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Influence of EB parameters on the temperature-time profile during EB hardening as a single or combined surface treatment

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Abstract. This paper focuses on the influence of EB parameters on temperature-time profiles when using an electron beam hardening field with surface isothermal energy distribution. Along with the energy-transfer density eF , the power density in the EBH field q plays a key role in determining the microstructure and hardening depth. For the combined treatment of magnetron-sputtered Ti1-xAlxN coatings with subsequent EBH, it was shown that crack formation was reduced and technically relevant surface-hardening depths were achieved without negatively influencing the wear-resistant PVD hard coatings if an EBH field with lower power density was used.

1. Introduction

Electron beam hardening (EBH) with the CI (continuous interaction) technique is a well-established surface hardening process used in the production of a wide range of components. In this case, the EB and the component move in relation to each other, thus generating a track-shaped hardening zone. A two-dimensional mode of beam deflection (field scan) has been proven to be advantageous in comparison to a line scan technique. Because of the longer interaction time, technically relevant transformation depths are realized without near-surface remelting [1]. EBH using rectangular hardening fields, which cause surface isothermal energy transfer, have been the state of the art for some 30 years [2, 3]. In this case, a field with variable energy density in the direction of feed (see Figure 1a) passes over the component, ensuring that the energy density is higher at the front of the field than at the end.

This energy distribution can be adapted by the position and density of the grid lines [3]. The energy distribution in the feed direction, the exposure time (field length, feed rate) and, above all, the thermal conductivity of the steel determine the temperature-time profile in the treated surface layer [4].

For optimized hardening results, fundamental knowledge of the influence of the EB parameters on the resulting temperature-time cycles is required. By varying the EB parameters beam current I_b , feed rate v_x and field length A_x , respectively, the surface hardening depth (SHD) can be adjusted with a high degree of reproducibility. In general, a maximum power density is applied during single-process EBH to achieve the required SHD. In this case, the surface temperature is just below the melting point of the



steel. Consequently, the SHD increases linearly with increasing energy input, and is usually given by the transfer energy density e_F , see equation 1.

$$SHD \sim e_F = \frac{U_a \cdot I_b}{v_x \cdot A_y} \quad (1)$$

with U_a ...acceleration voltage of the EB, I_b ...beam current, v_x ...feed rate, A_y ...width of the energy-transfer field.

The transfer energy density can be described as a product of power density q (equation (2)) and interaction time t_H (equation (3)). This contribution shows that these parameters also play a key role regarding the effect on microstructure and hardening depth. At a given feed rate v_x , the beam power (beam current I_b) and the length of the energy-transfer field (A_x), as shown in Figure 1b and c, are possible regulating variables for the power density in the energy-transfer field.

$$q = \frac{P_0}{A_x \cdot A_y} \quad (2)$$

$$t_H = \frac{A_x}{v_x} \quad (3)$$

with P_0 ...beam power, A_x ...length and A_y ...width of the energy-transfer field v_x , ...feed rate.

Especially in connection with a combined treatment, such as PVD hard coating with subsequent EBH [5–7], it is not expedient to generate the hardening depth demanded with maximum power density in the EBH field [8]. With this combined treatment, the load-supporting capacity of heat-treatable low-alloyed steels (e.g. 42CrMo4 and 51CrV4, among others) for the hard and brittle coatings is significantly increased [9]. However, the thermal stability of the mostly metastable PVD coatings is limited, and cracks and delaminations might form depending on the surface temperature during EBH [10]. For the combination of magnetron-sputtered $Ti_{1-x}Al_xN$ coatings with subsequent EBH, it is shown that crack formation can be reduced and technically relevant SHDs are achieved without negative influence on the wear-resistant PVD coatings if an EBH field with lower power density is used.

