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Využitie spektroskopických metód na sledovanie mikroštruktúry reaktorových ocelí

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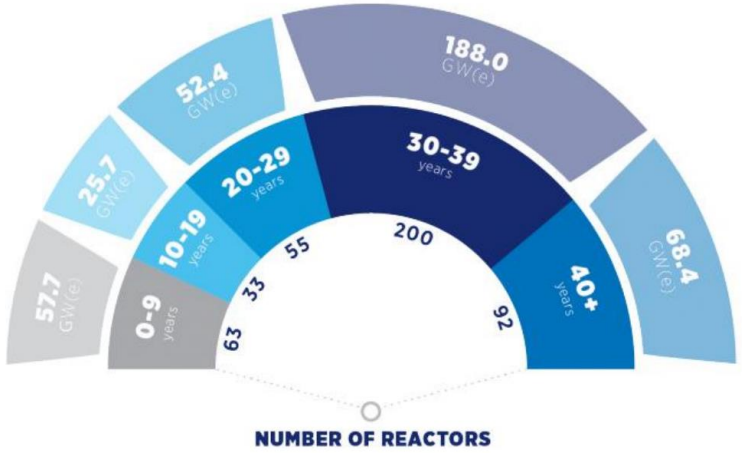
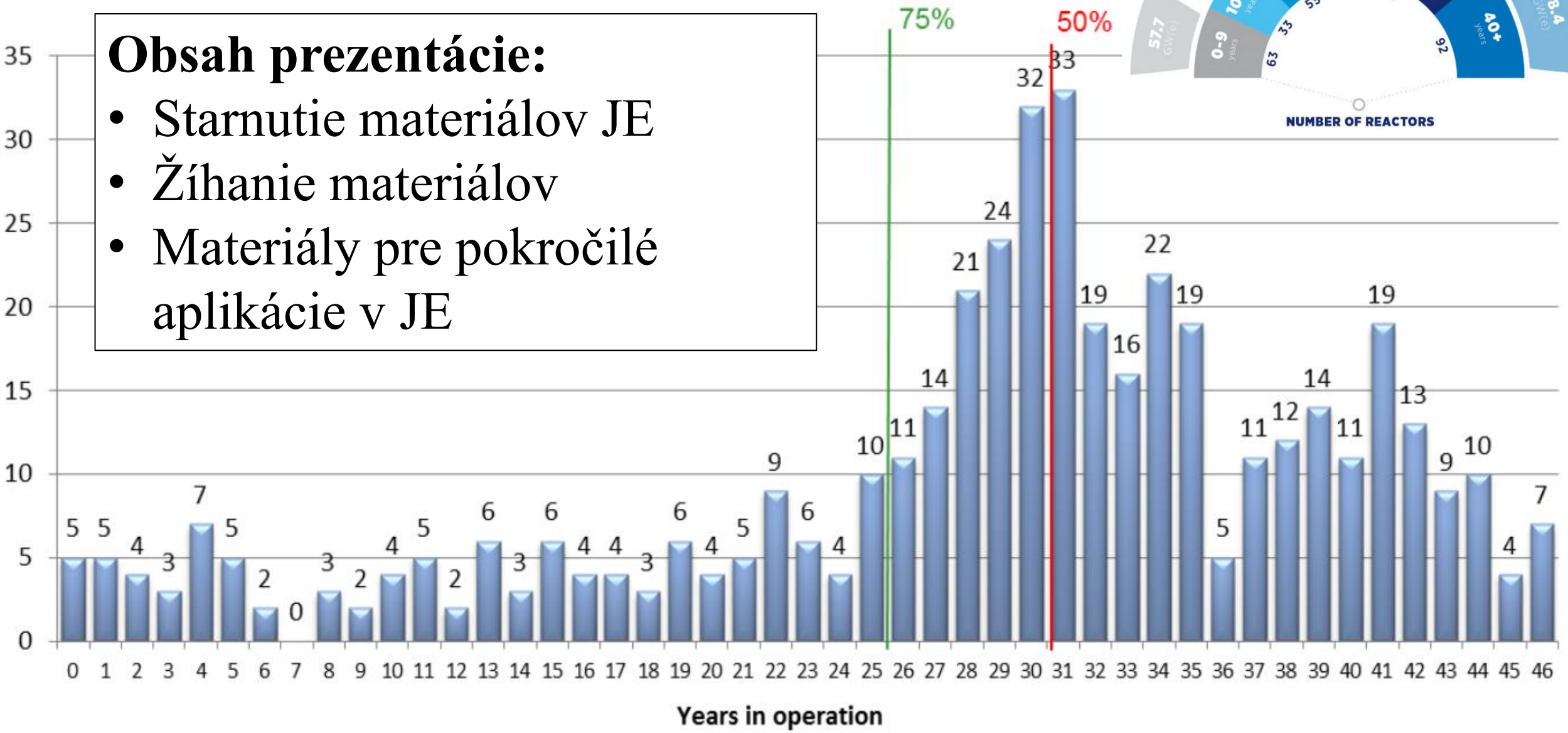
Obsah prezentácie:

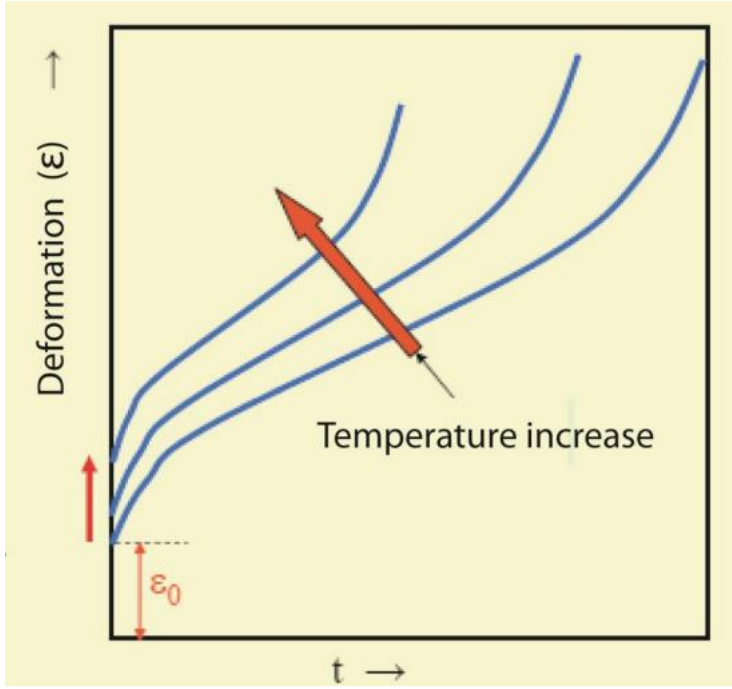
- Starnutie materiálov JE
- Žíhanie materiálov
- Materiály pre pokročilé aplikácie v JE

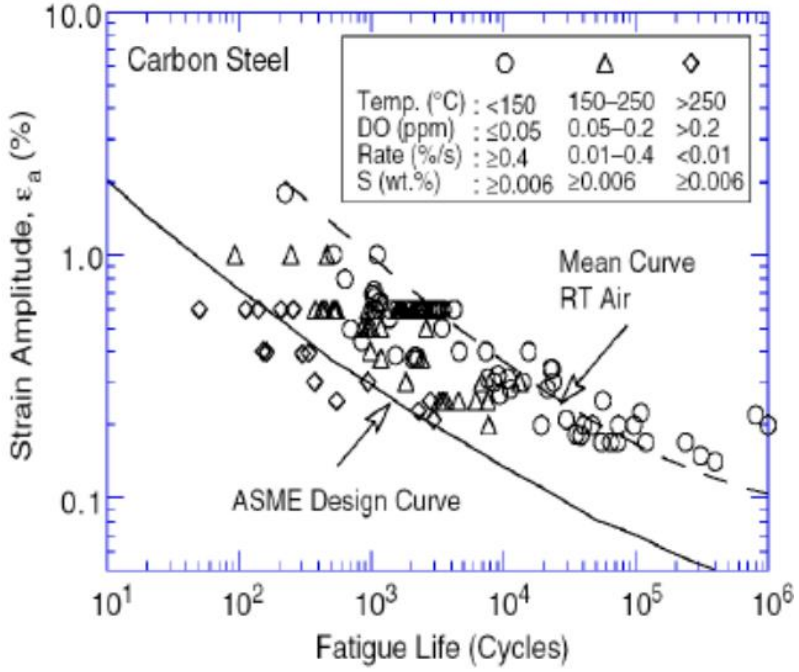


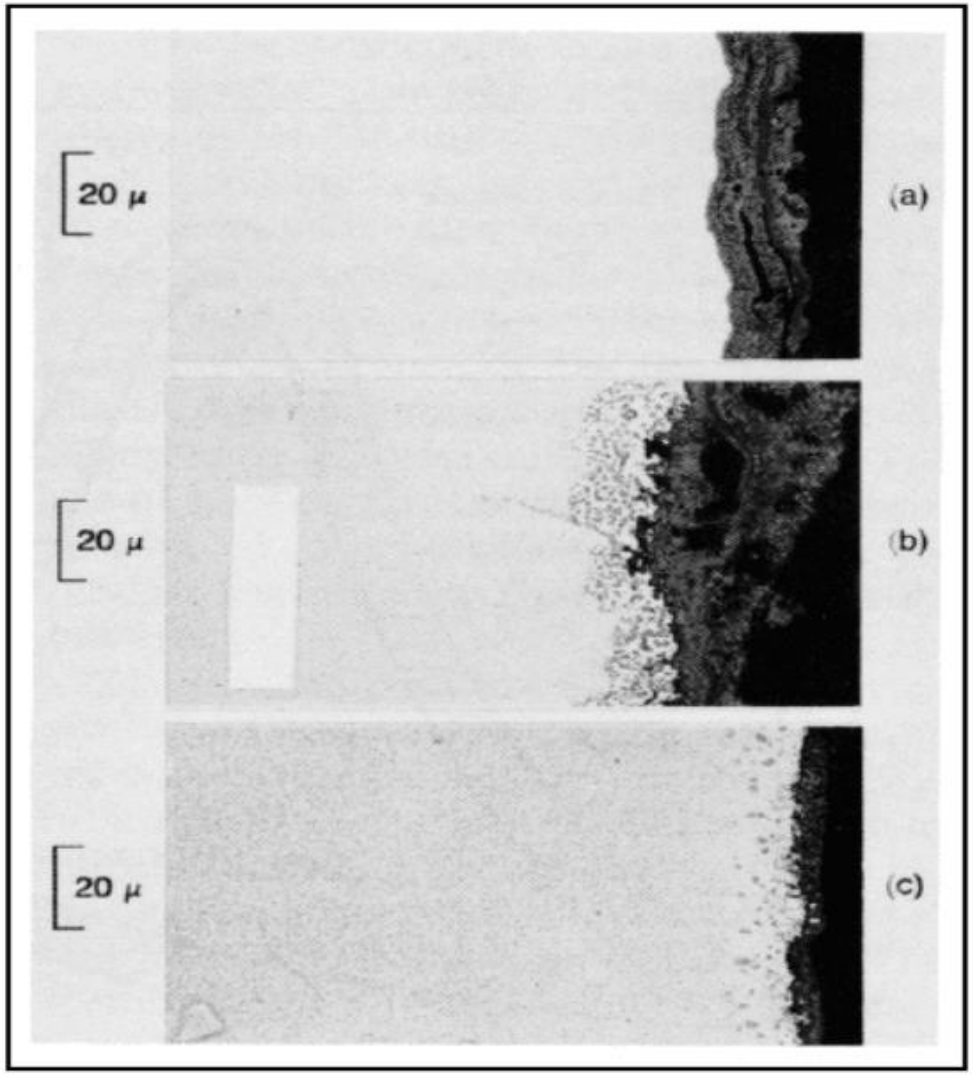


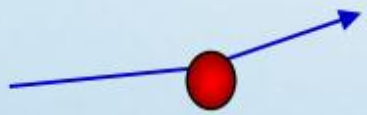
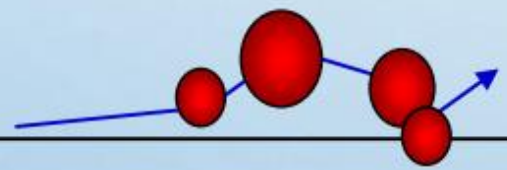
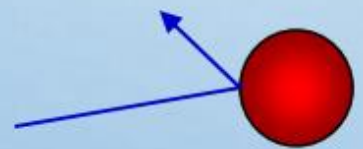
Starnutie materiálov v primárnom okruhu

- Termomechanické namáhanie – teplota, tlak,
- Cyklické napätie
- Vplyv korozívneho prostredia (N, H, He, C, S)
- Radiačná záťaž



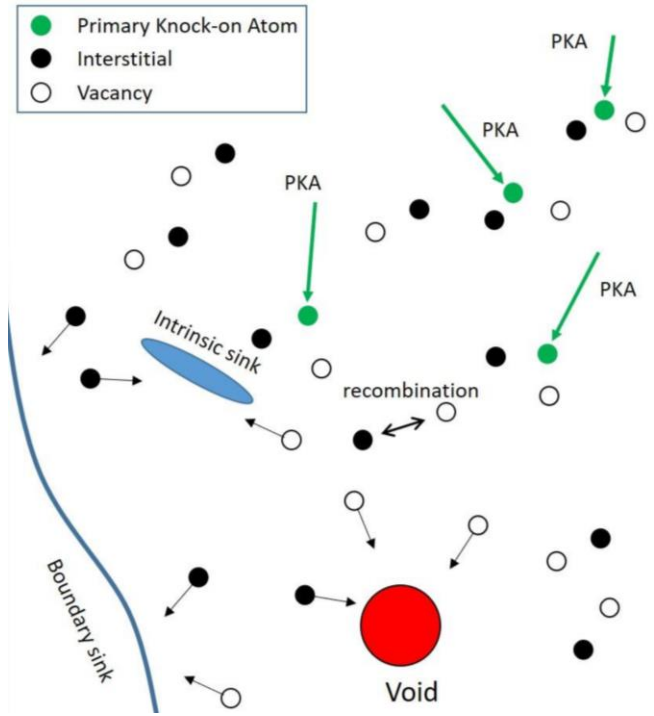


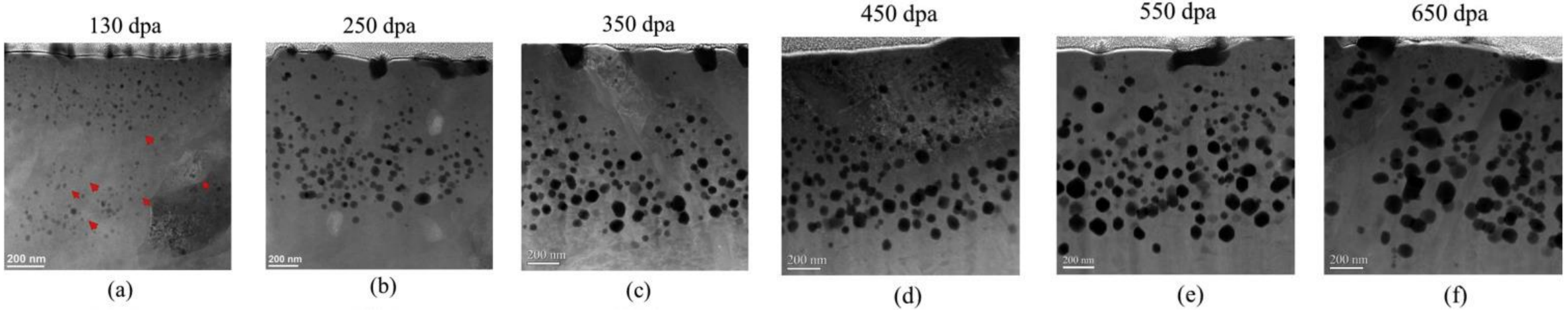


Particle type (E_{kin} = 1 MeV)	Typical recoil (or PKA) feature	Typical recoil energy T	Dominant defect type
Electron		25 eV	• Frenkel pairs (Vacancy-Insterstitial pair) • Cascades & sub-cascades • Transmutation
Proton		500 eV	
Fe-ion		24 000 eV	
Neutron		45 000 eV	

