

Bevezetés a lézeres anyag- megmunkálásba

FBN332E-1

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Diagram - grafikon

Diagram:

empirikus

általában elegendő trendek, átfogó változások bemutatására

Grafikon:

egy (matematikai) modell áll mögötte

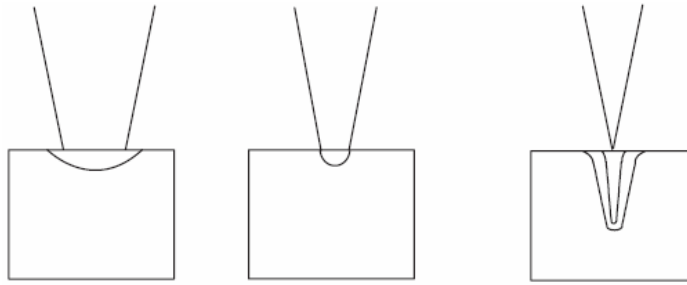
kalibrációval pontosítható

következtetések levonására, becslések megtételéhez elengedhetetlen

Process variables, principal process variables (PPV)

Processing mechanisms, principal processing mechanism (PPM)

Lézeres hőkezelés (egyensúly)



PPV

nyaláb teljesítmény (q)
nyaláb sugár (r_B)
anyagi jellemzők

teljesítménysűrűség $E = \frac{q}{r_B^2 \pi}$

PPM

fűtés

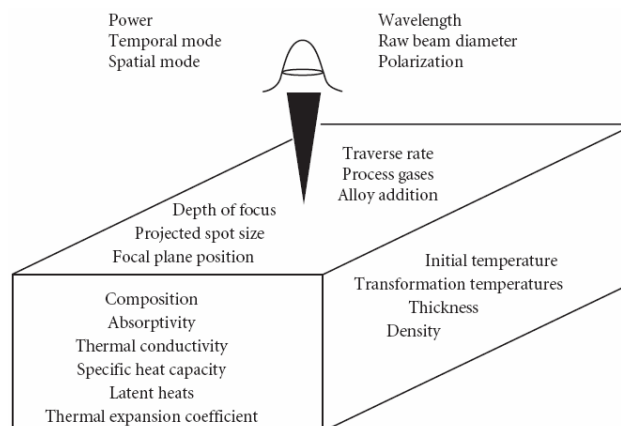
olvadás

párologtatás

$E \approx 10Wmm^{-2}$ $E \approx 100Wmm^{-2}$ $E \approx 10000Wmm^{-2}$

acél, cw, $\lambda=10.6\mu m$

Lézeres hőkezelés (tranziciens)



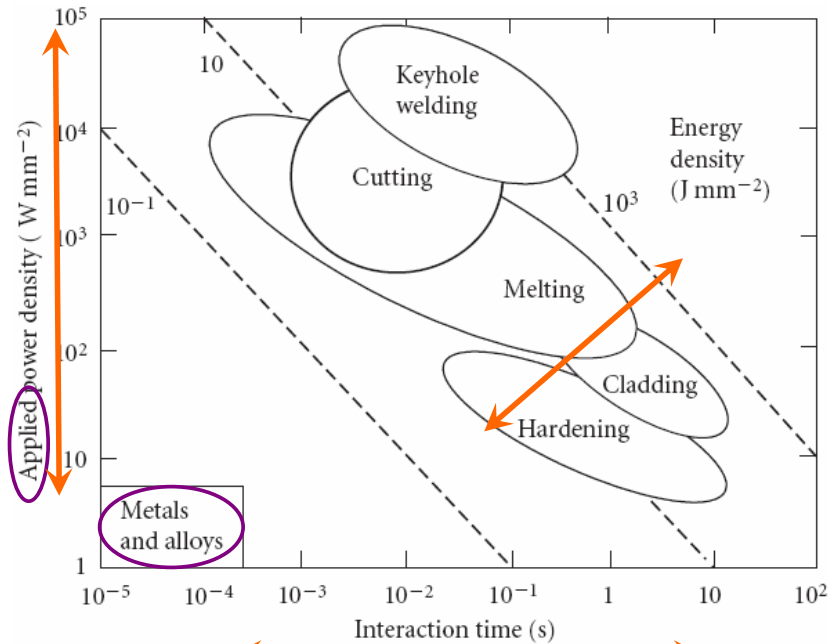
relatív sebesség, v

PPV

teljesítménysűrűség (E)
fűtési idő ($t \sim \tau$)
anyagi jellemzők

$$\tau = \frac{2r_B}{v}$$

Az empírikus diagram 1.



csoportok -> a PPV "jók"

átfedések

Az empírikus diagram 2.

