution. As mentioned before, surface melting occurred for $I_B = 66.8$ mA, which led to homogenised element distributions, and thus equalised hardness values up to a depth of 0.5 mm as a result of dissolved segregations (cf. Figure 11c, Figure 12a).

![Figure 12](image)

**Figure 12.** Influence of beam current on the hardness-depth profiles and the characteristic parameters resulting from the martensitic transformation.

The hardening depth improved from 0.44 mm (50.0 mA) to 1.02 mm (58.4 mA) for the criterion free of melting (Figure 12b). Similarly to the other test series, the volume expansion increased with increasing surface hardening depth (Figure 12b).
3.2. Work section 2: Temperature-controlled power regulation

The advantage of the temperature-controlled power regulation was the avoidance of surface melting when the conditions of heat conduction proved more difficult to influence. Nevertheless, surface melting occurred at a low deflection frequency of 250 Hz. It was assumed that the P-term selected for the PID controller integrated in the pyrometer was too small for this deflection frequency, such that surface temperatures close to the melting point were reached. No surface melting was detected for deflection frequencies higher than 250 Hz. In addition, the treatment results were largely independent of the deflection frequency and the beam current control range. Almost the same geometries and areas were achieved for the EBH surfaces and EBH layers. However, the area of the EBH surface was still smaller than the energy transfer field area applied. The average maximum surface layer hardness determined from the hardness-depth profiles was approx. 686 ± 10 HV0.3 regardless of the deflection frequency and the beam current control range. The surface hardening depths achieved mean values of approx. 0.82 mm.

When comparing the macroscopic images for the tests without (Figure 13a) and with temperature-controlled power regulation (Figure 13b), it can be established that a more homogeneous hardening field was achieved with temperature-controlled power regulation.

\[
\begin{align*}
(a) & \quad I_B, \text{constant} = 58.4 \text{ mA}, f = 1000 \text{ Hz (without temperature-controlled power regulation)} \\
& \quad A_{EBH} = 3.2 \text{ cm}^2 \\
(b) & \quad I_B = 20–90 \text{ mA, } f = 1000 \text{ Hz (with temperature-controlled power regulation)} \\
& \quad A_{EBH} = 3.0 \text{ cm}^2
\end{align*}
\]

Figure 13. Comparison of the macroscopic appearance of the EBH surface without (a) and with (b) temperature-controlled power regulation.

The reason for this becomes clear upon examination of the images of the thermographic measurements (Figure 14), which were recorded as an example for a selected parameter set without and with temperature-controlled power regulation for certain process times (cf. Figure 13).

\[
\begin{align*}
(a) & \quad \text{Process start} \\
& \quad 2.5 \text{ s} \\
& \quad 3.0 \text{ s} \\
& \quad 3.5 \text{ s} \\
\end{align*}
\]

Figure 14. Stills of thermographic measurements at defined holding times during the EBH process without and with temperature-controlled power regulation.
It can be seen that with temperature-controlled power regulation, surface isothermal energy transfer could be achieved over a larger area in the centre of the sample (Figure 14b), which resulted in more homogeneous hardening within the flash field. In contrast, the temperature increased continuously with a constant beam current during the process without regulation (Figure 14a).

4. Conclusion
For EBH using the flash technique without temperature-controlled power regulation ($I_B = \text{constant}$), low deflection frequencies ($f \leq 250 \text{ Hz}$) were not found to be suitable due to local surface melting. In terms of EBH layer size and surface layer hardness, the best results were achieved at higher deflection frequencies ($f \geq 5000 \text{ Hz}$). By increasing the point density and the beam current, it was possible to increase the area of the EBH surface as well as the surface layer hardness values and the surface hardening depth.

Despite temperature-controlled power regulation, surface melting could not be avoided at a low deflection frequency of 250 Hz. No surface melting was detected for deflection frequencies of $f \geq 500 \text{ Hz}$, whereby the treatment result appeared to be largely independent of the beam current control range and the deflection frequency. Furthermore, surface isothermal energy transfer was achieved in the centre of the sample over a larger area than in the tests without temperature-controlled power regulation. This resulted in more homogeneous surface hardening within the energy transfer field.

5. References
[1] Ruge J, Wohlfahrt H 2001 Technologie der Werkstoffe: Für Studenten des Maschinenbaus und Bauingenieurwesens, der Verfahrenstechnik und der Werkstoffkunde, 6., vollständig neubearbeitete Auflage. Studium Technik. Vieweg+Teubner Verlag, Wiesbaden
[2] Zenker R, Buchwalder A 2010 Elektronenstrahl-Randschichtbehandlung: Innovative Technologien für höchste industrielle Ansprüche, 2nd edn. pro beam AG & Co. KGaA
[3] Zenker R 2013 IFHTSE Global 21: Heat treatment and surface engineering in the twenty-first century Part 15 – Progress in surface heat treatment using electron beam surface hardening. International Heat Treatment and Surface Engineering 5(2) pp 50–56. doi: 10.1179/174951411X12956207253465
[4] Zenker R 1992 Härten mit dem Elektronenstrahl. Taschenbuch der Stahl-Eisen-Werkstoffblätter pp 57–60
[5] Schiller S, Panzer S 1987 Härten von Oberflächenbahnen mit Elektronenstrahlen: Teil I: Verfahrenstechnische Grundlagen. HTM 42(5) pp 293–300
[6] Rödel J 1997 Beitrag zur Modellierung des Elektronenstrahlhärten von Stahl. Zugl.: Freiberg, Techn. Univ., Bergakademie, Diss., 1996. FLUX-Verl., Chemnitz
[7] Zähner R, Müller M 1988 Härten von Oberflächen mit Elektronenstrahlen: Teil II: Experimentelle Ergebnisse und Anwendung. HTM 43(2) pp 103–111
[8] Opbris GmbH 1997 Grundlagen der berührungslosen Temperaturmessung. Accessed 01 Dec 2017
[9] Halbauer L, Hofner M, Proksch P et al. 2017 Prospects and limitations of a temperature controlled power regulation system for electron beam technologies. In: International Conference on Joining Materials - JOM 19, vol 1
[10] Kahnert M 2015 Scanstrategien zur verbesserten Prozessführung beim Elektronenstrahlschmelzen (EBM). Zugl.: München, Techn. Univ., Diss., 2014. Forschungsberichte / IWB, vol 293. Utz, München
[11] Zenker R, Müller M 1987 Randschichthärten mit Elektronenstrahlen - Verfahrenstechnische Möglichkeiten und werkstofftechnische Effekte. Neue Hütte 32(4) pp 127–134

Acknowledgments
The authors gratefully acknowledge the Dobeneck Technology Foundation for its financial support of the “EB-Flash” research project.