Žiarením vyvolané zmeny vlastností

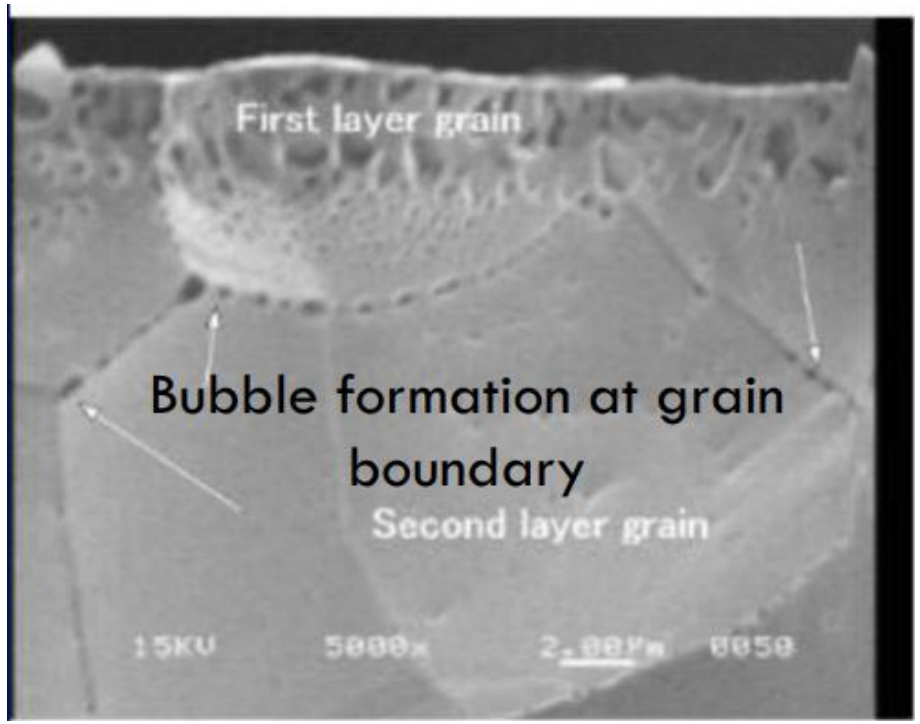
Tvorba Frenkelových párov vedie k:
Zvýšenie hustoty dislokácií → krehnutie
Tvorba dutín → napučiavanie (typické pre fcc oceľ)
Zvýšená difúznosť → lokálna segregácia
Amorfizácia alebo kryštalizácia → neočakávaná zmena fázy
Plastická nestabilita – dislokačné tunely

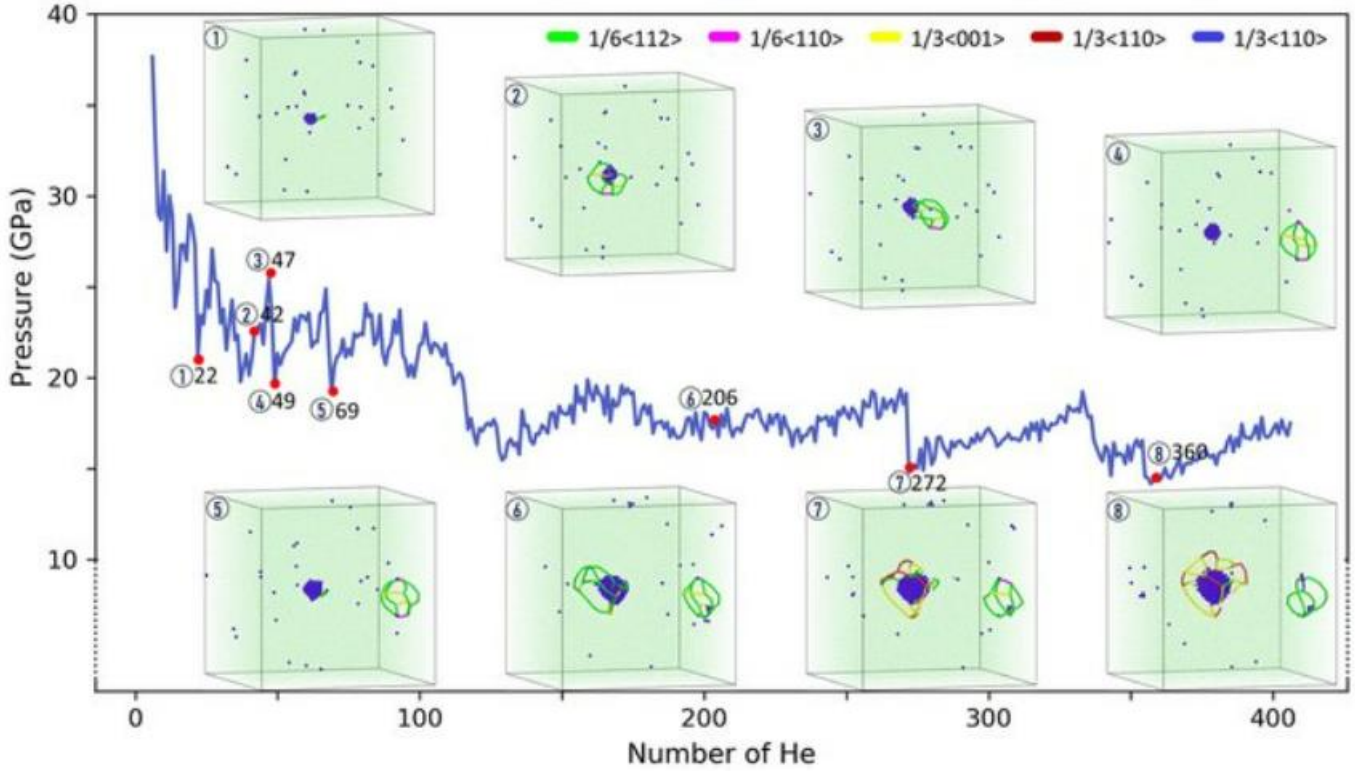




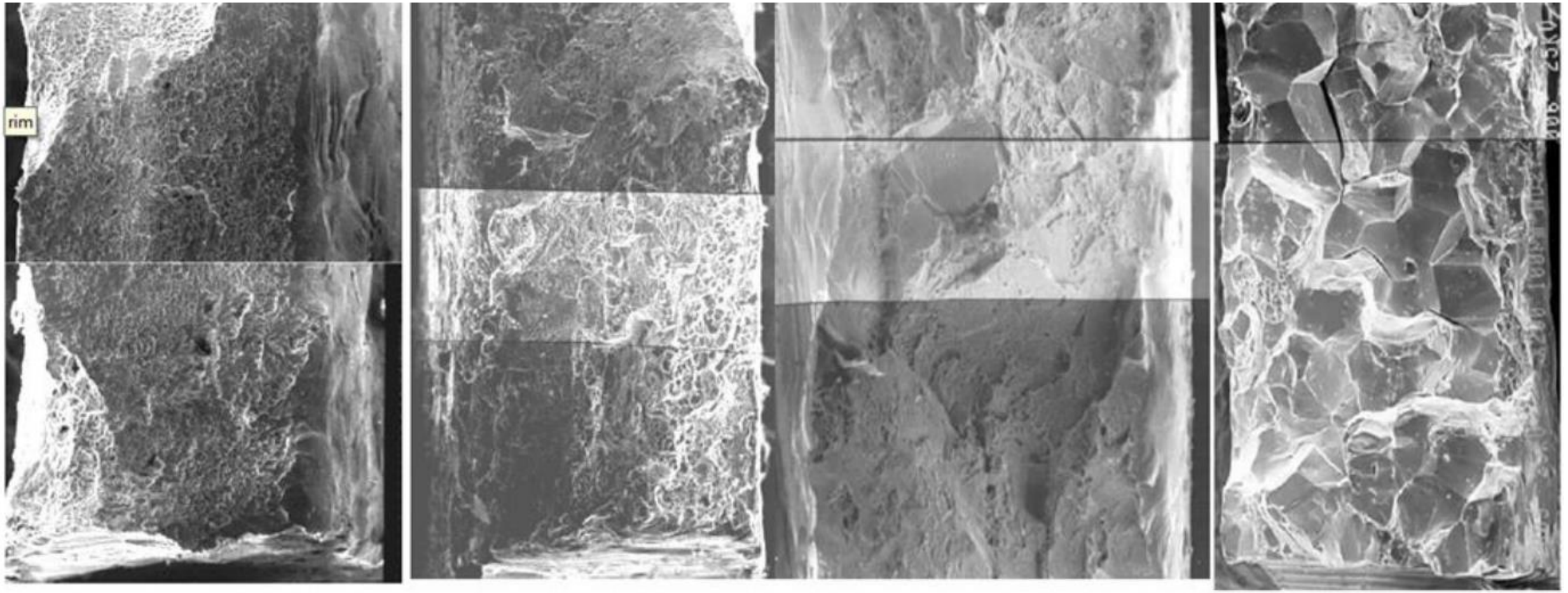
Transmutácia vedie k:

- Zvýšenie rádioaktivity
- Tvorba prvkov citlivejších na žiarenie – zmeny termomechanických vlastností, korózia
- Tvorba H/He bublín, napr. $^{56}Fe(n, \alpha)^{53}Cr$, $^{58}Ni(n, \alpha)^{55}Fe$





ÚČINKY ŽIARENIA V OCELI INCONEL 718 - ZLIATINA 50Ni17Cr (FCC ŠTRUKTÚRA) PRI 50-200°C



0 dpa | 4.6 dpa | 10.5 dpa | 19.8 dpa

Žíhanie – spôsob obnovenia vlastnosti materiálu

Možné spôsoby žíhania:

- „mokré“ žíhanie bez odstránenia jadra
- „mokré“ žíhanie s odstránením jadra
- malé zvýšenie teploty chladiva primárneho okruhu (napr. od 280 °C do 340 °C) – nízky vplyv, nízke náklady
- „suché“ žíhanie s odstránením jadra
- výrazné zvýšenie teploty pomocou externých zdrojov tepla

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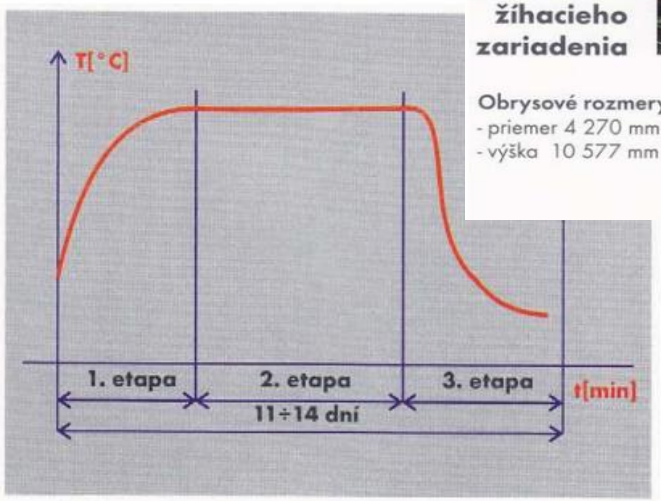
Základné údaje regeneračného žíhania

Činnosť pozostáva z troch etáp:

1. etapa
- ohrev na pracovnú teplotu predpísanou rýchlosťou, zároveň dochádza k dosušeniu tlakovej nádoby reaktora

2. etapa
- výdrž na žíhacej teplote

3. etapa
- chladnutie po regeneračnom žíhaní predpísanou rýchlosťou



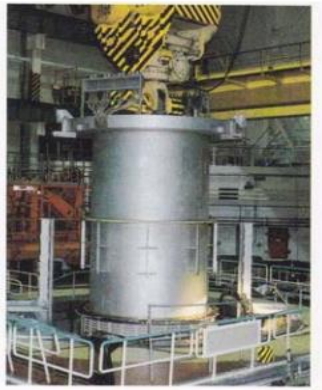
Priebeh teplôt počas regeneračného žíhania

Základný tepelný režim:

Pre reaktory typu VVER 440 je používaný nasledovný základný tepelný režim:

- teplota regeneračného žíhania 475 °C ±30 °C
- výdrž na teplote v trvaní 100 až 168 hodín podľa požiadaviek zákazníka
- rýchlosť náhrevu max. 20 °C za hod.
- max. teplotný gradient: - axiálny 250 °C/m
  - radiálny 50 °C/m
- pokrytie oblasti zvarového spoja na každú stranu od jeho osi v šírke 300 mm
- rýchlosť chladenia max. 30 °C/hod.