Mire jó?

- fizikai tartalom
- megkülönbözteti az egyes folyamatokat
- rávilágít az energiasűrűség szerepére

Mire nem jó?

- nem teszi lehetővé a becslést
- anyagspecifikus
- vajon található-nánk az energiasűrűségnél jobb PPVt?

Table E2.1 (Contd)

Type	Shape	Energy distribution	Equation	Eqn no.	Source			
Moving	Point		$T_{(0,0,0,t)} - T_0 = \frac{Aq}{\pi^{3/2}\lambda r_B} \tan^{-1} \left(\frac{4at}{r_B^2} \right)^{1/2}$	E2.8	(Ready, 1971)			
			$T_{0,0,0,\infty} = \frac{\pi^{1/2}}{2} \frac{Aq}{\pi \lambda r_B} = 0.866 \frac{Aq}{\pi \lambda r_B}$	E2.9	(Ready, 1971)			
			$T_{(r,0,0,t)} - T_0 = \frac{Aq}{2\pi \lambda v t} \exp \left(\frac{r^2}{4at} \right)$	E2.10	(Rosenthal, 1946; Ashby and Easterling, 1982)			
			$\left(\frac{dT}{dt} \right)_{T>T_p} = -2\pi \lambda \frac{v}{Aq} (T - T_0)^2$	E2.11				
			$T_p - T_0 = \frac{2}{\pi e} \frac{Aq}{\rho c v r^2}$	E2.12				
			$(\Delta t T_2 - T_1)_{T>T_p} = \frac{Aq}{v} \frac{1}{2\pi \lambda \theta_1}$	E2.13				
			$t_p = \frac{Aq}{v} \frac{1}{2\pi \lambda e} \frac{1}{T_p - T_0} = \frac{\Delta t T_2 - T_1 \theta_1}{e(T_p - T_0)} = \frac{r^2}{4a}$	E2.14				
			$T - T_0 = \theta_1 \frac{\Delta t}{t} \exp \left[-\frac{\Delta t}{et} \left(\frac{\theta_1}{(T_p - T_0)} \right) \right]$	E2.15				
			where $\frac{1}{\theta_1} = \frac{1}{T_1 - T_0} - \frac{1}{T_2 - T_0}$					
			and $T_2 > T_1$					
			$w_{T_{p1} - T_{p2}} = \left\{ \frac{Aq}{v} \frac{2}{\pi e \rho c} \left[\frac{1}{(T_{p1} - T_0)} - \frac{1}{(T_{p2} - T_0)} \right] \right\}^{1/2}$	E2.16				
			Fast moving	Circular	Gaussian	$T_{(0,y,z,t)} - T_0 = \frac{Aq}{2\pi \lambda v [t(t+t_0)]^{1/2}} \times \exp \left[-\frac{1}{4a} \left(\frac{z^2}{t} + \frac{y^2}{t+t_0} \right) \right]$	E2.17	(Rykalin <i>et al.</i> , 1978)
			Moving	Circular	Gaussian	$T_{(0,y,z,t)} - T_0 = \frac{Aq}{2\pi \lambda v [t(t+t_0)]^{1/2}} \times \exp \left[-\frac{1}{4a} \left(\frac{(z+z_0)^2}{t} + \frac{y^2}{t+t_0} \right) \right]$	E2.18	(Ashby and Easterling, 1984)
						$T_{(0,0,z,t)} - T_0 = \frac{Aq}{2\pi \lambda v [t(t+t_0)]^{1/2}} \times \exp \left[-\frac{1}{4a} \left(\frac{(z+z_0)^2}{t} \right) \right]$	E2.19	
						$\frac{dT}{dt} = \frac{(T - T_0)}{t} \left(\frac{(z+z_0)^2}{4at} - \frac{(2t+t_0)}{(2t+2t_0)} \right)$	E2.20	
			$t_p = \frac{t_0}{4} \left(\frac{2 \frac{(z+z_0)^2}{r_B^2} - 1}{\left(\frac{4 \frac{(z+z_0)^4}{r_B^4}}{+ \frac{12 \frac{(z+z_0)^2}{r_B^2} + 1}{r_B^2}} \right)^{1/2}} \right)$	E2.21				