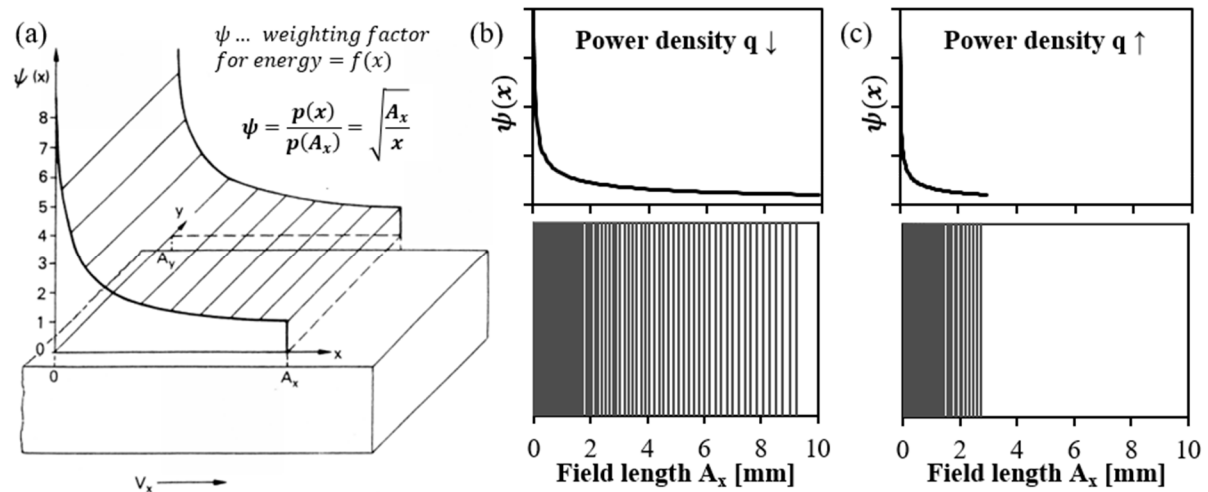


Figure 1. Schematic representation of the energy distribution in the energy-transfer field [3] (a) and influence of the field length on the power density in the EBH field (b, c).

2. Experimental Details

2.1. Base material

The QT steel 51CrV4 (DIN 1.8159; AISI 6150) was chosen as the base material. Hardening (850 °C/0.5 h) and tempering (630 °C/1 h) resulted in a defined hardness of 30 HRC. Prior to coating deposition, the specimens were ground and polished ($R_z < 0.1 \mu\text{m}$).

2.2. Coating deposition

The $\text{Ti}_{1-x}\text{Al}_x\text{N}$ coatings with varying compositions ($x = 0.32\text{--}0.68$) and with different thicknesses (1–6 μm) were deposited in a CemeCon CC800 coating facility at Fraunhofer IST, Braunschweig (Germany), using a reactive magnetron-sputter deposition process as described by Keunecke [11]. A pulsed DC bias voltage (U_{BIAS}) of 90 V was applied. The chemical composition of the coatings was adjusted by using combinations of targets with different compositions (Ti, TiAl (50:50), TiAl (33:67)). The layer thickness was controlled by adjustment of the coating time. After substrate pre-heating and sputter cleaning with argon, a thin adhesion-improving ($\text{Ti}_{1-x}\text{Al}_x$) interlayer was deposited by sputtering.

2.3. Electron beam hardening

For electron beam hardening of the uncoated and PVD-coated specimens, the multi-purpose electron beam facility K26-15/80 (pro-beam systems GmbH, Neukirchen, Germany) at TU Bergakademie Freiberg, Germany was used. A continuous interaction (CI) technique with a rectangular energy-transfer field was applied. This resulted in track-shaped hardening with an almost surface-isothermal energy distribution during the interaction time (t_H). The adjacent areas remained almost unaffected. For the present investigations, the track width (A_y) was limited to 20 mm and the acceleration voltage (U_a) of 60 kV was held constant. The hardening temperature, the time of interaction and, thus, the hardening depth were controlled by varying the field length (A_x), beam current (I_b), and feed rate (v_x).

The surface temperature-time cycle was recorded by means of a Sensortherm METIS MI 16 pyrometer (temperature range: 350 – 1800 °C). The measuring point ($\varnothing 3 \text{ mm}$) was positioned in the middle of the EBH track, i.e. directly in the interaction area. An emission ratio of $\varepsilon = 0.29$ was used for the steel. The emission ratio of $\text{Ti}_{1-x}\text{Al}_x\text{N}$ ranged from 0.41 ($x = 0.32$) to 0.63 ($x = 0.63$) depending on the chemical composition.