Technické parametre žíhacieho zariadenia



Obrysové rozmery
- priemer 4 270 mm
- výška 10 577 mm

Hmotnosť
- strojná časť 62 330 kg
- elektrická časť 2 470 kg
- spolu 64 800 kg

Inštalovaný príkon
- 975 kW
/13 pásiem po 75 kW/

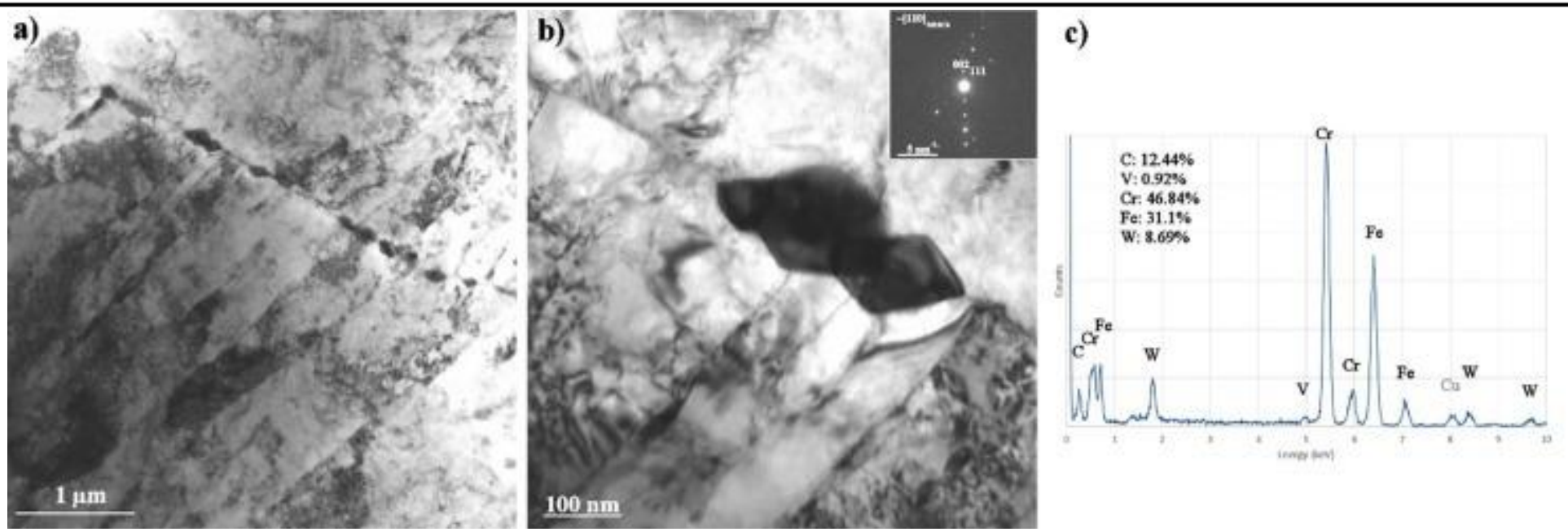
Menovitý prúd
1 490 A

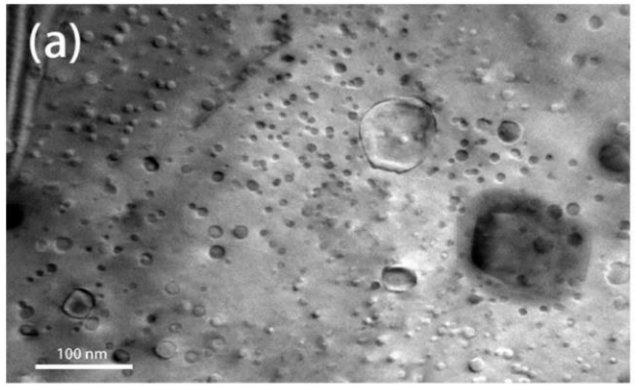
Napájanie
3 x 380 V, 50 Hz

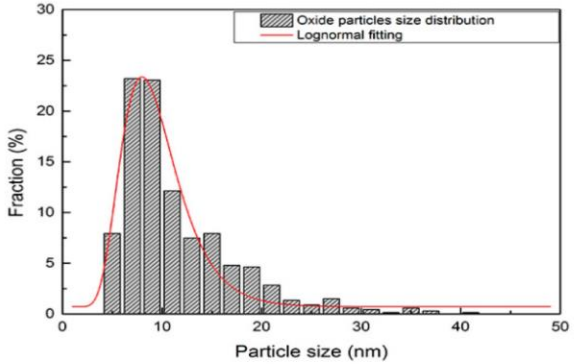
Reactor	Year	Temperature/time (°C/h)
Novovoronezh 3	1987	430 ± 20°C / 150 h
Armenia 1	1988	450 + 50°C / 150 h
Greifswald 1 (Nord 1)	1988	475 - 10°C / 150 h
Kola 1	1989	475°C / 150 h
Kola 2	1989	475°C / 150 h
Kozloduy 1	1989	475°C / 150 h
Kozloduy 3	1989	475°C / 150 h
Greifswald 2 (Nord 2)	1990	475 - 10°C / 150 h
Greifswald 3 (Nord 3)	1990	475°C/150 h
Novovoronezh 3 (re-annealing)	1991	475 ± 15°C / 100 h
Novovoronezh 4	1992	475°C / 150 h
Kozloduy 2	1992	475°C / 150 h
J. Bohunice V-1/2	1993	475 - 503°C / 160 h
J. Bohunice V-1/1	1993	475 - 496°C / 168 h

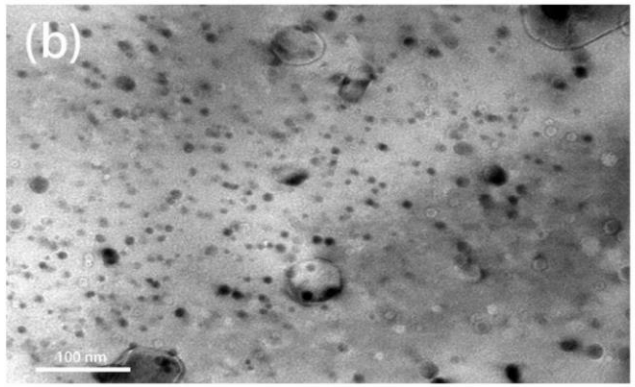
ODS a RAFM ocele pre III+ gen. reaktorov

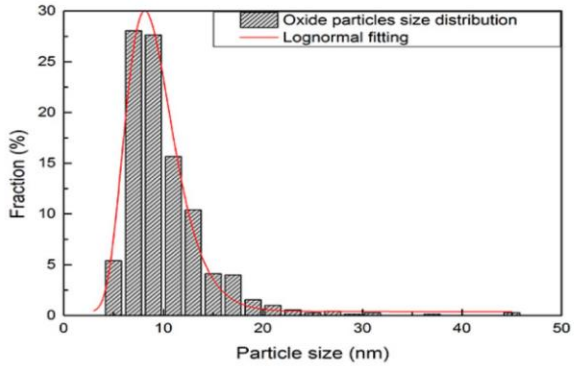
Sample	Chemical composition [wt. %]								
	Fe	Cr	C	Si	Mn	Mo	Ni	Ti	Y
RAFM T91	89.90	8.32	0.09	0.15	0.48	0.86	0.10	-	-
ODS PM2000	80.09	19.30	0.07	0.05	0.02	0.01	0.03	0.05	0.43

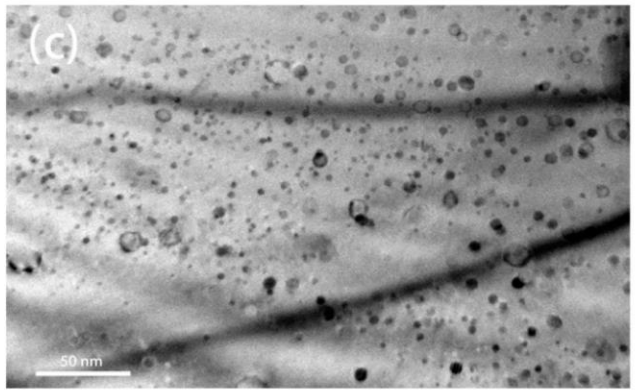


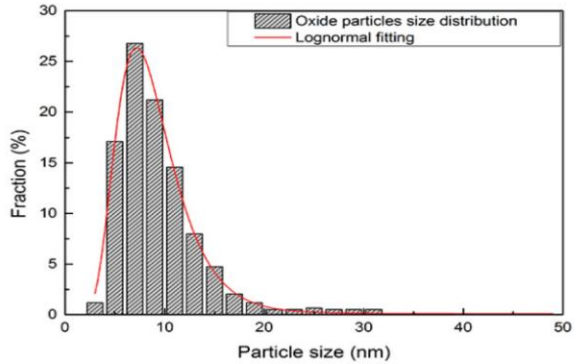

(a)
100 nm

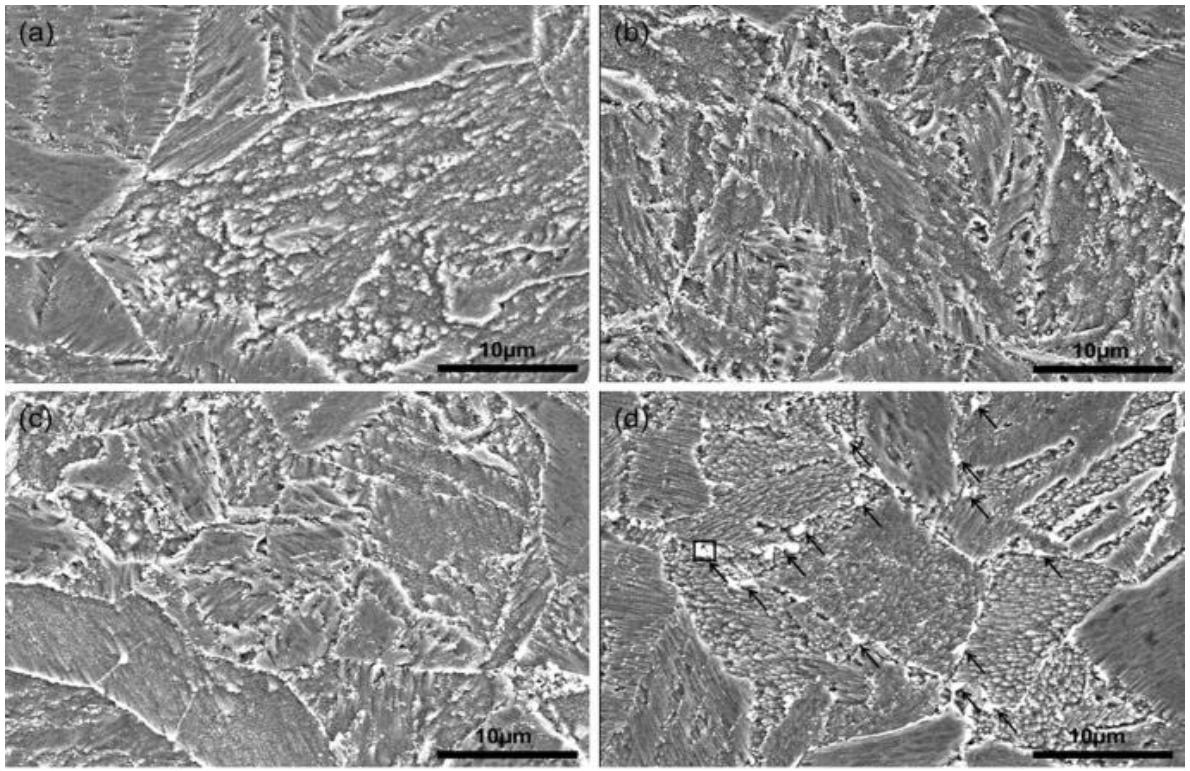

Oxide particles size distribution
Lognormal fitting
Fraction (%)
Particle size (nm)

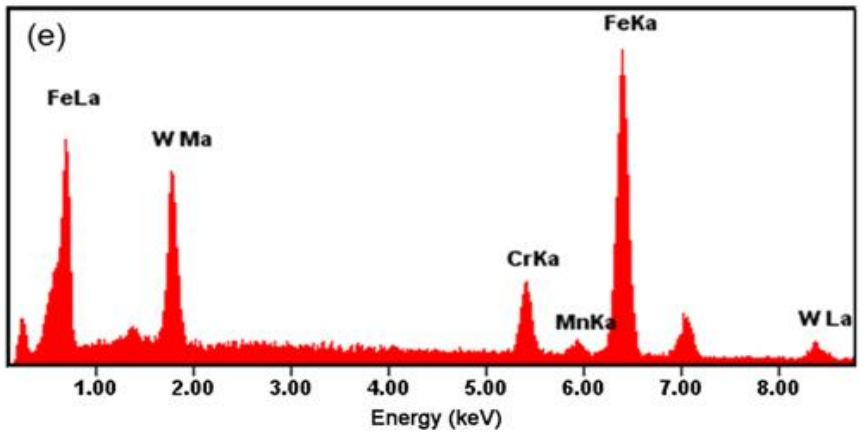

(b)
100 nm


Oxide particles size distribution
Lognormal fitting
Fraction (%)
Particle size (nm)

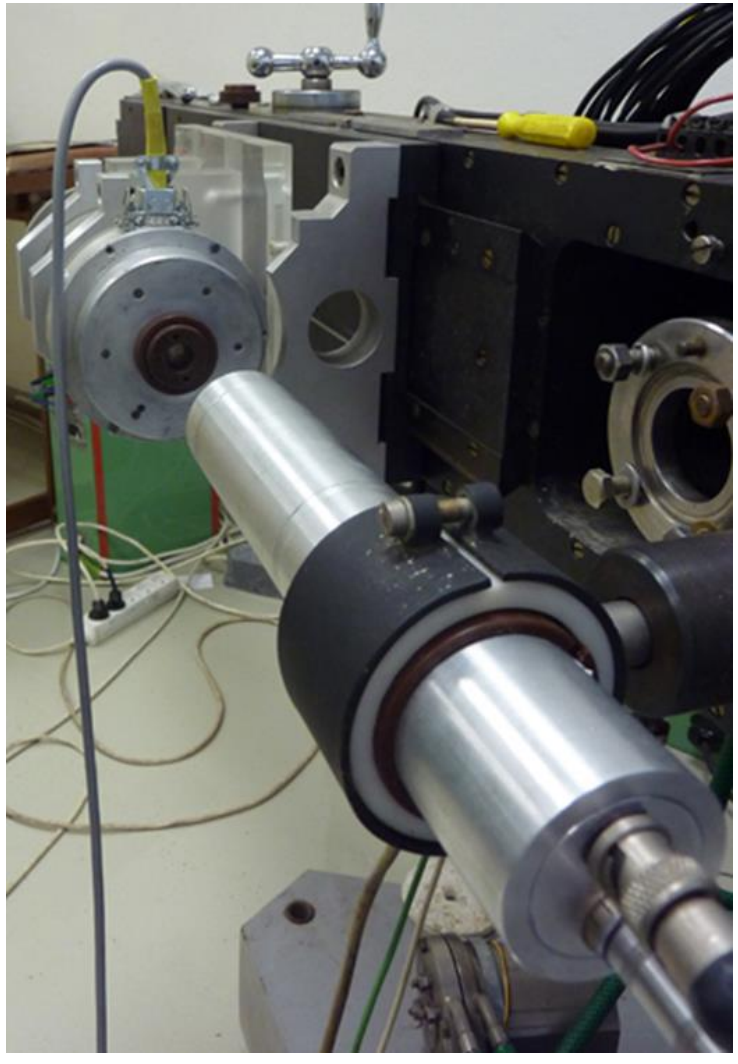

(c)
50 nm


Oxide particles size distribution
Lognormal fitting
Fraction (%)
Particle size (nm)