Analitikus hőmérsékleteloszlások (vonalmenti forrás)

Table E3.1 Analytical equations for the temperature field around a through-thickness energy source

Type	Shape	Equation	Eqn no.	Source
Stationary	Line	$\frac{Aq}{d} = \frac{2\pi\lambda(T_1 - T_2)}{\ln\left(\frac{r_2}{r_1}\right)}$	E3.1	(Klemens, 1976)
Moving	Line	$T_{(r,t)} - T_0 = \frac{Aq}{vd} \frac{1}{(4\pi\lambda\rho ct)^{1/2}} \exp\left(-\frac{r^2}{4at}\right)$	E3.2	(Rosenthal, 1941; Ashby and Easterling, 1982)
		$\frac{dT}{dt} = -\left(\frac{vd}{Aq}\right)^{1/2} \frac{1}{4(\pi\lambda\rho c)^{1/2}} (T - T_0)^{3/2}$	E3.3	
		$T_p - T_0 = \frac{Aq}{vd} \left(\frac{1}{2\pi e}\right)^{1/2} \frac{1}{\rho cr}$	E3.4	
		$(\Delta t T_2 - T_1)_{T > T_p} = \left(\frac{Aq}{vd}\right)^2 \frac{1}{4\pi\lambda\rho c} \frac{1}{\theta_2^2}$	E3.5	
		$t_p = \left(\frac{Aq}{vd}\right)^2 \frac{1}{4\pi\lambda\rho c} \frac{1}{(T_p - T_0)^2}$ $= \frac{\Delta t \theta_2^2}{e(T_p - T_0)^2} = \frac{r^2}{2a}$	E3.6	
		$T - T_0 = \theta_2 \left(\frac{\Delta t}{t}\right)^{1/2} \exp\left(-\frac{\theta_2^2 \Delta t}{2et(T_p - T_0)^2}\right)$	E3.7	
		where $\frac{1}{\theta_2^2} = \frac{1}{(T_1 - T_0)^2} - \frac{1}{(T_2 - T_0)^2}$		
		and $T_2 > T_1$		
		$w_{T_{p1} - T_{p2}} = \frac{Aq}{vd} \left(\frac{1}{2\pi e}\right)^{1/2}$ $\times \frac{1}{\rho c} \left[\frac{1}{(T_{p1} - T_0)} - \frac{1}{(T_{p2} - T_0)} \right]$	E3.8	

Jelölések

Symbol	Definition	Units
A	Absorptivity	-
A _B	Constant of precipitate solubility product	m ²
B	Beam area	K
C _{eq}	Constant of precipitate solubility product	wt%
C _m	Carbon equivalent	wt%
	Concentration of metal species of precipitate	
	M _d C _p in solution	
C _c	Concentration of non-metal species of precipitate	wt%
	M _d C _p in solution	
D	Diffusion coefficient, D = D ₀ exp -(Q/RT)	m ² s ⁻¹
D ₀	Pre-exponential of diffusion coefficient	m ² s ⁻¹
E	Beam power density	J s ⁻¹ m ⁻²
F	Heat flux	J m ⁻² s ⁻¹
H	Vickers hardness number	VPN
H _b	Vickers hardness number of bainite	VPN
H _{fp}	Vickers hardness number of ferrite-pearlite mixture	VPN
H _m	Vickers hardness number of martensite	VPN
I	Kinetic strength of a thermal cycle	-
L _m	Volumetric latent heat of melting	J m ⁻³
L _m *	Normalized latent heat of melting,	-
	L _m * = L _m /[ρc(T _m - T ₀)]	
L _v	Volumetric latent heat of vaporization,	J m ⁻³
L _v *	Normalized latent heat of vaporization,	-
	L _v * = L _v /[ρc(T _m - T ₀)]	
M _f	Martensite finish temperature	K
M _s	Martensite start temperature	K
Q	Activation energy	J mol ⁻¹
R	Gas constant, 8.314	J mol ⁻¹ K ⁻¹
T	Temperature	K
T ₀	Initial temperature	K
T _{Ac1}	Temperature at which pearlite transforms to austenite on heating	K
T _{Ac3}	Temperature at which ferrite transforms to austenite on heating	K
T _{M_s}	Temperature at which martensite starts to form on cooling	K
T _{M₅₀}	Temperature at which martensite formation is 50% complete on cooling	K
T _{M_f}	Temperature at which martensite formation is complete on cooling	K
T _m	Melting temperature	K