2.4. Characterization methods

The results after the individual treatment EBH as well as after the combined treatment PVD + EBH were characterized by examination of the surface and metallographic cross sections by means of light optical microscopy (LOM) and scanning electron microscopy (SEM). The surface deformation and the surface roughness within the EBH track were measured by means of a contactless surface scanning system (BMT Breitmeier Messtechnik).

The hardness gradient of the EB-treated steel was described by hardness-depth profiles (LECO M400, $F = 0.4903 \text{ N}$, Vickers-shaped diamond indenter), and the surface hardening depth was determined according to DIN ISO 15787, with a hardness limit of 550 HV 0.05 (SHD 550 HV0.05) for the steel 51CrV4.

The load-supporting capacity of the base material was characterized by measuring the surface hardness HV 1 (a mixed value of substrate and hard-coating hardness) and by evaluating the coating's adhesion by scratch testing according to DIN EN 1071-3 (progressive load: $F_N = 1\text{--}80 \text{ N}$, 10 N/mm).

3. Results and Discussion

3.1. Electron beam hardening

To obtain deeper insights into the mechanisms of EBH with variable energy distribution, the influence of different parameters – namely the geometry of the EBH field (field length A_x and field width A_y), beam current I_b and feed rate v_x – on the power density and, hence, on the results of EBH were investigated.

The linear dependence of the SHD on the transfer energy density e_F (red lines in Figure 2) is a function of an exact combination of transfer energy density and interaction time. To this end, Schiller et al. [3] offer a helpful chart for defining the field length and feed rate depending on the required hardening depth.

To reduce the power density at given interaction times, the **beam current I_b** was reduced, while keeping the other parameters constant. For each interaction time, the SHD was again proportional to the transfer energy density. The slopes of the regression lines are nearly the same for each interaction time t_H . At a constant interaction time, the transfer energy density or, rather, the power density was limited by surface remelting. With decreasing interaction time (increasing power density), surface remelting occurred at surface hardening depths that were more and more shallow. The highest possible power density, which did not lead to surface remelting, corresponded with the general linear dependence described by Panzer et al. [12] and experimentally proved for the given steel by Zenker et al. [13] (Figure 2) [8].

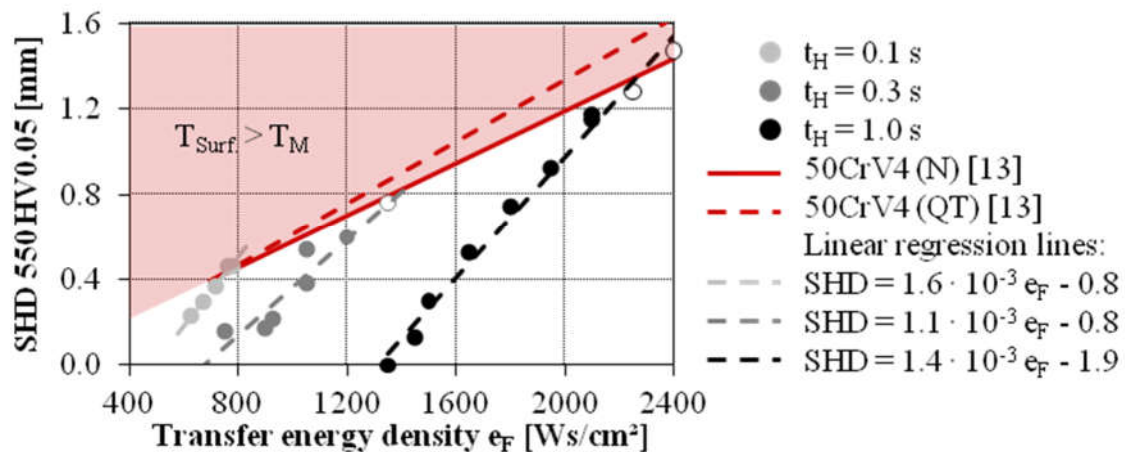


Figure 2. Correlation between transfer energy density e_F and surface hardening depth SHD during EBH for three different interaction times t_H . Open dots denote surface melting. Red lines: linear dependence between e_F and SHD at optimal power density (N ...normalized, QT ...quenched and tempered) [13].

