FKITMCMXIX

Sveučilište u Zagrebu
Fakultet kemijskog
inženjerstva i tehnologije

Thermal analysis methods

Workshop, postgraduate course of study
Kemijsko inženjerstvo i primijenjena kemija

Prof. dr. sc. Jelena Macan

Plan of the workshop

- Intoduction to thermal analysis, the methods
- Break
- Experimental parameters
- Break
- Eaxmples of curve analysis, applications, kinetics

What is thermal analysis (TA)?

How a property is connected to temperature while the sample is heated/cooled in controlled manner.

Proučavanje veze svojstva tvari i njezine temperature dok se uzorak kontrolirano zagrijava ili hladi.

(definicija ICTAC-a, *International Confederation for Thermal Analysis and Calorimetry*)

TA Methods

- **TGA:** Termogravimetrijska analiza / Thermogravimetric analysis
- **DSC:** Diferencijalna/razlikovna pretražna kalorimetrija / Differential scanning calorimetry
- **DTA:** Diferencijalna/razlikovna toplinska analiza / Differential thermal analysis
- **TMA:** Termomehanička analiza / Thermomechanical analysis
- **DMA:** Dinamička mehanička analiza / Dynamical mechanical analysis
- **EGA:** Analiza oslobođenih plinova / Evolved gas analysis

TA Methods

Vezane tehnike / Coupled techniques:

- DSC-TGA
- TGA-EGA
- TMA-DTA

TA Methods

- I još… / Also…

  TD: (termo)dilatometrija / dilatometry
  DEA: dielektrična toplinska analiza / dielectric themal analysis
  TSC: toplinski potaknuta struja / thermally stimulated current
  TOA: termooptometrijska analiza / thermooptometric analysis
  TL: luminiscencija / thermoluminiscence

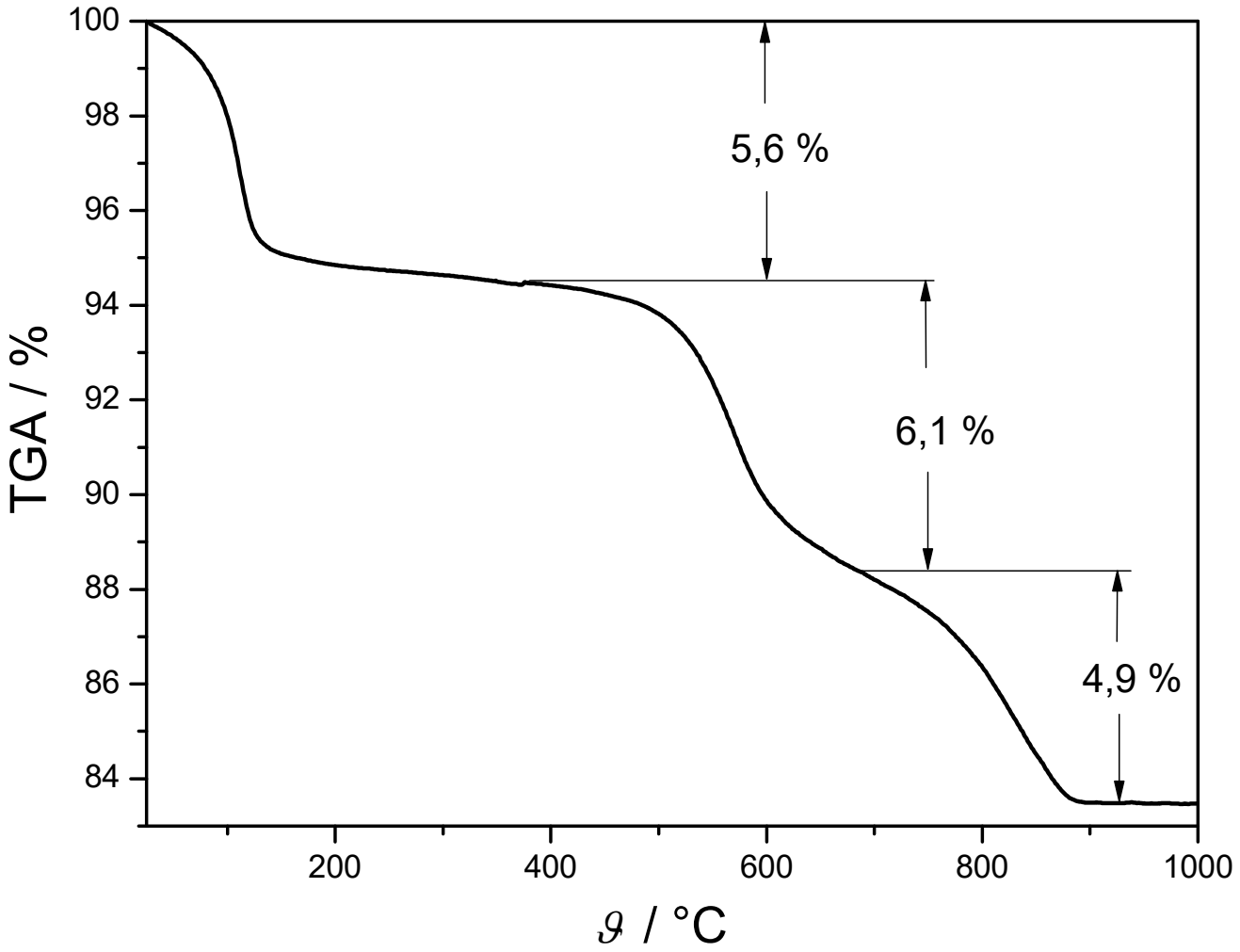
- Spectrometry, microscopy, acoustic methods…

Which methods do you know?