Symbol	Definition	Units
T_s	Dissolution temperature of a precipitate	K
T_v	Vaporization temperature	K
V	Volume fraction	-
V_b	Volume fraction of bainite	-
V_{fp}	Volume fraction of ferrite-pearlite mixture	-
V_m	Volume fraction of martensite	-
V'	Volume fraction of bainite	-
a	Cooling rate at 923 K	K h^{-1}
c	Thermal diffusivity, $\lambda/(\rho c)$	$\text{m}^2 \text{s}^{-1}$
d	Specific heat capacity	$\text{J kg}^{-1} \text{K}^{-1}$
e	Plate thickness	m
f	Base of natural logarithms, 2.718	-
g	Matrix volume fraction available for precipitate dissolution	-
g_0	Grain size	m
k	Original grain size	m
l	Kinetic constant	Various
l	Depth of treatment	m
p	Precipitate size	m
p_0	Original precipitate size	m
q	Beam power	J s^{-1}
q_{max}	Peak beam power in a Gaussian distribution	J s^{-1}
q_v	Volumetric rate of heat generation	$\text{J s}^{-1} \text{m}^{-3}$
r	Radial distance from centre of a surface heat source	m
r	Lateral distance from centre of a through-thickness heat source	m
r_B	Beam radius defined where $q = q_{max}/e$, or beam half-width	m
t	Time	s
t_0	Time for heat to diffuse over beam radius, $r_B^2/(4a)$	s
t_p	Time taken to attain peak temperature	s
v	Beam traverse rate	m s^{-1}
w	Width (spacing of two isotherms)	m
z	Depth	m
z_0	Model displacement of workpiece surface	m
z_t	Thermal penetration depth	m
$\Delta t_{2/1}$	Time to cool from T_2 to T_1	s
$\Delta t_{8/5}$	Time to cool from 800 to 500°C	s
Δt_{m}^{100}	Characteristic $\Delta t_{8/5}$ for 100% martensite formation	s
Δt_{m}^{50}	Characteristic $\Delta t_{8/5}$ for 50% martensite formation	s
Δt_{m}^{0}	Characteristic $\Delta t_{8/5}$ for 0% martensite formation	s
Δt_{f}^{0}	Characteristic $\Delta t_{8/5}$ for 0% ferrite formation	s
Δt_{p}^{0}	Characteristic $\Delta t_{8/5}$ for 0% pearlite formation	s
Δt_{b}^{50}	Characteristic $\Delta t_{8/5}$ for 50% bainite formation	s
Δt_{b}^{0}	Characteristic $\Delta t_{8/5}$ for 0% bainite formation	s
λ	Thermal conductivity	$\text{J s}^{-1} \text{m}^{-1} \text{K}^{-1}$
ρ	Density	kg m^{-3}
τ	Beam interaction time	s

Termodinamikai egyensúly

Álló nyaláb, homogén kivilágítás

$$E2.2 \quad T - T_0 = \frac{Aq}{\lambda A_B} \left(\frac{4at}{\pi} \right)^{1/2}$$

$$t = \tau \quad \text{a kölcsönhatás ideje} \quad E = A \frac{q}{A_B} = A \cdot E_i$$