(a)
10μm
(b)
10μm
(c)
10μm
(d)
10μm


(e)
FeLa
W Ma
CrKa
MnKa
FeKa
W La
Energy (keV)

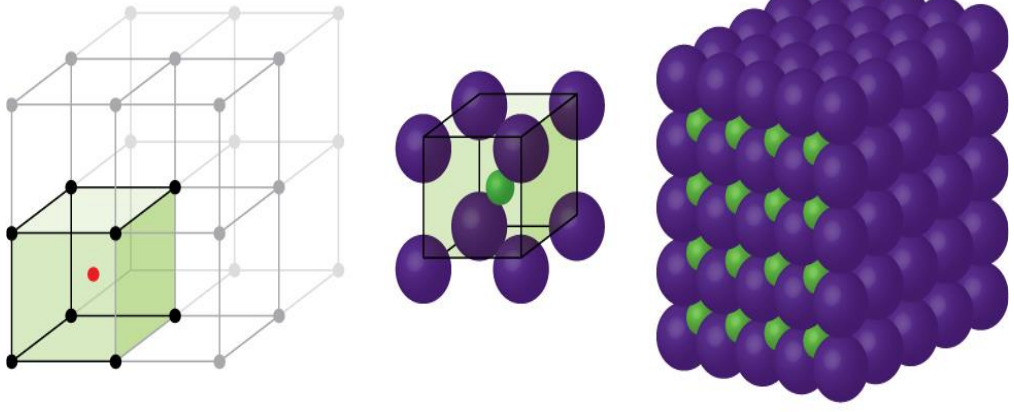
Analýza ocelí pomocou MS - Binomické rozdelenie pre MEA ocele (T91)

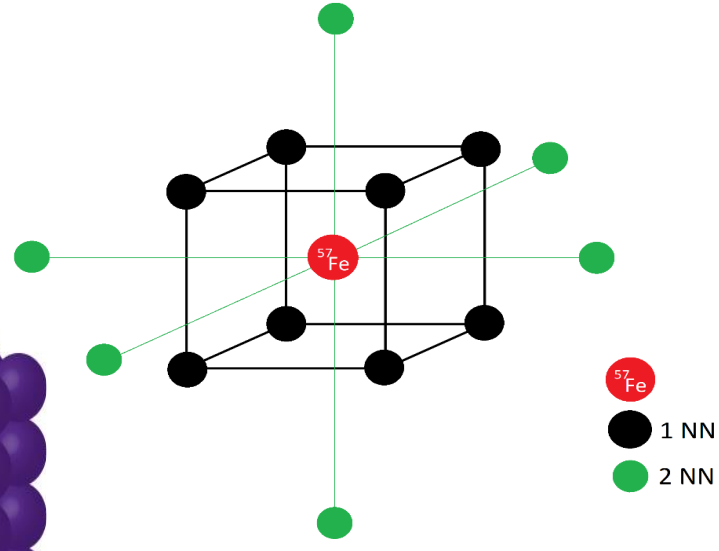


$$P(m,n) = c_1 c_2 x^{(m+n)} (1-x)^{(Z_1+Z_2-(m+n))}$$

$$\langle IS \rangle = \sum_{m,n} [P(m,n)\, IS(m,n)]$$

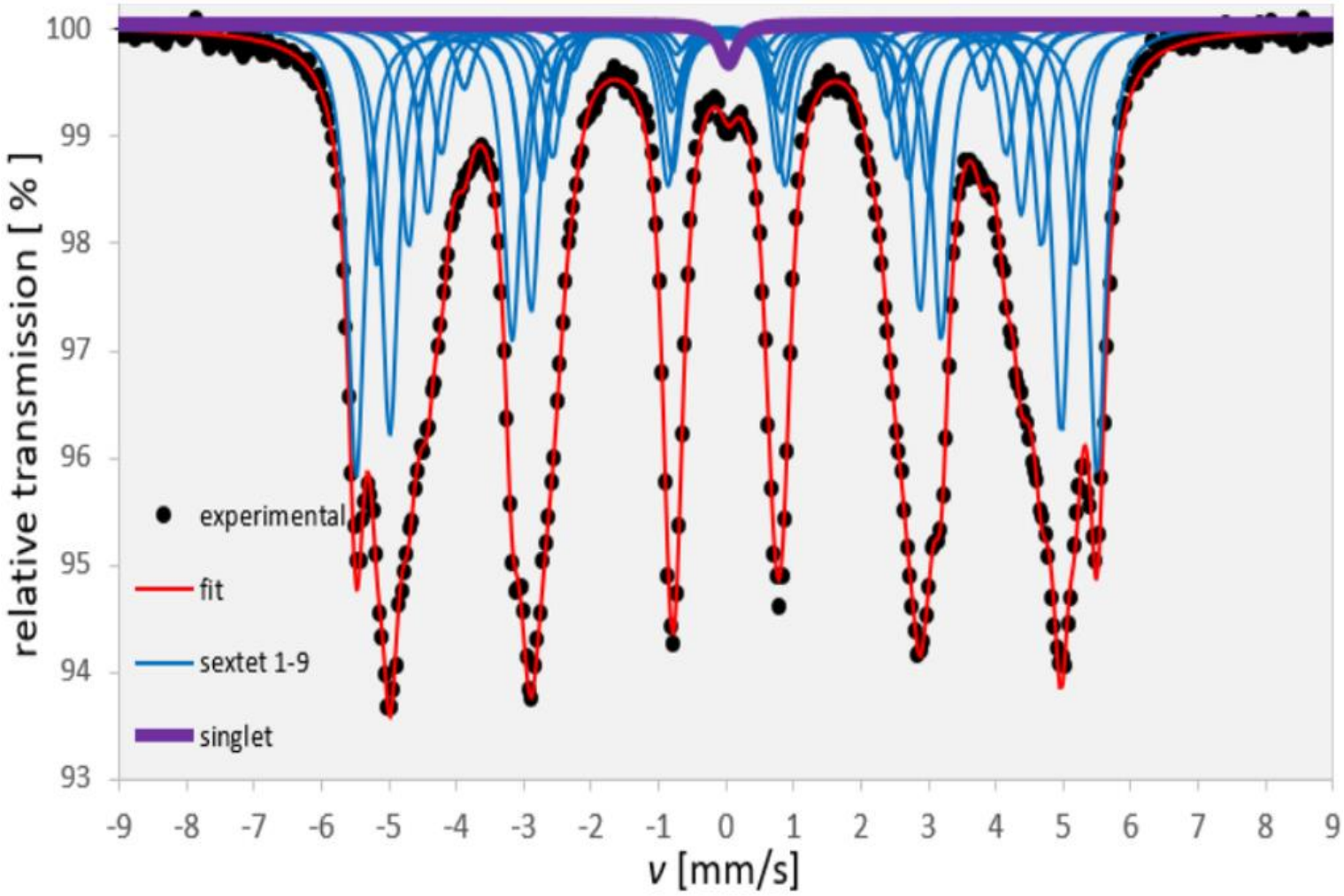
$$\langle B \rangle = \sum_{m,n} [P(m,n)\, B(m,n)]$$

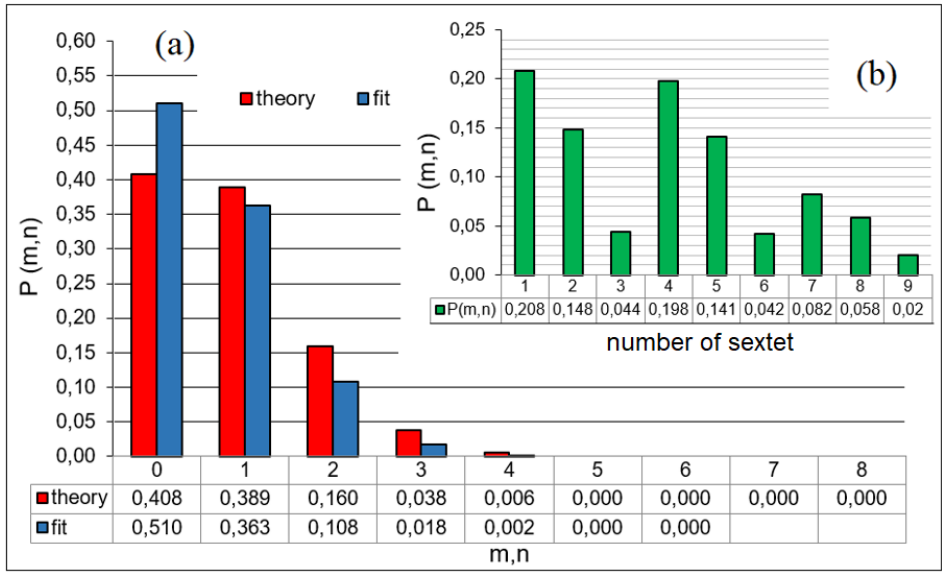




Kosovsky et al.: *Phys. Stat. Sol. (2022)*, 156, 18-27.

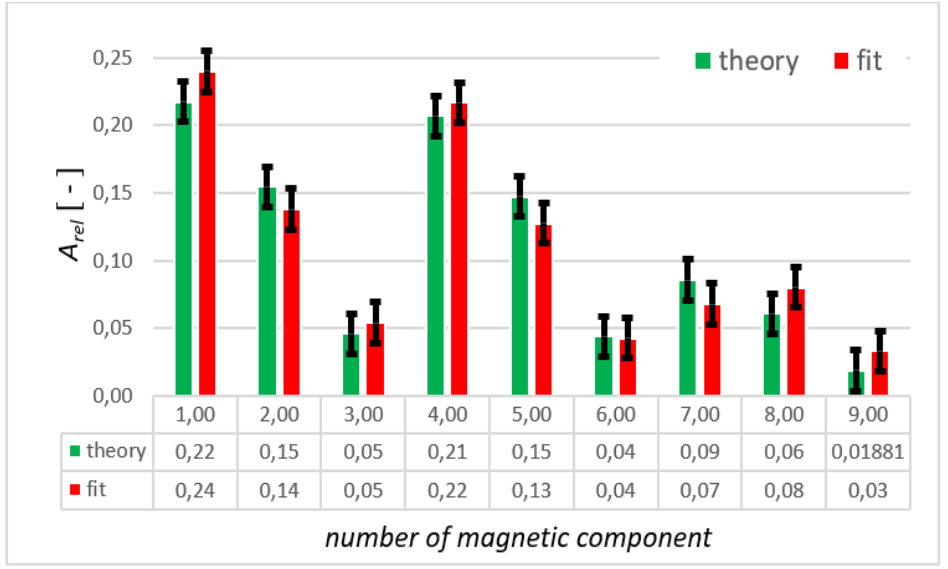
RAFM T91 ocel'



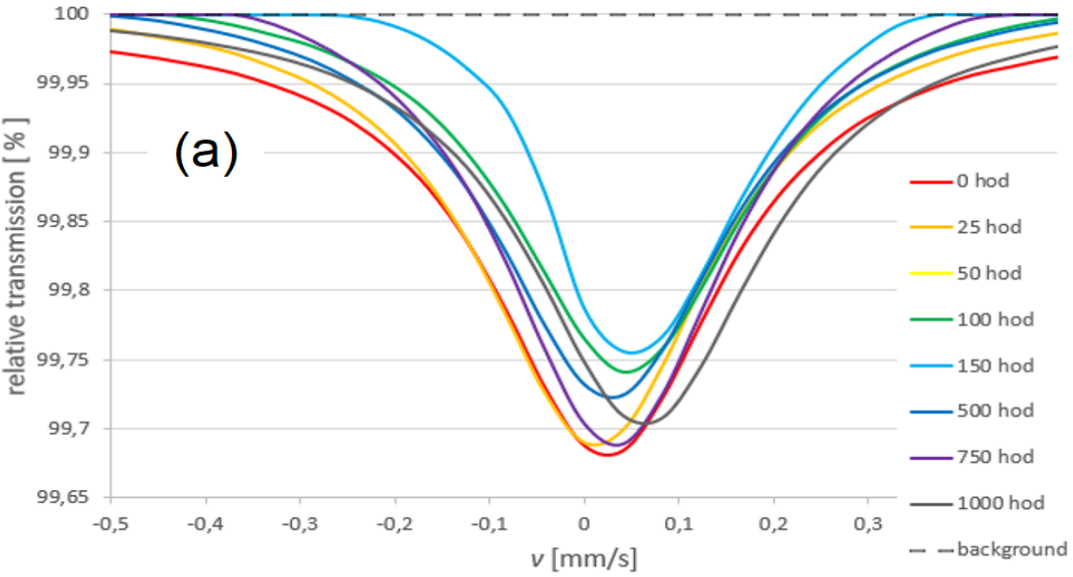


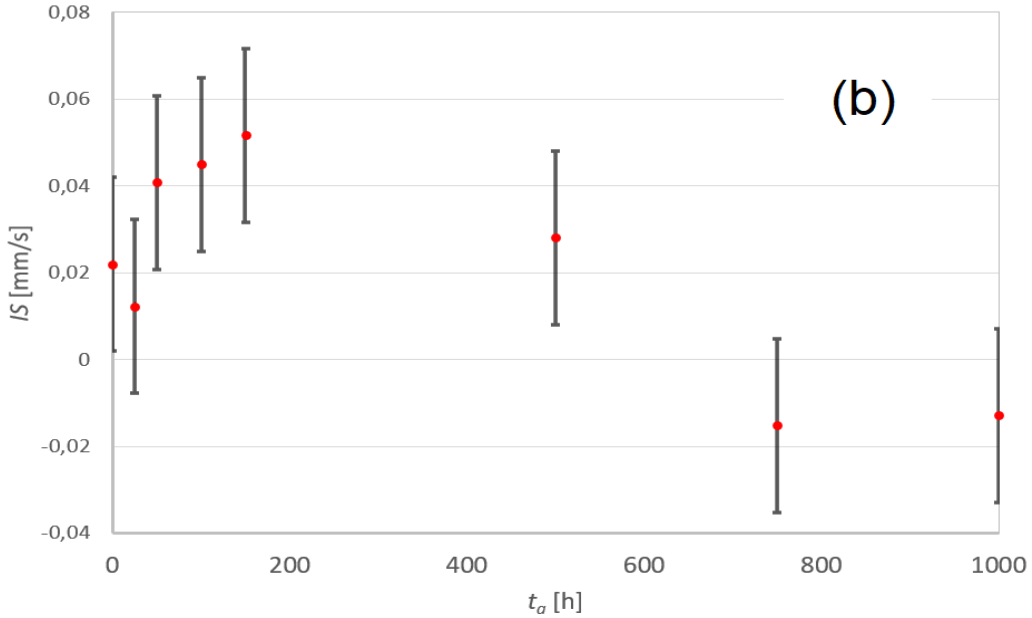
m,n	0	1	2	3	4	5	6	7	8
theory	0,408	0,389	0,160	0,038	0,006	0,000	0,000	0,000	0,000
fit	0,510	0,363	0,108	0,018	0,002	0,000	0,000		