- From the literature…
- Are available where you work…
- You worked with them yourselves…

Think – which methods would be useful to you?

TGA



Step ID: together with DSC or DTA, EGA

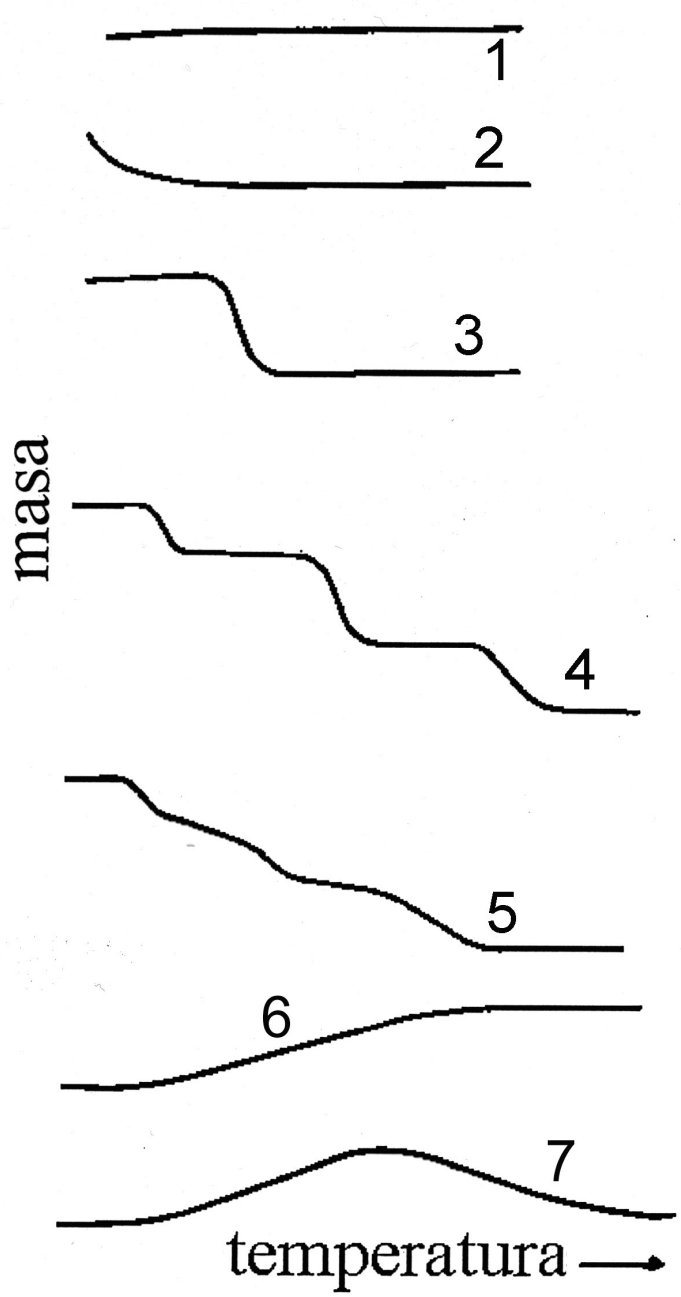
TGA – applications

Reakcije čvrsto/plinovito / Solid-gas reactions:

- Toplinska razgradnja u inertnoj ili reaktivnoj atmosferi / Thermal degradation
- Oksidacija metala (porast mase) / Oxidation

Sastav / Composition:

- Udio hlapive komponente (vlage, aditiva) / volatiles
- Udio gorive komponente / combustibles
- Udio anorganske komponente (pepela) / ash



Typical TGA curves:

(1) no change

(2) desorption, drying

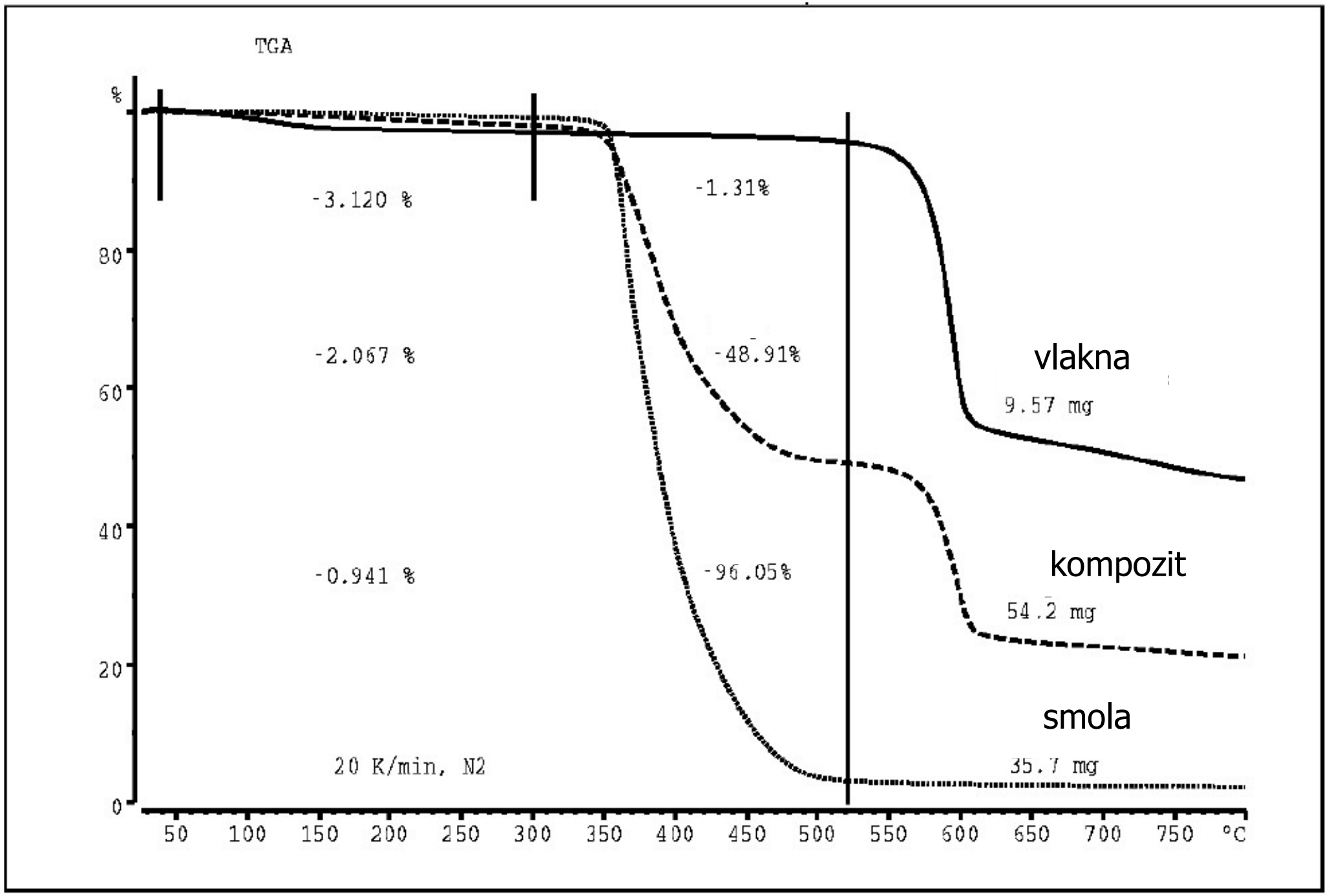
(3) one step degradation

(4) several step degradation

(5) same as (4) but without intermediates or fast heating

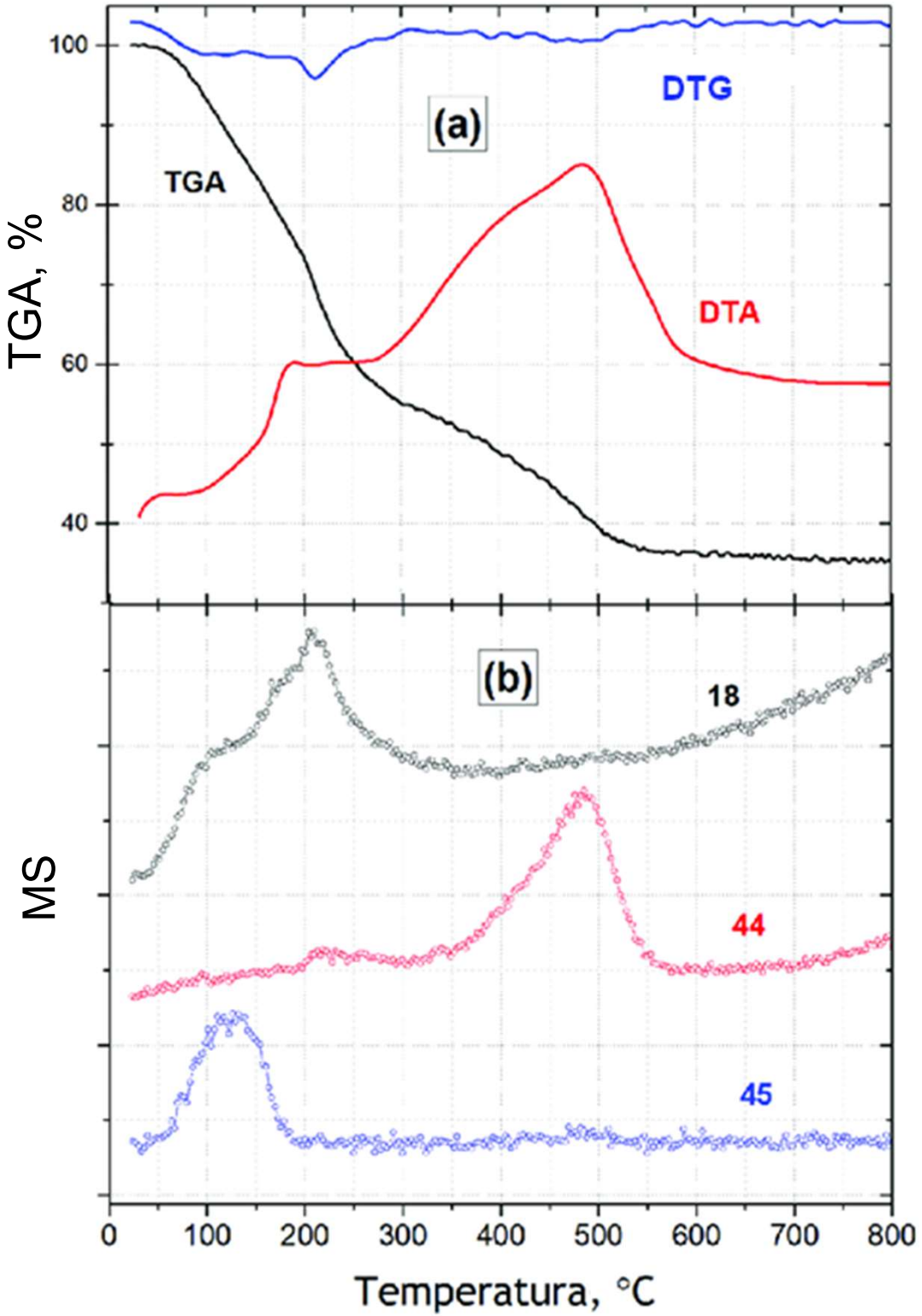
(6) reaction with atmosphere

(7) same as (6) but the products degrade at higher temperature


TGA
%
80
60
40
20
0
-3.120 %
-2.067 %
-0.941 %
-1.31%
-48.91%
-96.05%
vlakna
9.57 mg
kompozit
54.2 mg
smola
35.7 mg
20 K/min, N2
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
°C