$$T - T_0 = \frac{E}{\lambda} \left(\frac{4a\tau}{\pi} \right)^{1/2}$$

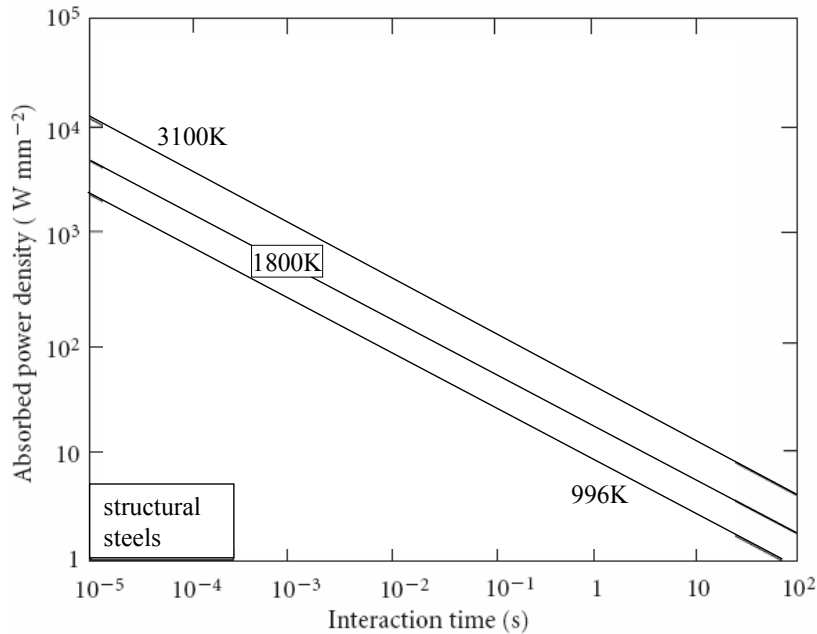
$$\log(T - T_0) = \log E + \frac{1}{2} \log \tau + \log \frac{2a^{1/2}}{\pi^{1/2} \lambda}$$

$$\log E = \log(T - T_0) + \log \frac{\pi^{1/2} \lambda}{2a^{1/2}} - \frac{1}{2} \log \tau$$

Figyelem! E most az **abszorbeált** teljesítménysűrűség, míg az empirikus diagramon a **mintára eső** E_i szerepelt!

A modellezés eredménye

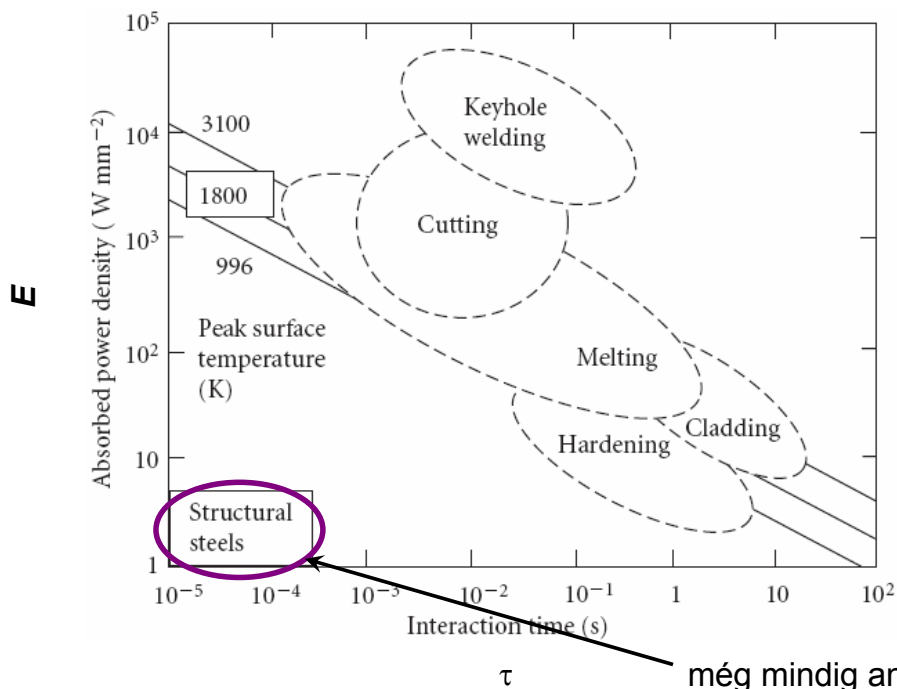
Karakterisztikus hőmérsékletek: $T_{\text{párolgás}}=3100\text{K}$
 $T_{\text{felszíni forrás}}=1800\text{K}$
 $T_{\text{ausztenit képz.}}=996\text{K}$



A grafikon

$E_i \rightarrow E$ konverzió után

az abszorptivitás közelíthető:
 0.5 hardening
 0.3 melting
 0.5 cladding
 0.5 cutting
 0.8 keyhole welding



még mindig anyagspecifikus!