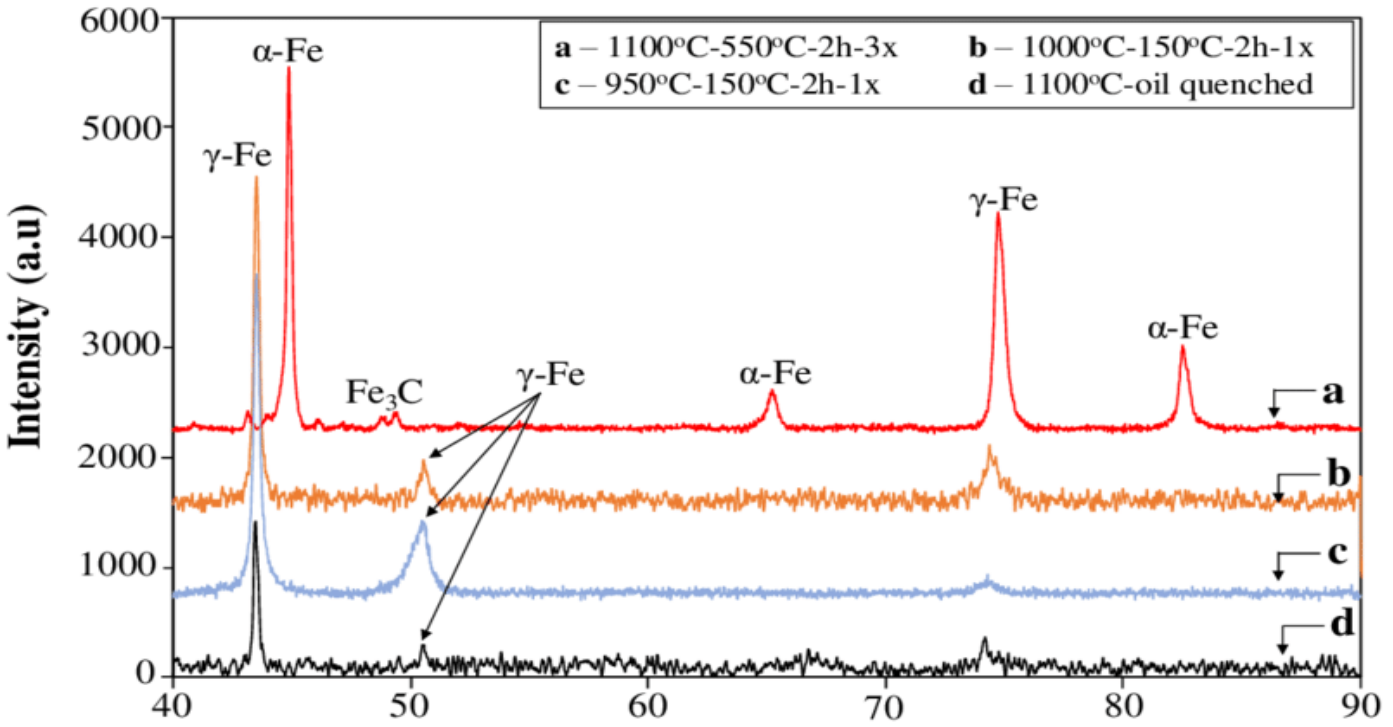
number of sextet	1	2	3	4	5	6	7	8	9
P(m,n)	0,208	0,148	0,044	0,198	0,141	0,042	0,082	0,058	0,02

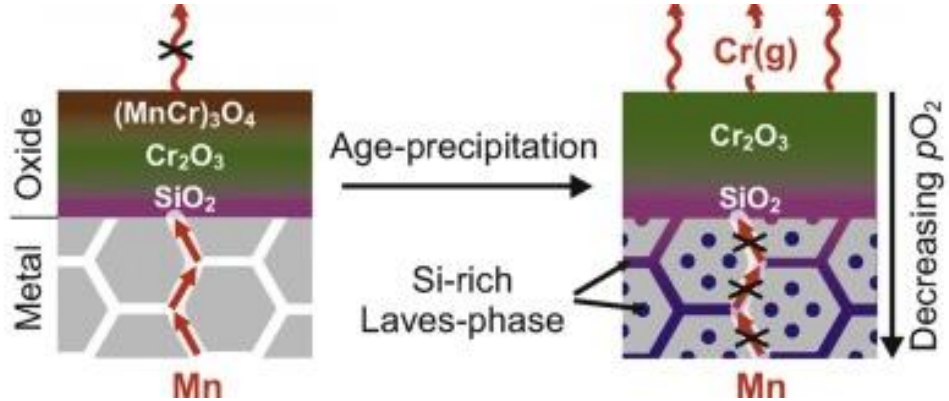


number of magnetic component	1,00	2,00	3,00	4,00	5,00	6,00	7,00	8,00	9,00
theory	0,22	0,15	0,05	0,21	0,15	0,04	0,09	0,06	0,01881
fit	0,24	0,14	0,05	0,22	0,13	0,04	0,07	0,08	0,03


(a)
relative transmission [%]
v [mm/s]
0 hod
25 hod
50 hod
100 hod
150 hod
500 hod
750 hod
1000 hod
background


(b)
IS [mm/s]
t_a [h]


a – 1100°C-550°C-2h-3x
b – 1000°C-150°C-2h-1x
c – 950°C-150°C-2h-1x
d – 1100°C-oil quenched
Intensity (a.u)
α-Fe
γ-Fe
Fe3C
a
b
c
d


Oxide
Metal
(MnCr)3O4
Cr2O3
SiO2
Mn
Age-precipitation
Cr(g)
Si-rich
Laves-phase
Decreasing pO2

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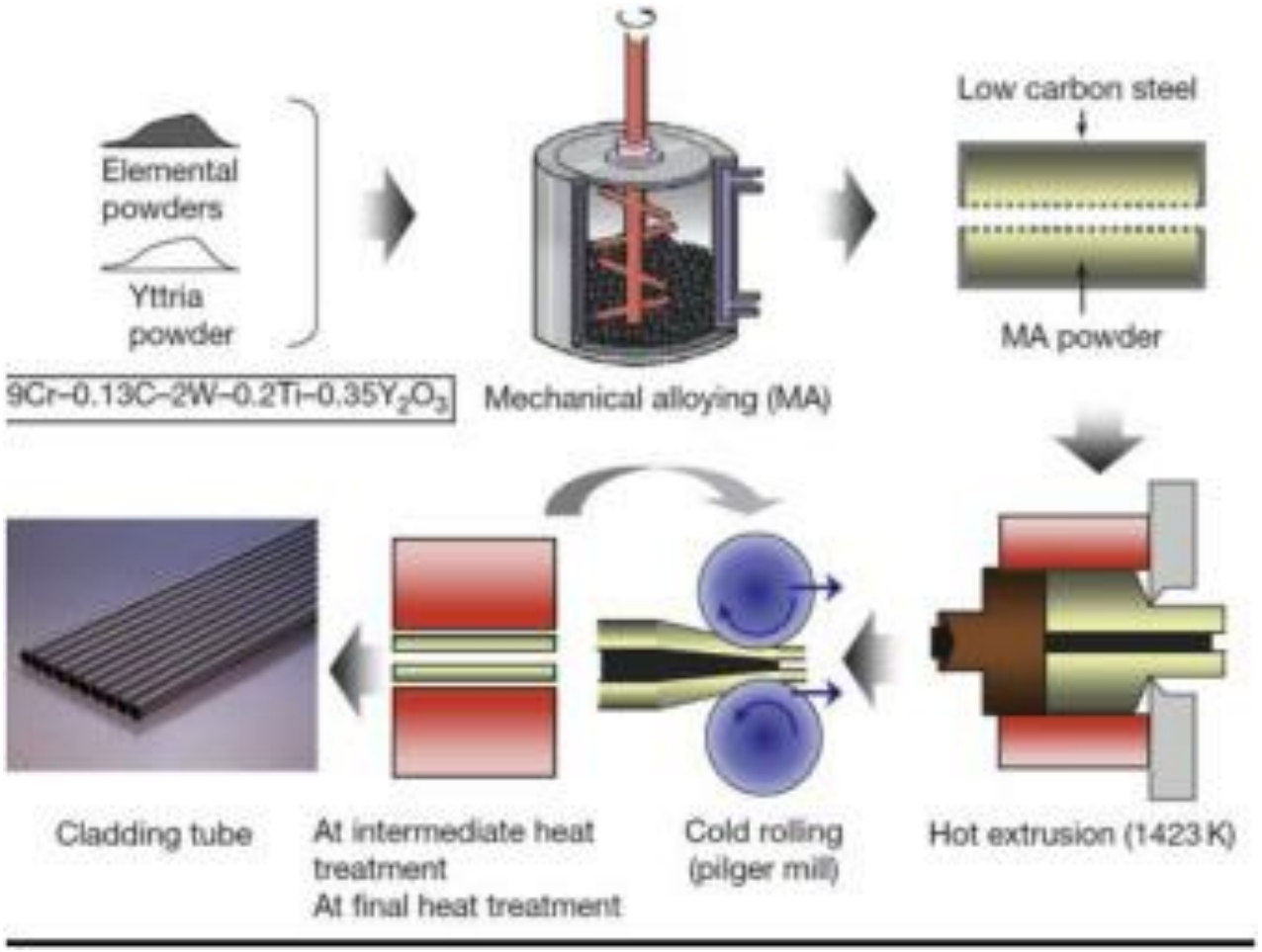
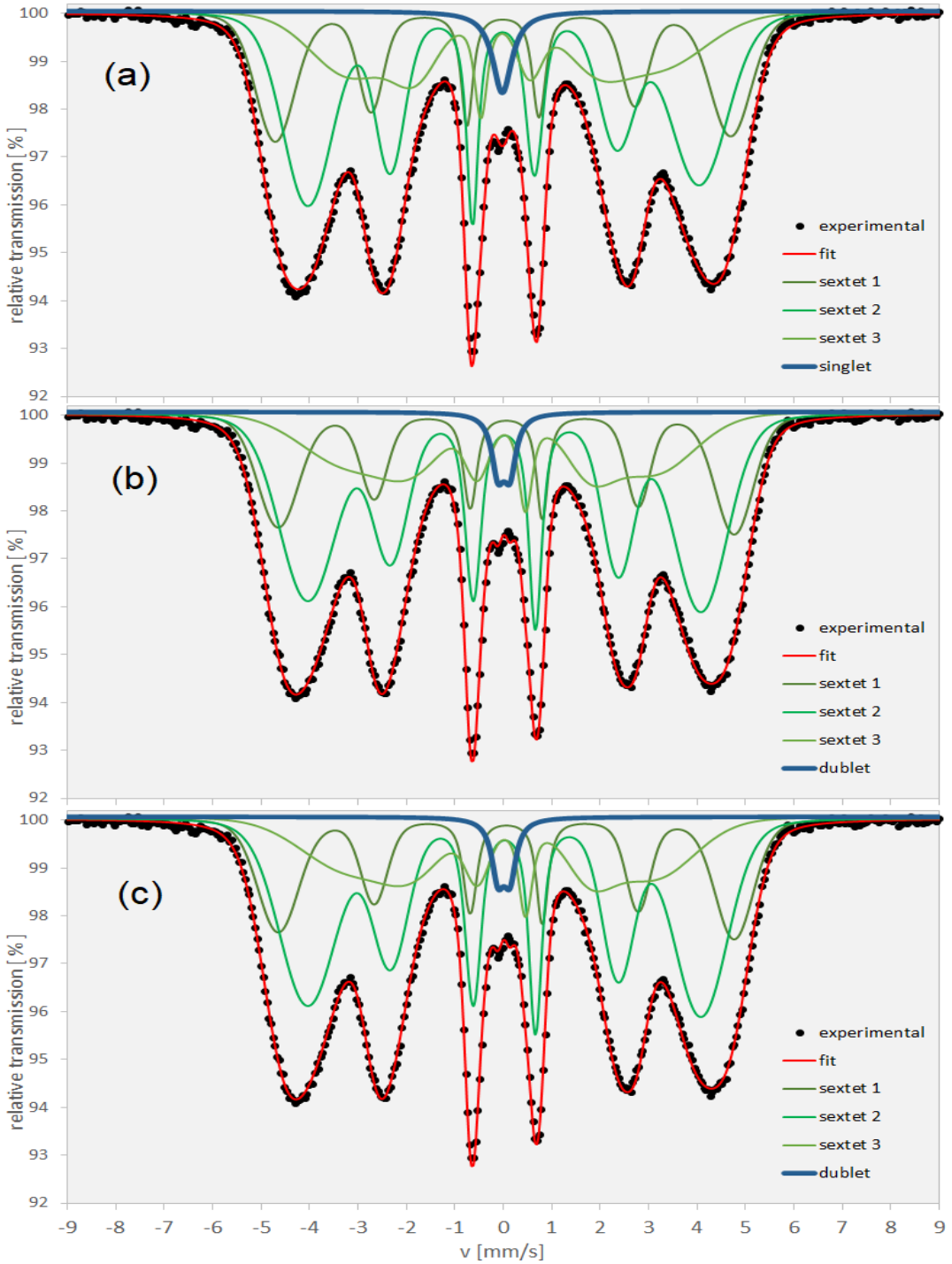
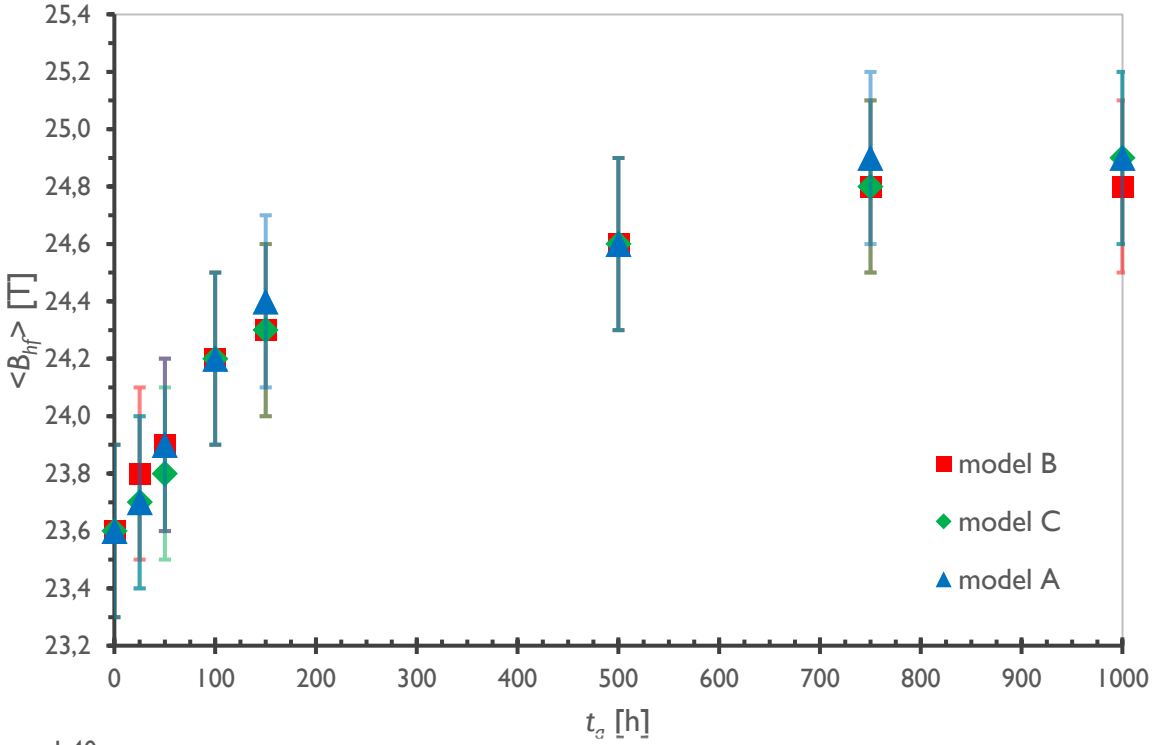
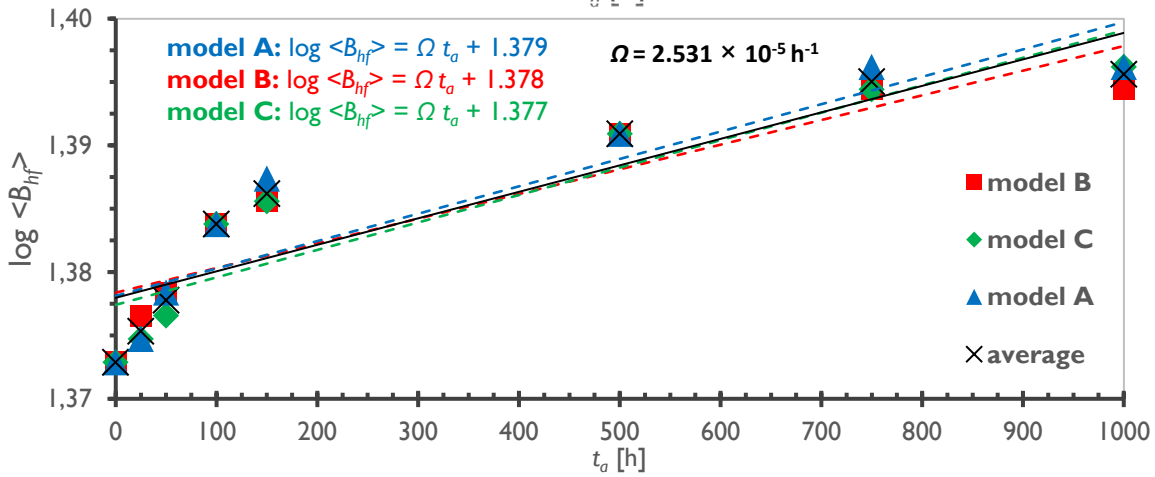
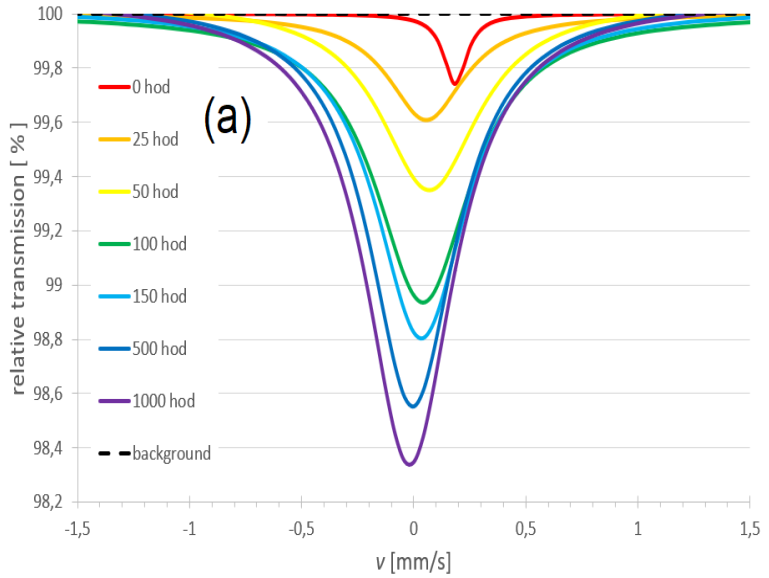
ODS PM2000 oceľ