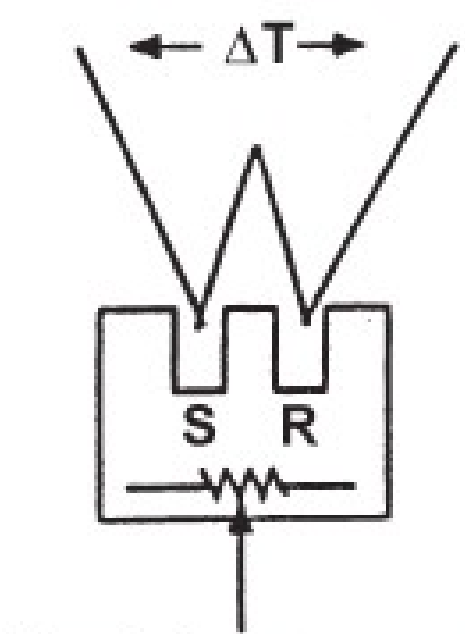
EGA

- Povezivanje TGA s FTIR, MS ili GC koji služe kao detektori i analizatori oslobođenih plinova / detection and analysis of evolved gases
- Točno definiranje reakcija/pojava na TGA krivulji (pomaže i analiza ostatka!) / ID of TGA effects
- Instrumenti povezani vrućom kapilarom: metalnom ili od kvarcnog stakla / hot capillary
- Integrirana krivulja količine plina: Gram-Schmidt integrated curve


100
80
60
40
TGA, %
DTG
(a)
TGA
DTA
(b)
18
44
45
MS
0
100
200
300
400
500
600
700
800
Temperatura, °C

	FTIR	MS	GC/MS
Istovremeno	Da	Da	Ne
Granica detekcije	normalna	visoka	vrlo visoka
Uzorak	svi oslobođeni plinovi	rascijepljeni plinovi	uhvaćeni plinovi
Identifikacija: plinovi male *M*	Da (osim IR inertnih plinova)	Da	zahtjeva skupljač plina
velike *M*	Da	problematično (ionizacija)	Da (velika točnost)
Noseći plin	bez ograničenja	helij	bez ograničenja
Poveznica	kapilara	kapilara uz vakuum	posebni mehanizam
Općenita ocjena	lako povezivanje, dobro za identificiranje	pogodno za praćenje određenog poznatog nastalog plina	najbolja za identifikaciju mješavine, dobra za mikroanalizu

DTA



Jedan grijač

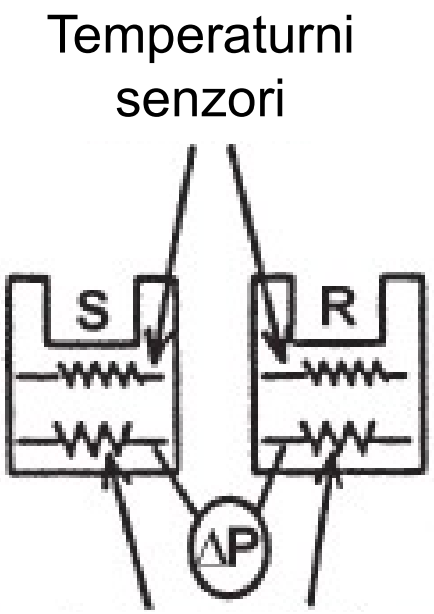
Mjerni i referentni uzorak
Measured and reference sample

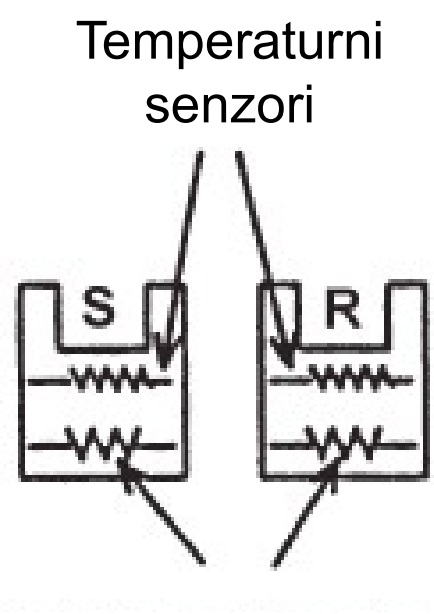
Razlika temperature, bliski kontakt termopara s uzorkom