With regard to a constant interaction time (for example $t_H = 1$ s in Figure 3), an increasing transfer energy density (increasing beam current I_b) led to an increasing amount of dissolved carbon. Consequently, the hardness in the EBH layer increased until the complete dissolution of carbon in the austenite. At first, however, the surface hardness increased at a higher rate than could be explained solely by the increasing martensite hardness. This was due to the shallow transformation depths and, therefore, to the influence of the softer substrate. Once the EBH layer was thick enough, surface hardness levelled out.

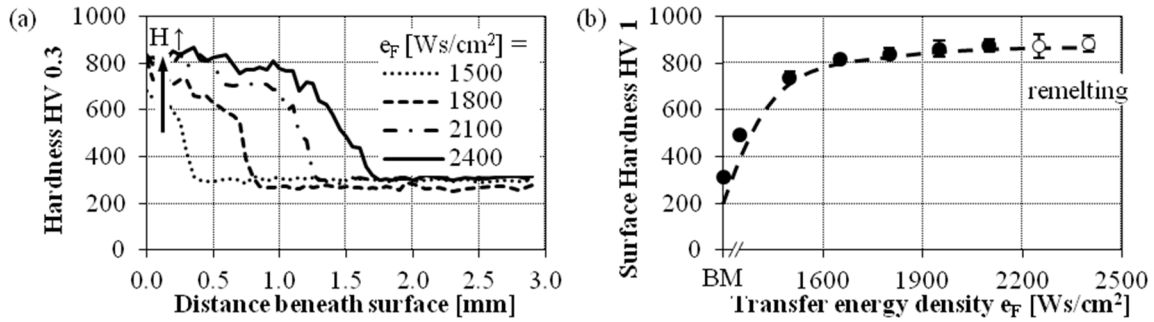


Figure 3. Influence of transfer energy density ($t_H = \text{const.} = 1$ s) on the hardness-depth profile (a) and the surface hardness (b) during EBH of the 51CrV4 steel.

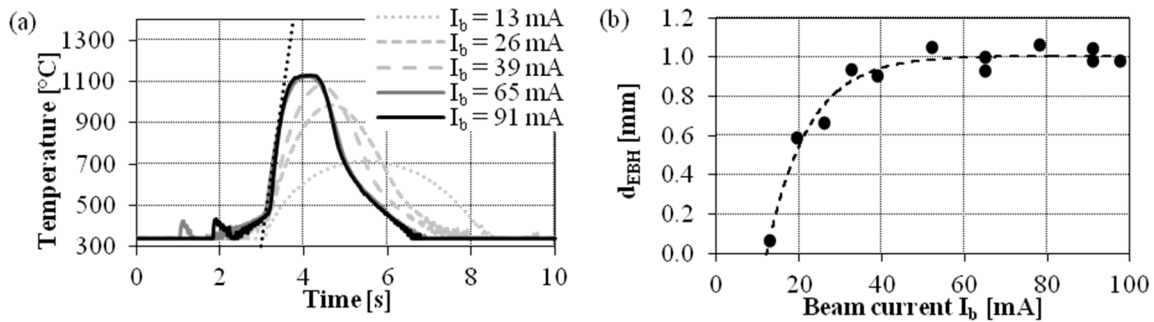


Figure 4. Influence of beam current on the temperature-time profile at the surface (a) and the transformation depth d_{EBH} (b) at $e_F = \text{const.} = 1950$ Ws/cm² and $t_H = \text{const.} = 1$ s.

At constant transfer energy density e_F and constant interaction time t_H , the beam current significantly influences the energy absorption (see [14]). With increasing beam current, surface temperature and transformation depth d_{EBH} also increased continuously until a critical beam current value of approx. $I_{b,crit.} = 40$ mA (Figure 4). At higher values, the parameters remained constant within narrow confines ($d_{EBH} = 1.0 \pm 0.1$ mm, $T \approx 1000$ °C).