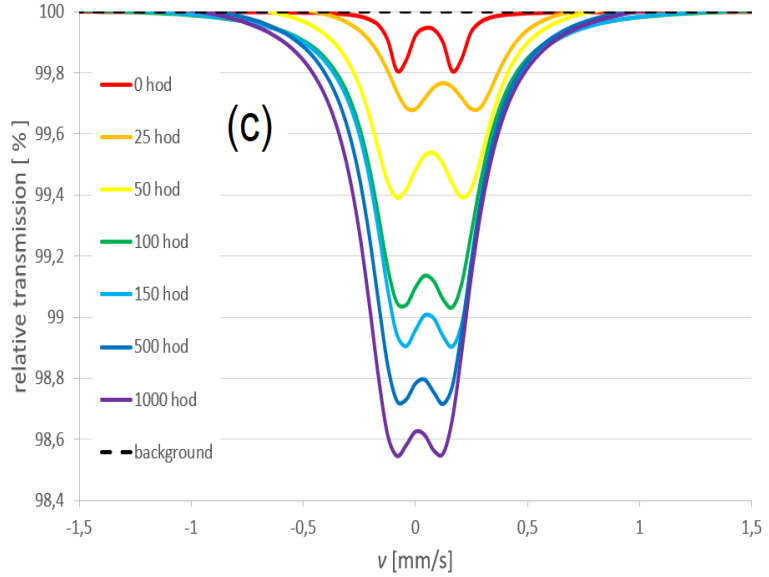


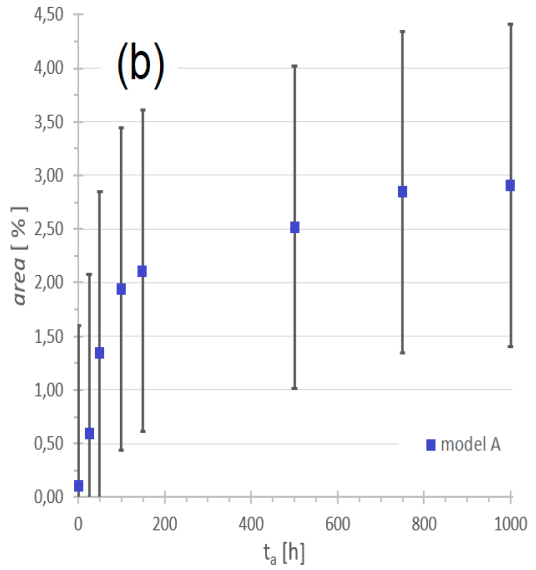


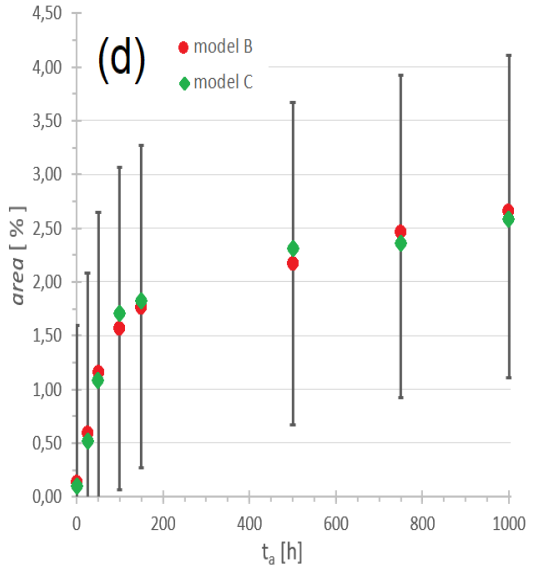

<B_hf> [T]
t_a [h]
model B
model C
model A

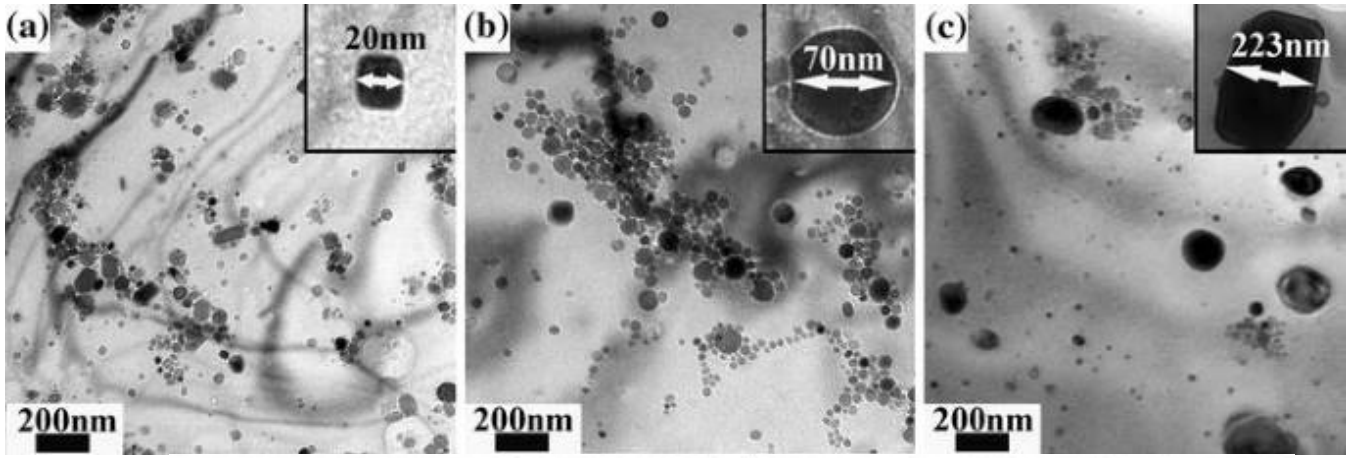

model A: log <B_hf> = Ω t_a + 1.379
model B: log <B_hf> = Ω t_a + 1.378
model C: log <B_hf> = Ω t_a + 1.377
Ω = 2.531 × 10⁻⁵ h⁻¹
log <B_hf>
t_a [h]
model B
model C
model A
average

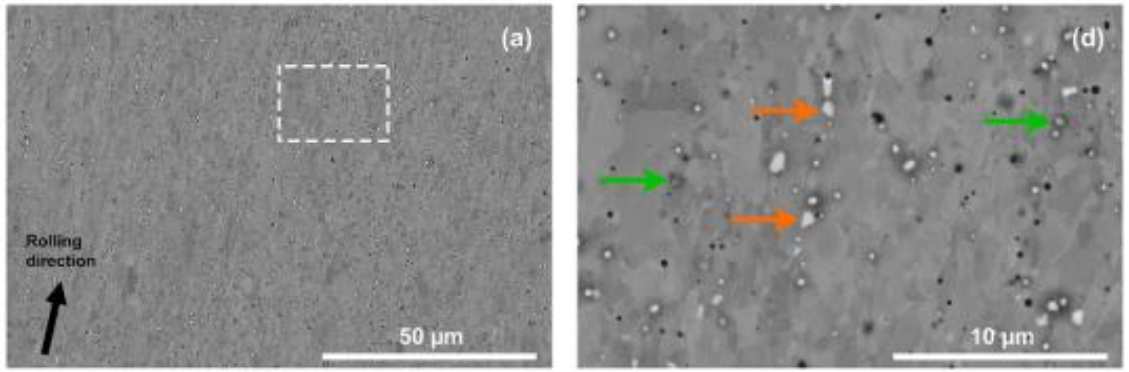

(a)
relative transmission [%]
v [mm/s]
0 hod
25 hod
50 hod
100 hod
150 hod
500 hod
1000 hod
background

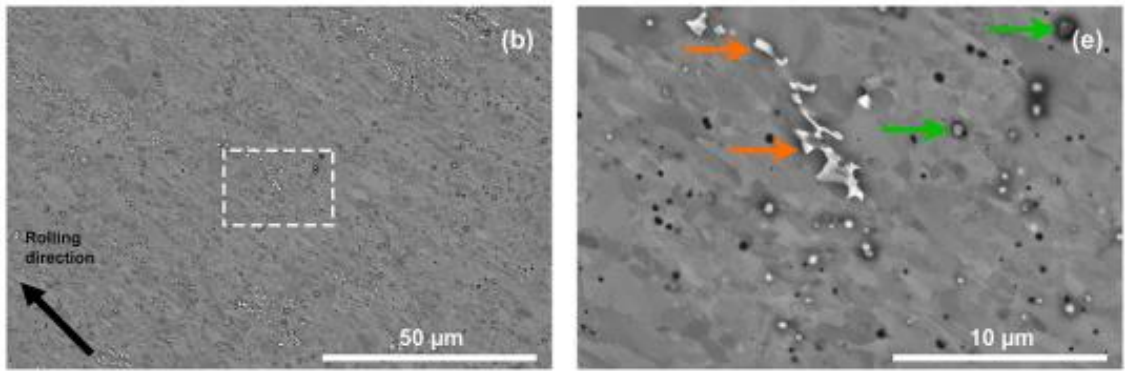

(c)
relative transmission [%]
v [mm/s]
0 hod
25 hod
50 hod
100 hod
150 hod
500 hod
1000 hod
background