Temperature difference, close contact with the sample

DTA-TGA

DSC





Mjerni i referentni uzorak

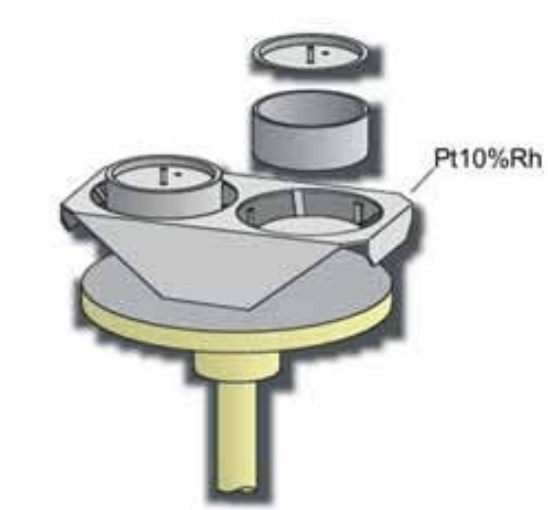
Kompenzacija snage

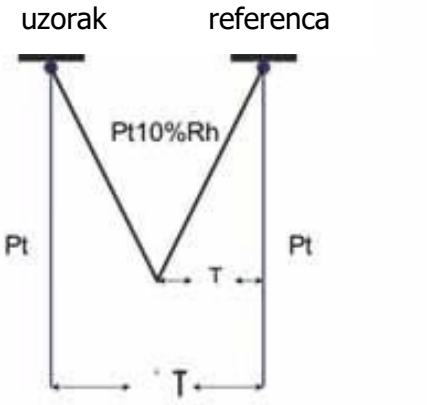
Power compensation

Toplinski tok

Heat flux


Sample Cell without Cover
Control Cell with Cover





DSC-TGA

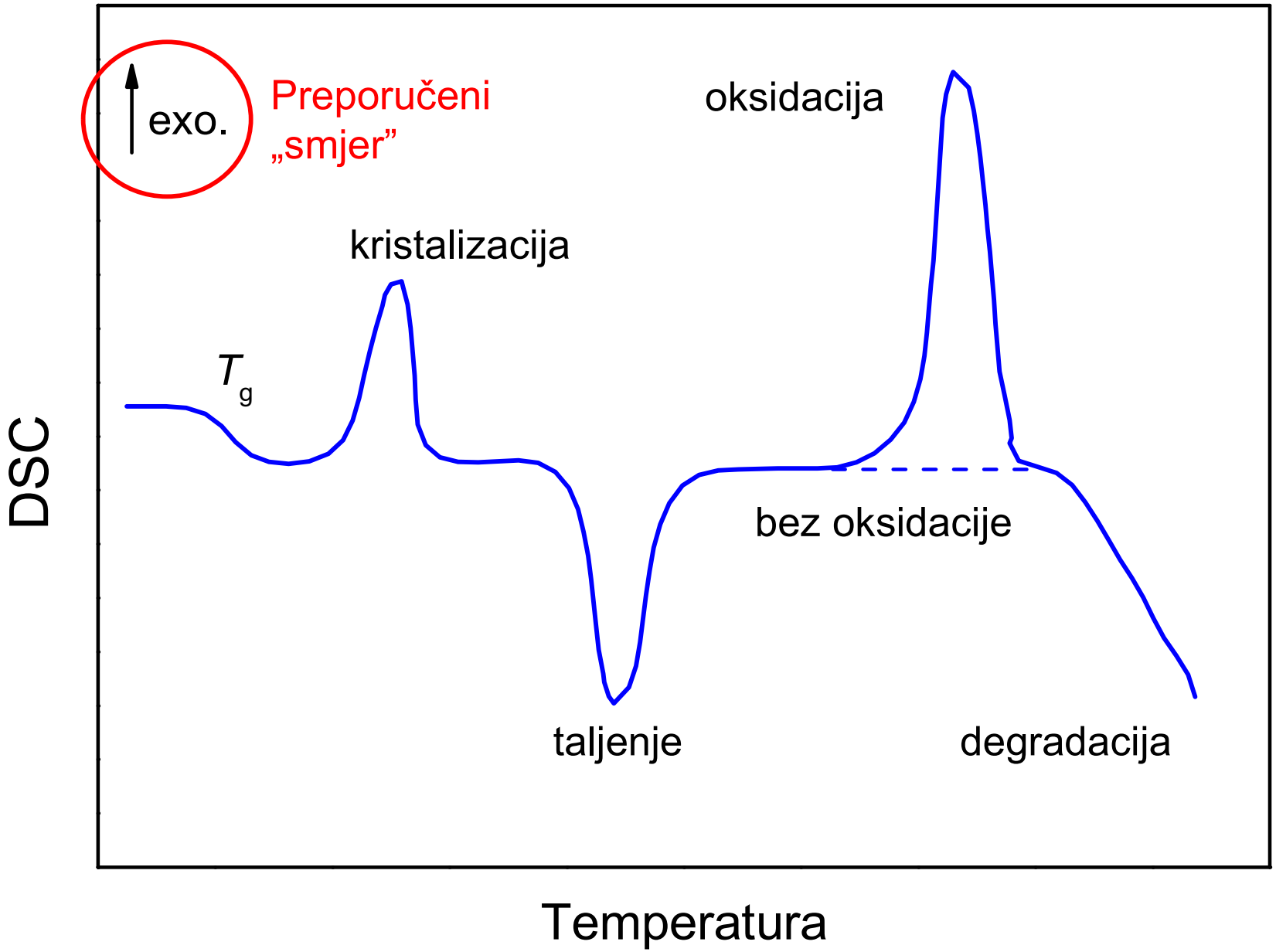
DTA ili DSC?