A further possibility to enable variation of the power density was the variation of the **field length** A_x (Figure 1b, c). At a constant transfer energy density, the power density decreased while the interaction time increased (equations (1-3)). The transformation depth was a linear function of the inverse of the power density (q^{-1}), see Figure 5. It reacted in a less sensitive manner to the variation of power density by variation of the field length ($e_F = \text{const.}$) than by variation of the beam current ($t_H = \text{const.}$), as the slopes of the curves in Figure 5 illustrate [8]. With increasing interaction time, the power density decreased, resulting in higher thermal loading of the whole component.

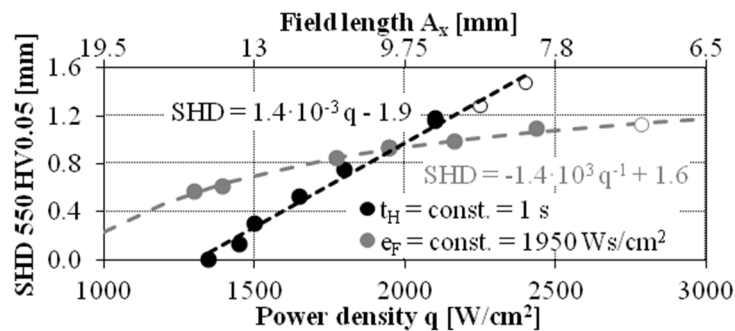


Figure 5. Surface hardening depth as a function of the power density (open symbols: surface melting).

3.2. Combined treatment PVD hard coating with subsequent electron beam hardening

3.2.1. Energy absorption during EBH considering inhomogeneous absorption layers. During EBH, the majority of the kinetic energy of the electrons transforms into thermal energy within the so-called absorption layer. The thickness of the absorption layer is equal to the absorption range of the electrons, R [15]. For most of the thermal EB processes, the spatial resolution of the energy absorption is negligible. However, in the case of the combined treatment PVD + EBH, the depth dose distribution has to be taken into account, because the PVD hard coating is thinner than the absorption range R , which means that the absorption layer is inhomogeneous. Therefore, influencing factors on energy absorption during EBH would be expected, such as thickness, density and the chemical composition of the PVD hard coating. The main parameter influencing the energy input is the backscattering coefficient, which depends on the atomic number of the material in the absorption layer. For steel, the atomic number of which is equal to Iron ($Z = 26$), the backscattering coefficient is 0.27. The average atomic number of $\text{Ti}_{1-x}\text{Al}_x\text{N}$ depends on the aluminium content of the hard coating. The theoretical value of the backscattering coefficient η_B^∞ decreased with increasing Aluminium content (open icons in Figure 6) and was 28 to 36% lower than that of steel. However, the backscattering coefficient of a layer-matrix compound $\eta_{B,tot}$ [16] – which has to be considered if the thickness of the hard coating d_C is less than half of the absorption range ($d_C < R/2$) – was almost independent of the chemical composition (filled icons in **Error! Reference source not found.**). For the investigated $\text{Ti}_{1-x}\text{Al}_x\text{N}$ coatings, $\eta_{B,tot}$ is approx. 0.21 [8].

Because of the smaller backscattering coefficient, the degree of efficiency during EBH of $\text{Ti}_{1-x}\text{Al}_x\text{N}$ -coated steels was significantly higher than that of the uncoated steel. At a given beam power, the real energy input increased, resulting in surface temperatures that were approx. 10% higher (Figure 7a). Therefore, the transformation depth of $\text{Ti}_{1-x}\text{Al}_x\text{N}$ -coated steels was 30-35% larger than that of the uncoated specimens (Figure 7b). The influence of the chemical composition on the treatment results was marginal.

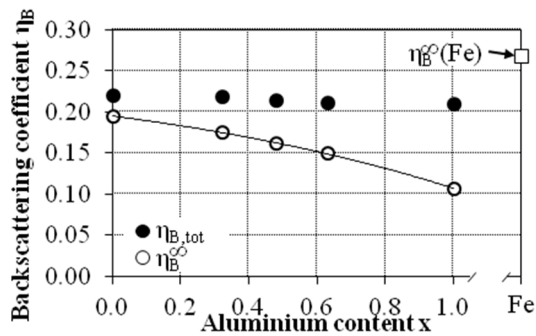


Figure 6. Influence of the aluminium content of $\text{Ti}_{1-x}\text{Al}_x\text{N}$ coatings ($d_C = \text{const.} = 3 \mu\text{m}$) on the calculated backscattering coefficient $\eta_{B,tot}$ (true for $d_C < R/2$) and η_B^∞ (true for $d_C \geq R/2$) compared to steel (Fe).