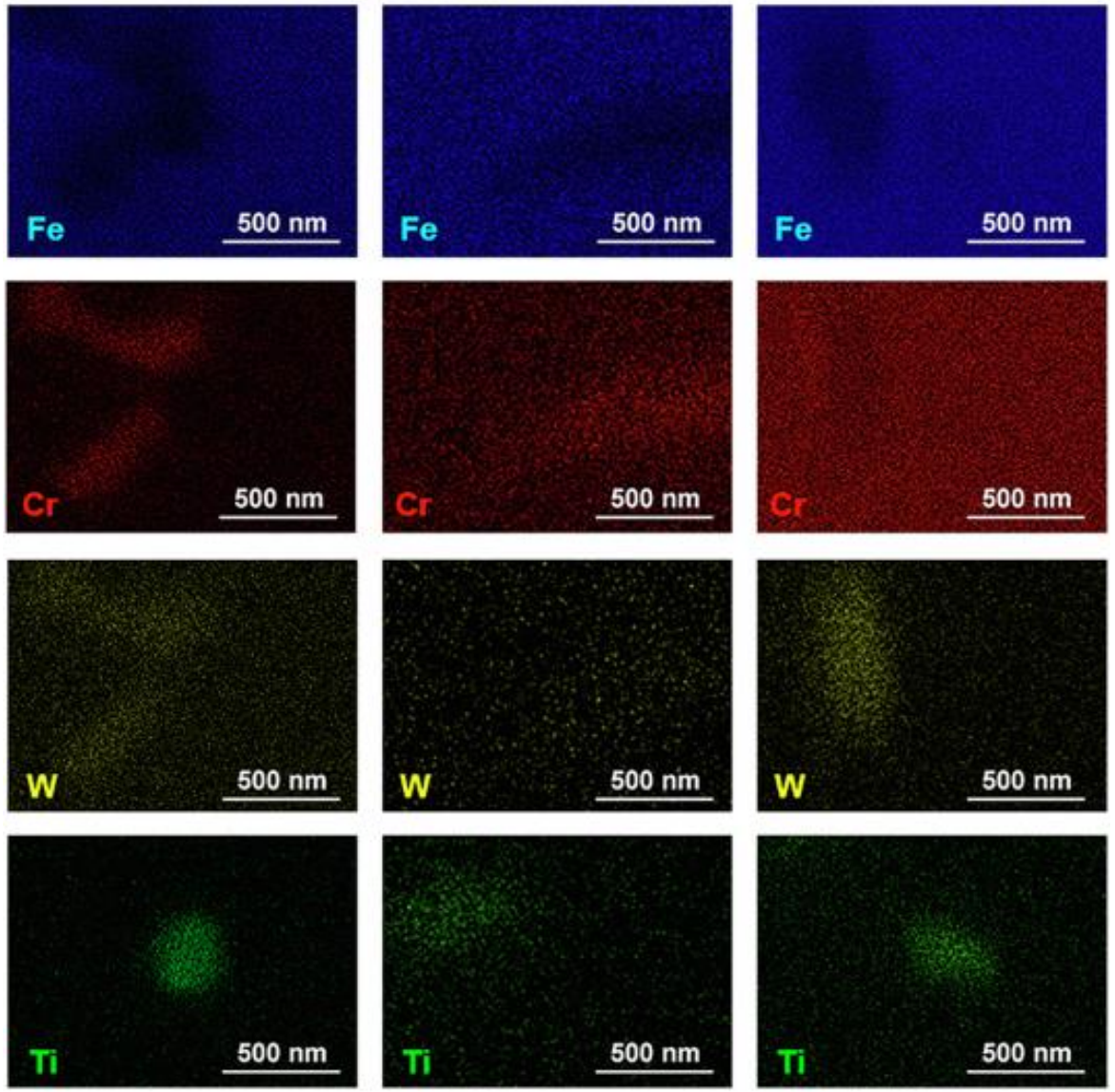

(b)
area [%]
t_a [h]
model A


(d)
area [%]
t_a [h]
model B
model C

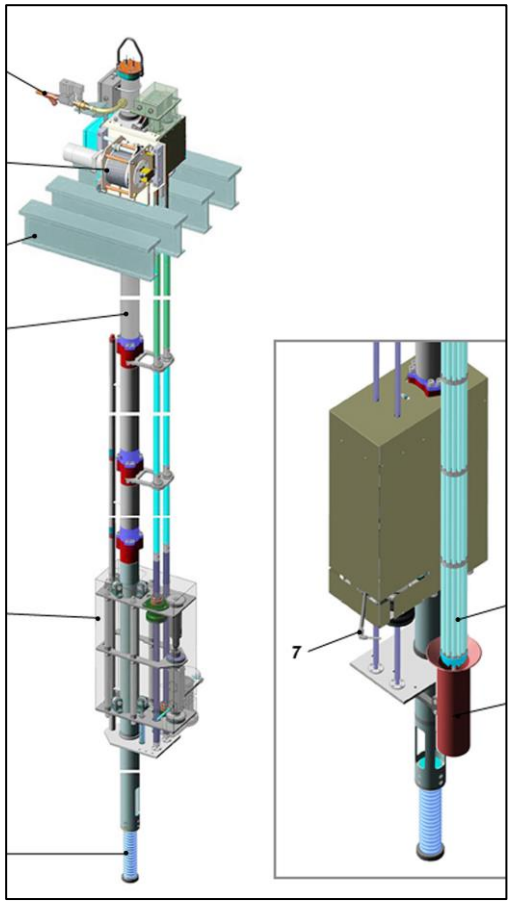

(a)
20nm
200nm
(b)
70nm
200nm
(c)
223nm
200nm

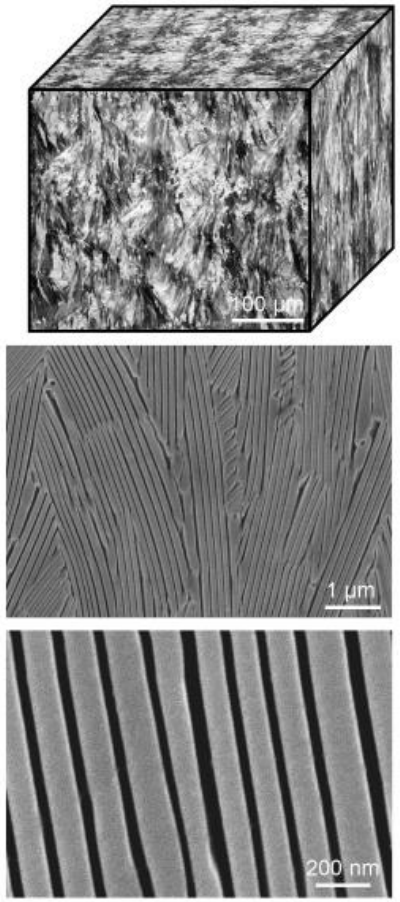

(a)
Rolling direction
50 μm
(d)
10 μm

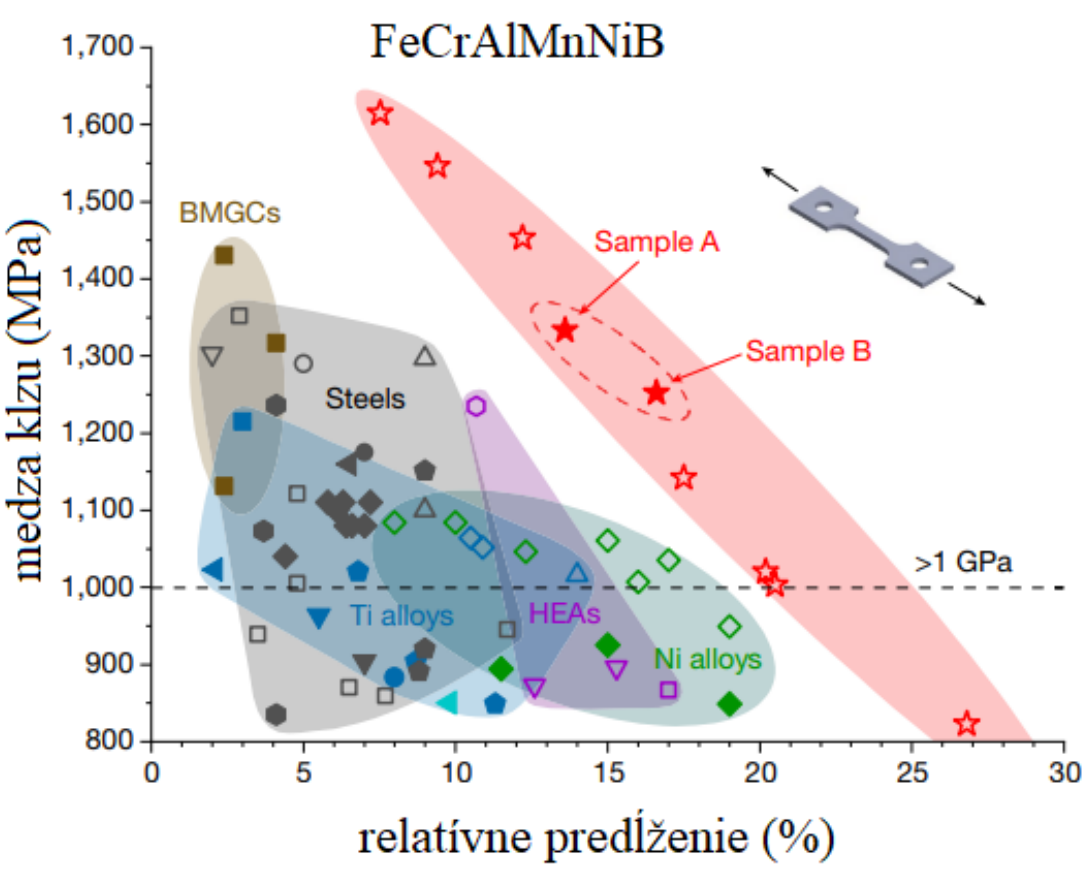

(b)
Rolling direction
50 μm
(e)
10 μm

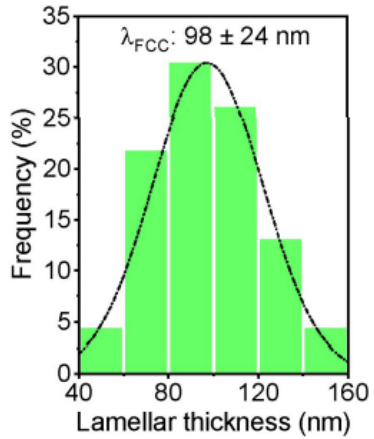

Fe
500 nm
Fe
500 nm
Fe
500 nm
Cr
500 nm
Cr
500 nm
Cr
500 nm
W
500 nm
W
500 nm
W
500 nm
Ti
500 nm
Ti
500 nm
Ti
500 nm

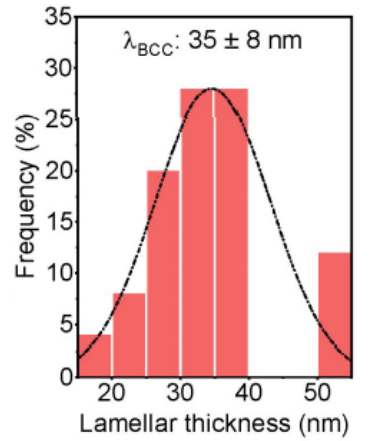
HEA ocele pre špeciálne aplikácie v JE





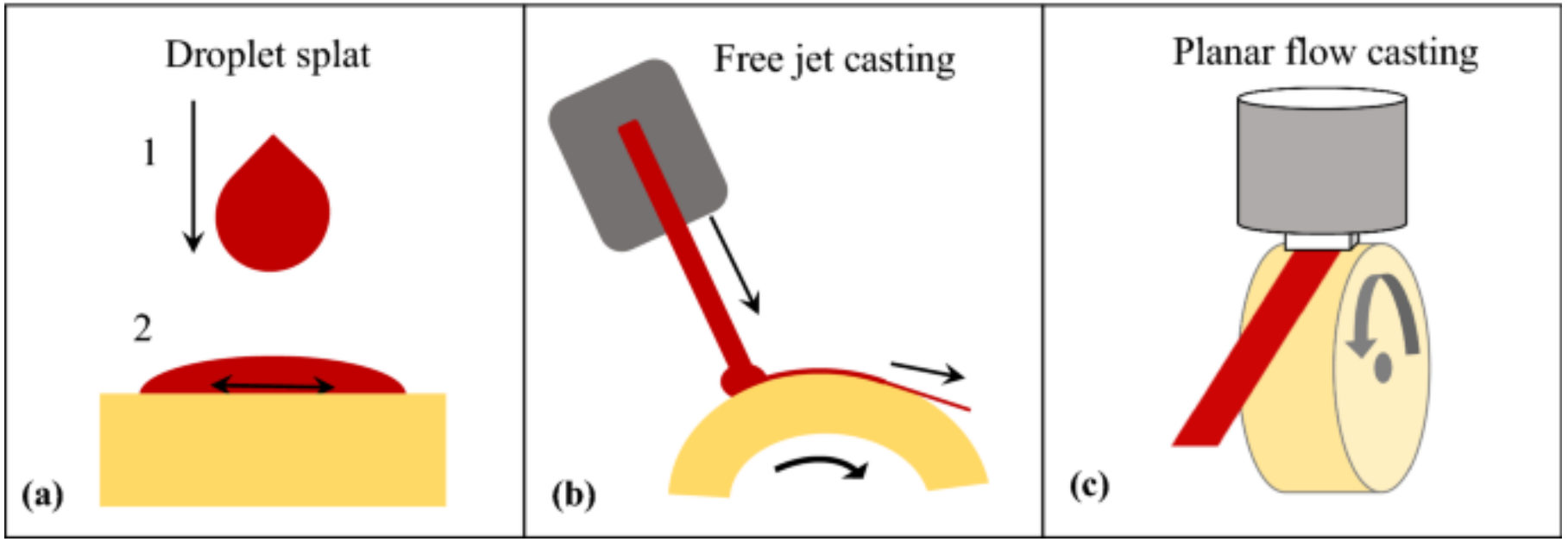




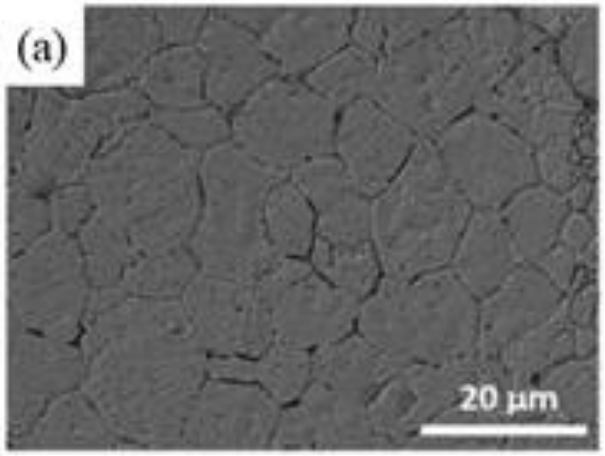


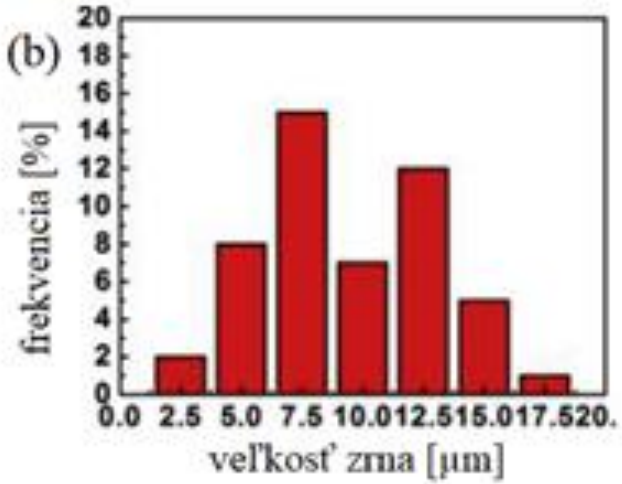
Vzorky HEA ocele

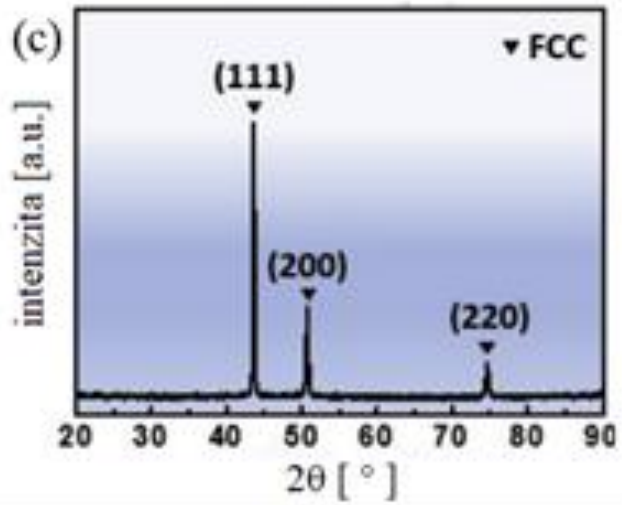
- ribbons (rapid quenching)
- planar flow casting technique
- melt spun (1700 K)
- thickness - 20 μm