DTA

- Robusnija / More robust
- Više temperature (danas i DSC) / Higher temperatures
- Bliski kontakt termopara i uzorka / Close contact

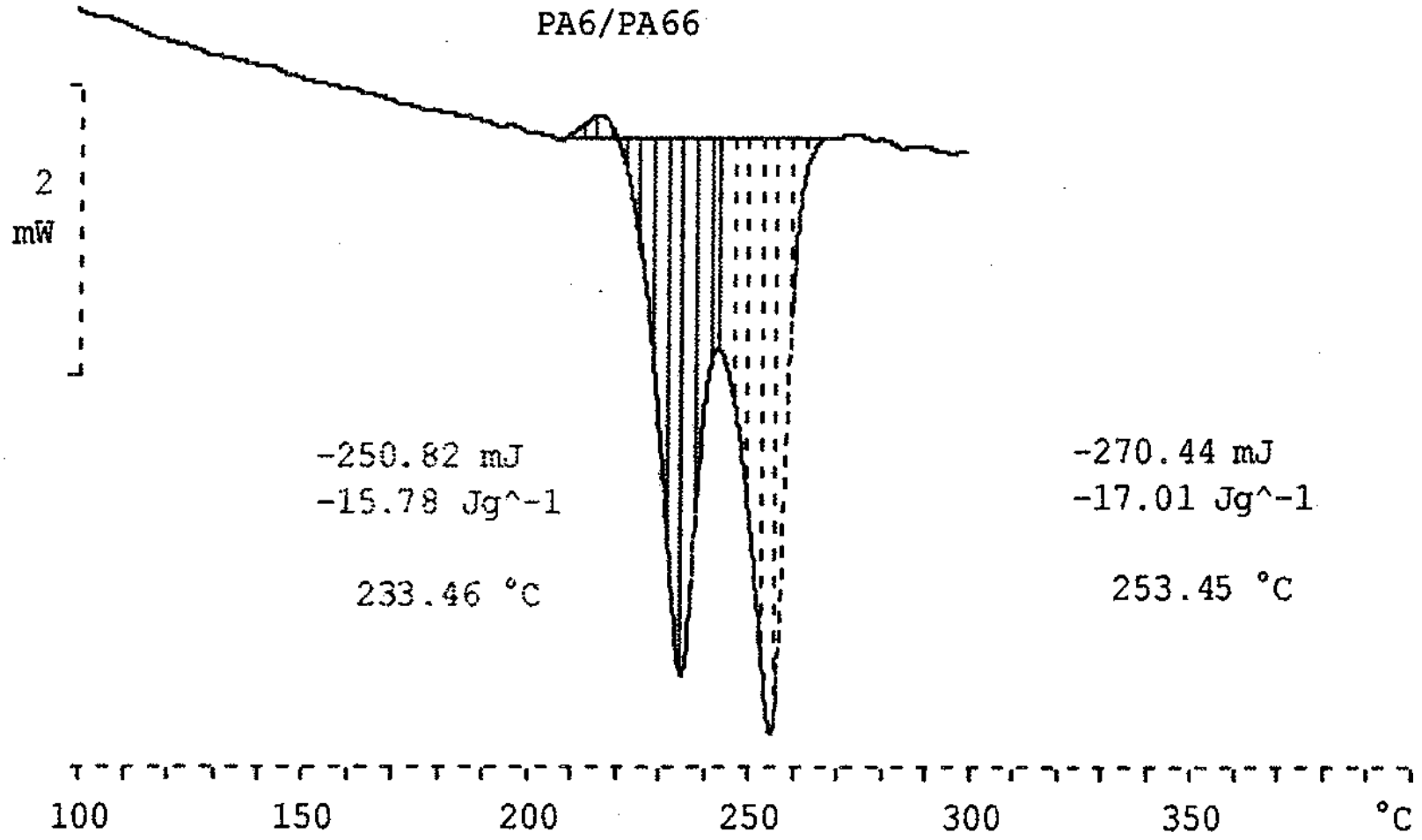
DSC

- Osjetljivija, manji utjecaj postavki / More sensitive
- Prikladnija < 500 °C / Better at < 500 °C
- Izravno mjerenje entalpija i C_p / direct enthalpies and capacities


exo.
Preporučeni
„smjer”
oksidacija
kristalizacija
T_g
DSC
bez oksidacije
taljenje
degradacija
Temperatura

DSC and DTA applications

- Kemijske reakcije i druge fizikalno-kemijske promjene / Phisical and chemical changes
- Staklište, toplinski kapacitet / glass transition, capacity
- Talište (onset vs. maksimum), čistoća uzorka, kristalnost i kristaliziranje / melting point, purity, cristalinity



Udjeli u polimernoj mješavini /
Polymer blend composition
(mješljivost/miscibility: T_g!)

Quantitative DSC

Površina ispod maksimuma:

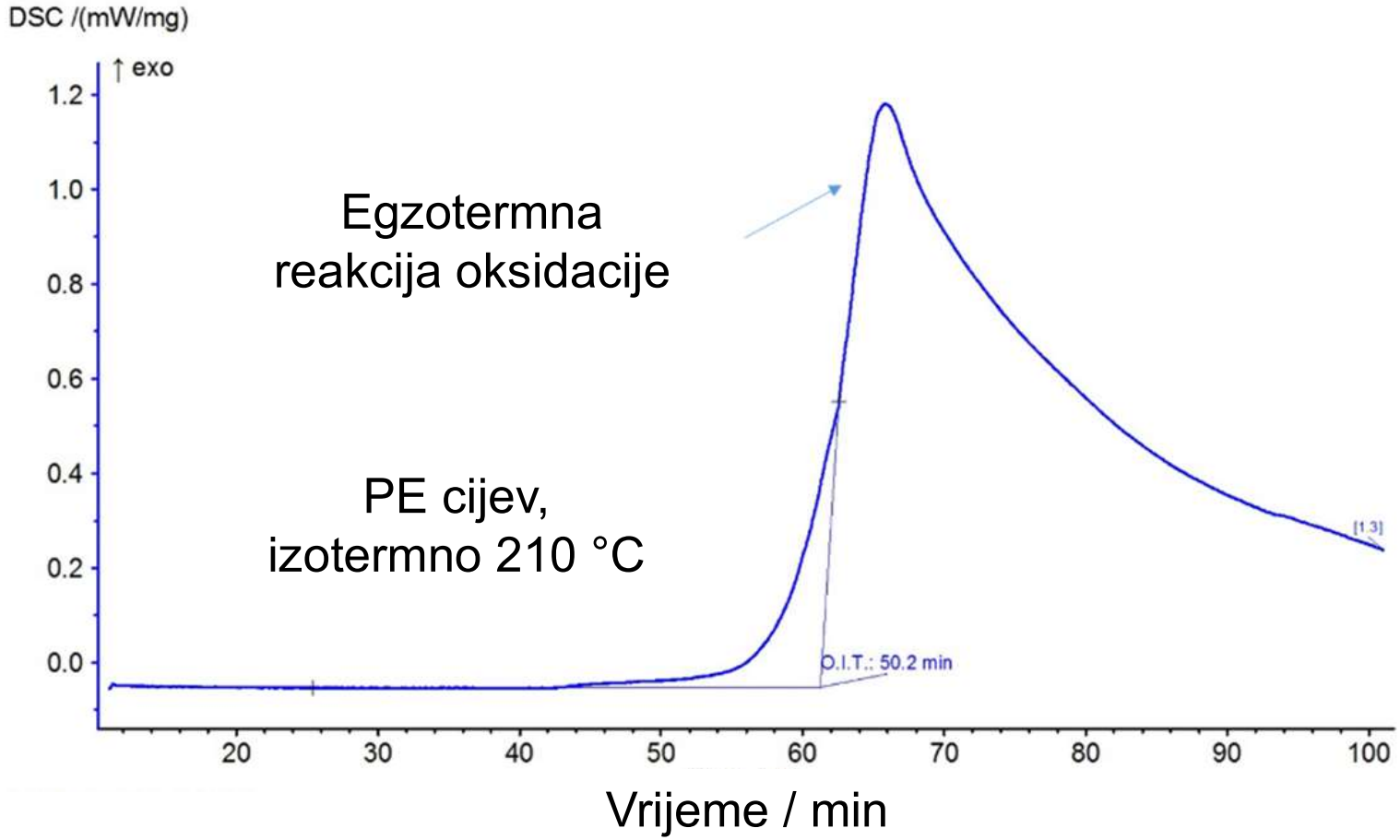
$$A = \frac{n\,\Delta H_{\mathrm{m}}}{g\,\lambda}$$

λ – toplinska provodnost! (praškasti, porozni… atmosfera oko uzorka!)

g – faktor oblika maksimuma

DSC: OIT

- Oxidation induction time (from time atmosphere switches to oxidative)



Photocalorimetry in DSC

- Exposing the sample to light of certain wavelength & duration, photoinduced reactions (polymerization etc.)
- Suscebility of food and pharmaceutics to light (also pre-treatment of samples prior to classical DSC measurement)
- Both crucibles exposed to the same intensity of light by splitting the same source

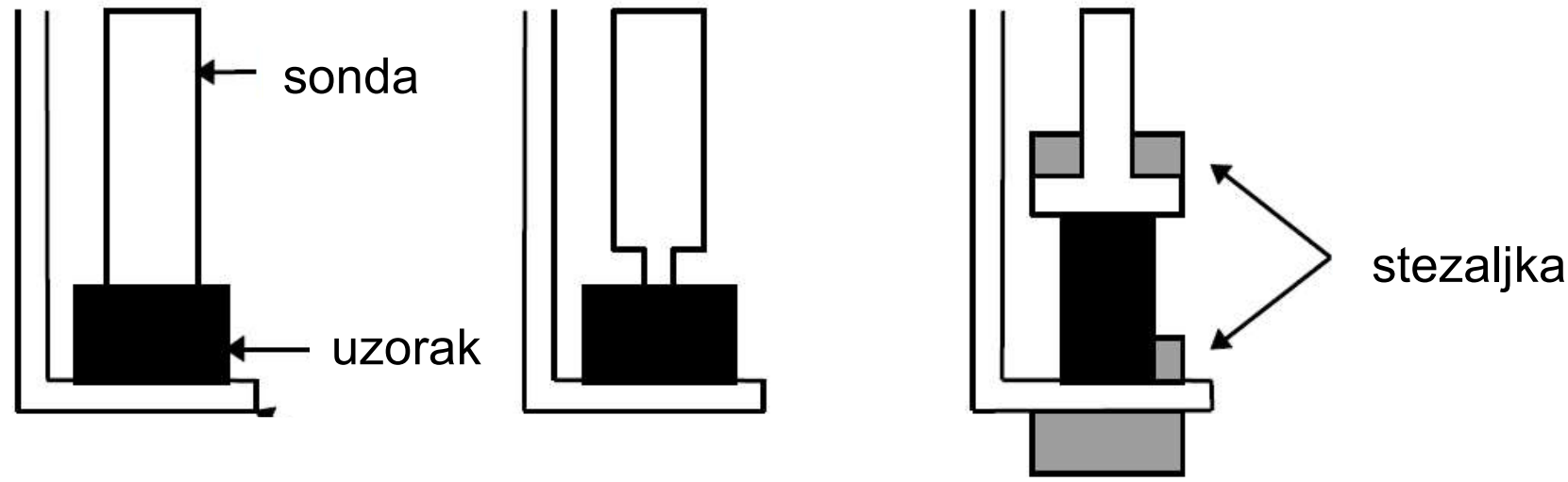
Thin / tiny samples methods

- DSC for samples < 1 µg, very fast heating/cooling rates: characterization of metastable states
  - Samples straight to sensor – single-use sensors!
- Influence of surface and sample size on properties, kinetics etc.