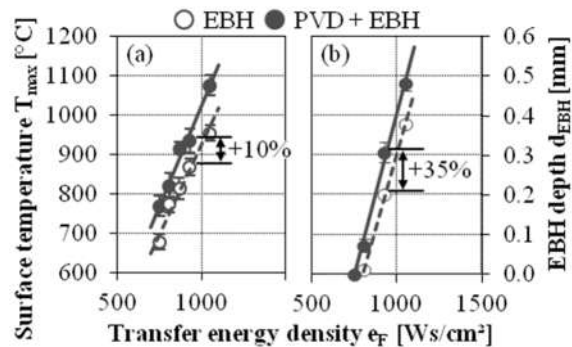


Figure 7. Surface temperature (a) and resulting transformation depth (b) as a function of transfer energy density for uncoated (open dots) and PVD coated steel (filled dots). Icons represent mean values and standard deviation of the three PVD hard coatings investigated, namely: $\text{Ti}_{0.68}\text{Al}_{0.32}\text{N}$, $\text{Ti}_{0.52}\text{Al}_{0.48}\text{N}$ and $\text{Ti}_{0.37}\text{Al}_{0.63}\text{N}$.

The **thickness of the $\text{Ti}_{1-x}\text{Al}_x\text{N}$ coating**, however, significantly influenced both the real energy input during EBH and the transformation depth. With increasing coating thickness, the backscattering coefficient of the layer-matrix compound $\eta_{B,tot}$ decreased (Figure 8a), because the energy transformation occurred increasingly in material with a lower degree of backscattering.

Consequently, at a given transfer energy density, the surface temperature and, therefore, the transformation depth increased with increasing coating thickness (Figure 8b) [8]. With higher transfer energy density (but lower power density), in particular, the surface hardening depth of the combined treated specimens was many times higher than that of the uncoated steel. Presumably, this effect was caused by the lower thermal conductivity of the PVD hard coating.

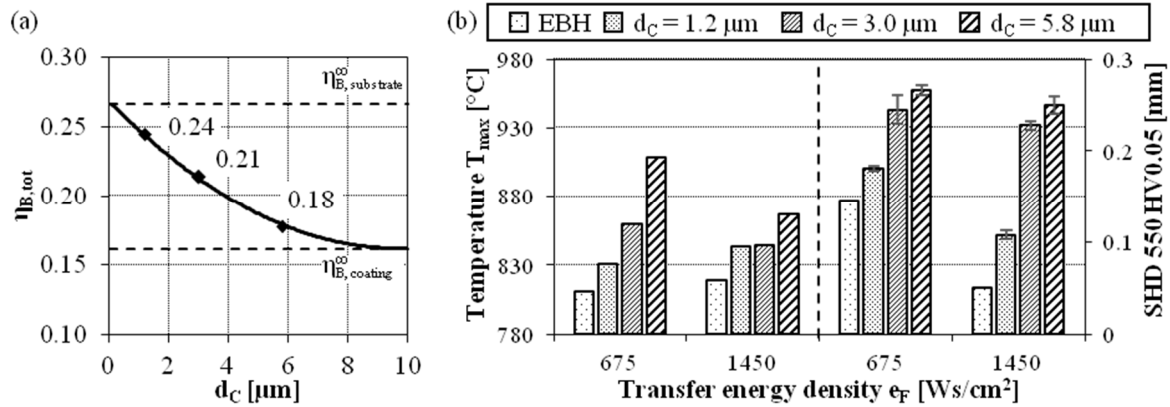


Figure 8. Backscattering coefficient of the layer-matrix compound (coating $Ti_{0.52}Al_{0.48}N$) as a function of coating thickness (a), and influence of coatings thickness on the maximal surface temperature (b, left), with the resulting surface hardening depth SHD (b, right).