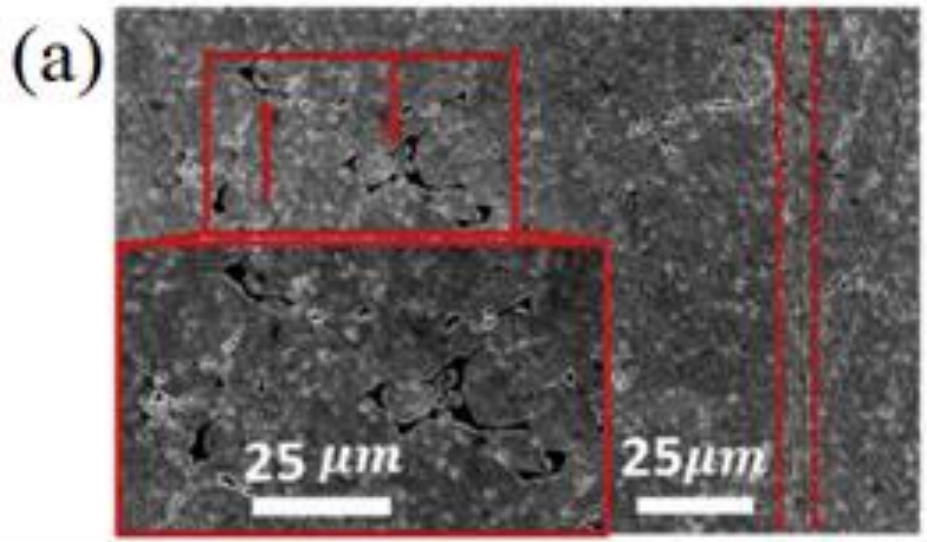


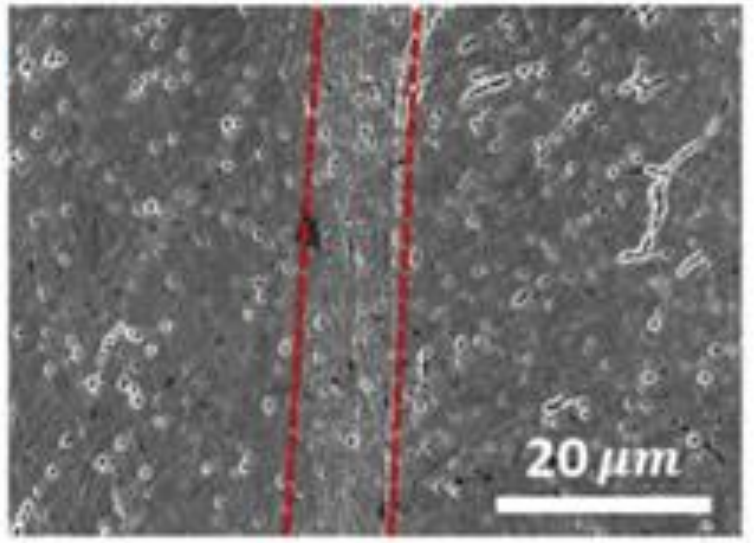
Mechanické vlastnosti HEA zliatiny (FeCrAlNiMnB)









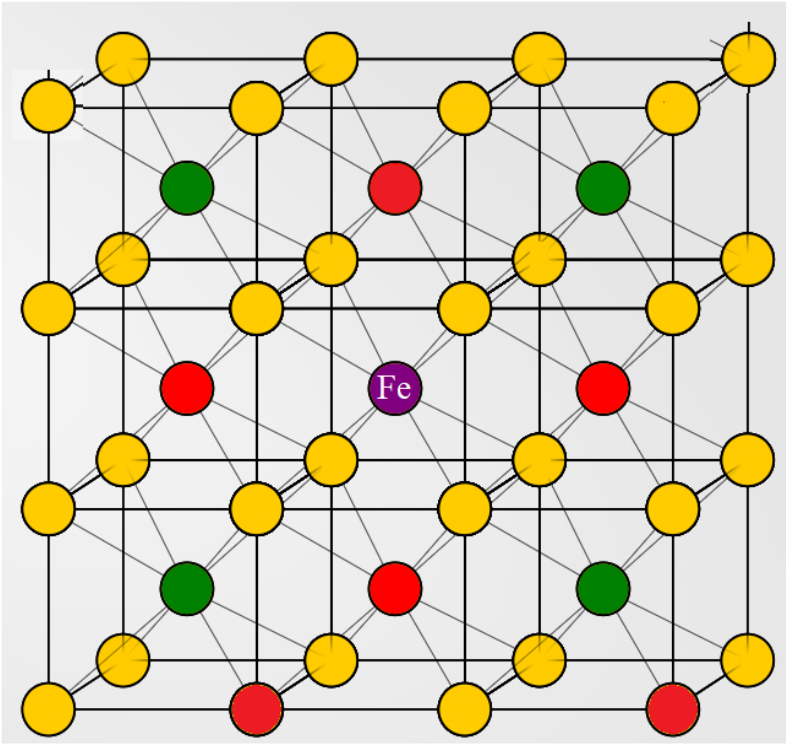


Perturbačný model pre bórovú HEA oceľ (pre HRK kazety)

(vzorka FeCrNiMnAlB)

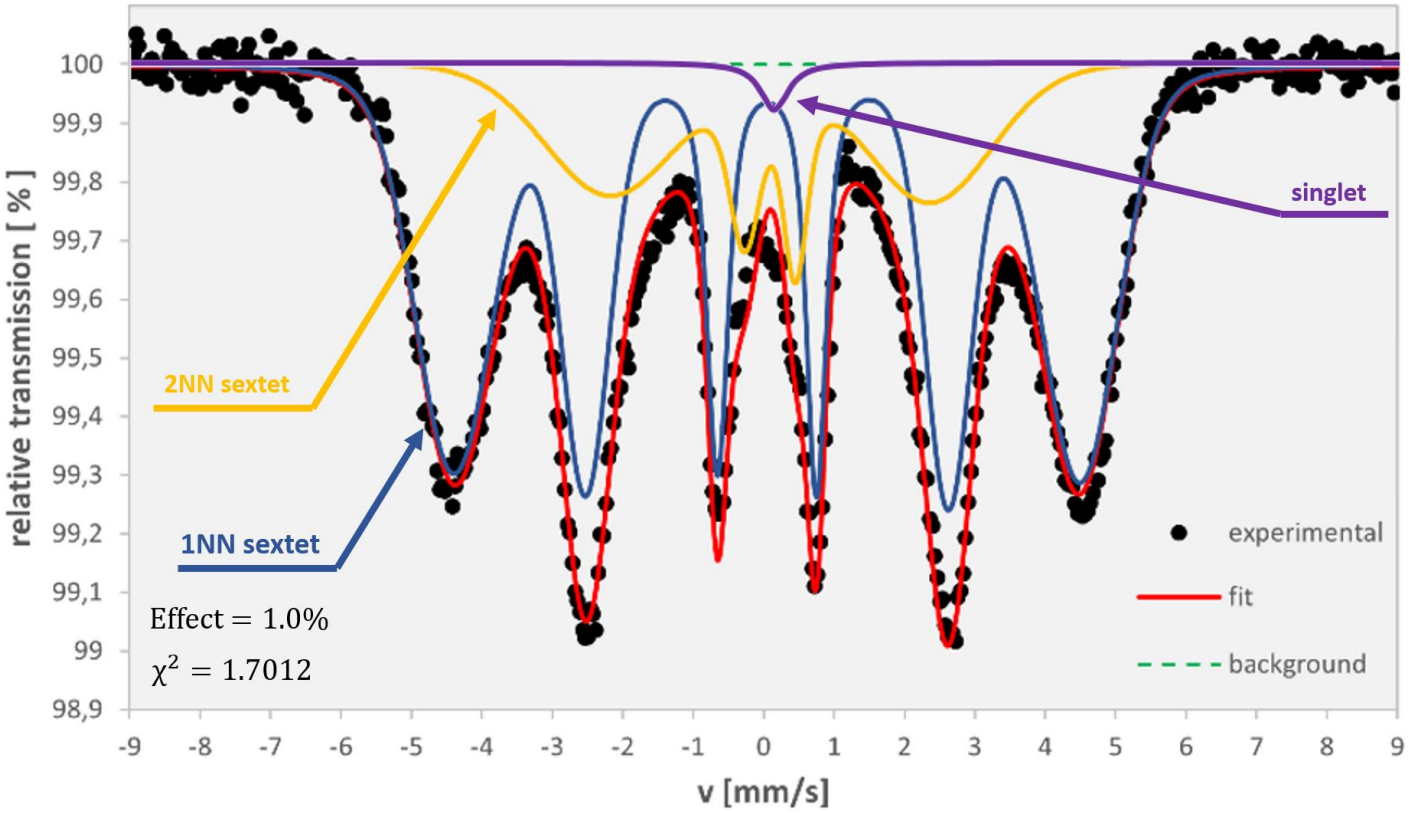
$$B = B_0 + \langle \Delta B \rangle$$

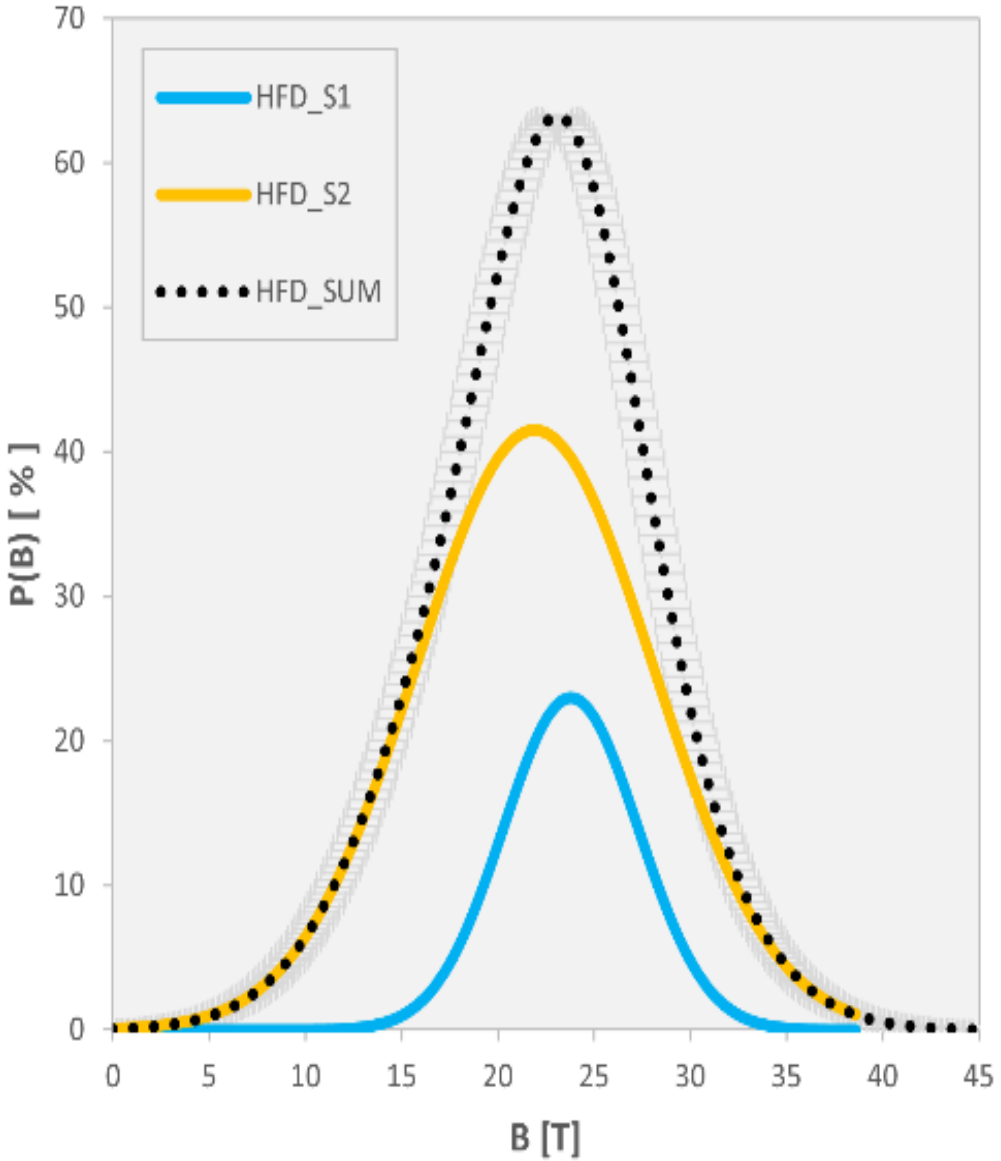
$$B = B_0 + [m\Delta B_1^x + n\Delta B_2^x + \gamma x]$$



$$\langle \Delta B \rangle = \sum_x c_x (m\Delta B_1^x + n\Delta B_2^x)$$

$$\langle B \rangle = \prod_{\mu=1}^{M} \sum_{\substack{m=1 \\ n=1}}^{\substack{Z_1 \\ Z_2}} P(m,n)\, B_{m,n} = B_0 + \langle \Delta B_{Fe} \rangle + \langle \Delta B_{Al} \rangle + \langle \Delta B_{Co} \rangle + \langle \Delta B_{Ni} \rangle + \langle \Delta B_{Mn} \rangle$$





component	A_{rel} [%]	*IS* [mm/s]	B_{hf} [T]
1NN sextet	72.9	0.047	26,1
2NN sextet	24.6	0.055	17,9
singlet	2.5	0.012	-

Ďakujem za pozornosť

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