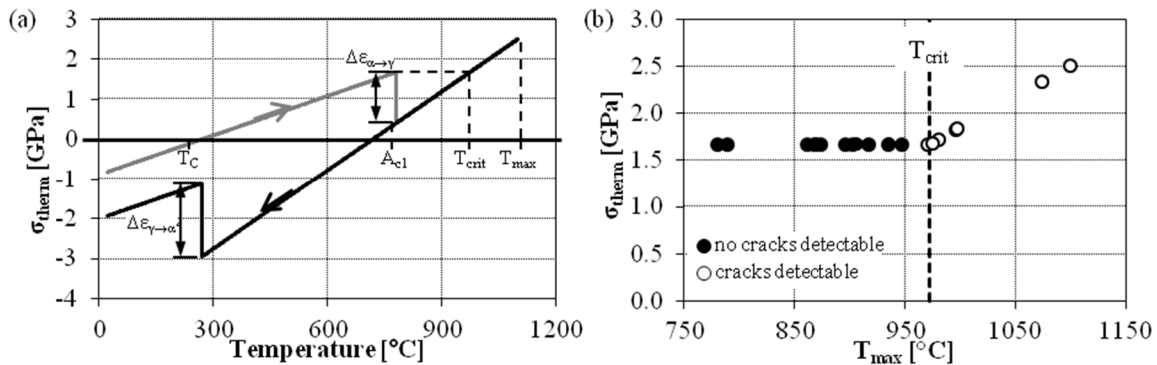


Figure 9. Estimation of the thermal stresses during EBH, with $T_{max} = 1100^{\circ}C$ [10] (a) and the relationship between thermal stresses and crack susceptibility (b) for the $Ti_{0.37}Al_{0.63}N$ coating ($d_C = 3 \mu m$).

3.2.2. Influence of power density on crack formation in the PVD hard coatings during EBH. Electron beam hardening temporarily exposes PVD hard coatings to high thermal loading, because the thermal expansion coefficients of layer and matrix differ significantly. In addition, the phase transformations in the steel have to be considered. Treatment in a vacuum and the very short interaction time minimize undesirable effects like changes in chemical composition by oxidation or diffusion and, consequently, loss of hardness.

With increasing energy input, damage occurred to the layers. First, cracks appeared perpendicular to the direction of the feed. For estimating the development of thermal stresses in the PVD coatings, Hollmann et al. [10] create a thermal model (Figure 9a), which shows that crack formation is related to a critical temperature T_{crit} . For the Al-rich coating $Ti_{0.37}Al_{0.63}N$ with relatively low crack resistance, cracks only occurred if the surface temperature exceeded the critical temperature T_{crit} (Figure 9b). As shown in Figure 2, the required transformation depth was achievable by using different values of transfer energy density, which were associated with different interaction times and power densities. To

prevent crack formation, it is advantageous to apply a lower power density and longer interaction time, so that the surface temperature during EBH does not exceed T_{crit} [8]. Hence, technically relevant surface hardening depths of SHD = approx. 0.3 to 0.4 mm can be attained without crack formation in PVD hard coatings.

4. Conclusions

For EB hardening with surface isothermal energy distribution, a relatively high power density is normally applied. For the combined treatment of PVD hard coating with subsequent EBH, it is not expedient to generate the hardening depth required with maximum power density in the EBH field. The thermal stability of the PVD coatings is limited, and cracks and delaminations might form – depending on the surface temperature during EBH. For the combination of magnetron-sputtered $Ti_{1-x}Al_xN$ coatings with subsequent EBH, it was shown that crack formation was reduced and technically relevant SHDs were achieved – without negatively influencing the wear-resistant PVD coatings – if an EBH field with lower power density was used. At a given feed rate v_x (fixed cycle time), the beam power (beam current I_b) and the length of the energy-transfer field (A_x) could be used to regulate the power density in the energy-transfer field. At a given field length ($A_x = \text{const.}$), the hardening depth was proportional to the power density in the EBH field. At a constant beam power ($I_b = \text{const.}$), it behaved in an inversely proportional manner to the power density in the EBH field.

Because of the eminently suitable beam guidance technique, EB technology is perfectly applicable for the combined treatment of PVD hard coatings with subsequent surface hardening.

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