Examples of DSC and TGA analysis

primjeri

TMA



a) širenje/tlačenje b) prodiranje c) istezanje

Constant strain on sample:
compressive, extension, bending, torsion
(must be defined) and measuring deformation

TMA – applications

- Toplinsko širenje i stezanje / expansion and shrinking
- Bubrenje u otapalima / swelling
- Mekšanje i staklište /softening and glass transition
- Toplinska postojanost / Thermal stability
- Puzanje i relaksacija u materijalu /Creep and rekaxation

…anything that includes changes in dimension.

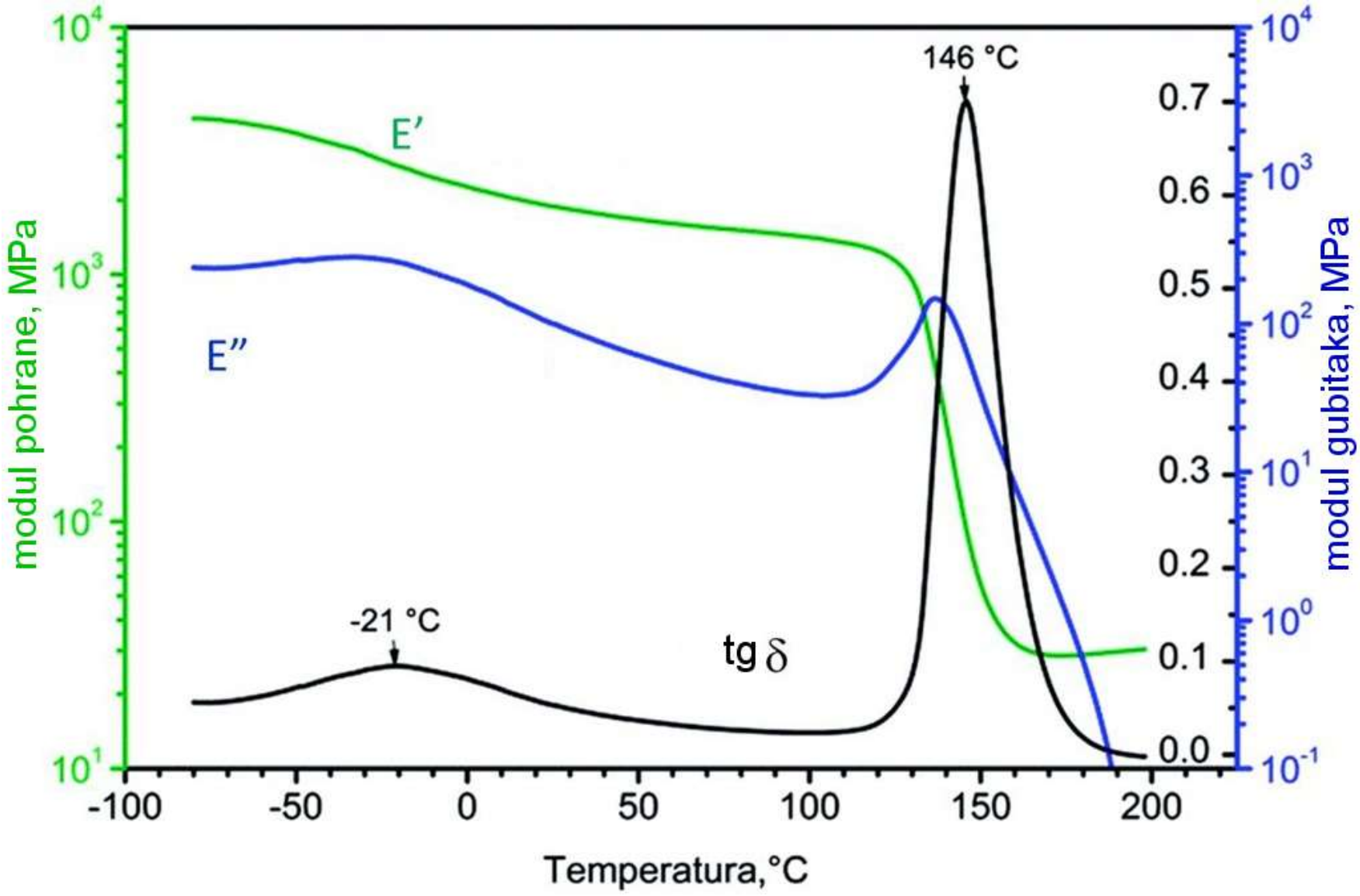
DMA

Oscillating (sinusoidal) exciation – viscoelastic properties:

- Modul pohrane / storage modulus, *E′* (in phase, elastic)
- Modul gubitaka / loss modulus, *E″* (out of phase, viscous)
- Tangens gubitaka / loss tangent, tg $\delta = E''/E'$

$$\sigma = \sigma_0 \sin(\omega t + \delta)$$

DMA


146 °C
E’
E”
-21 °C
tg δ
modul pohrane, MPa
modul gubitaka, MPa
Temperatura,°C
10^4
10^3
10^2
10^1
10^-1
10^0
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-100
-50
0
50
100
150
200

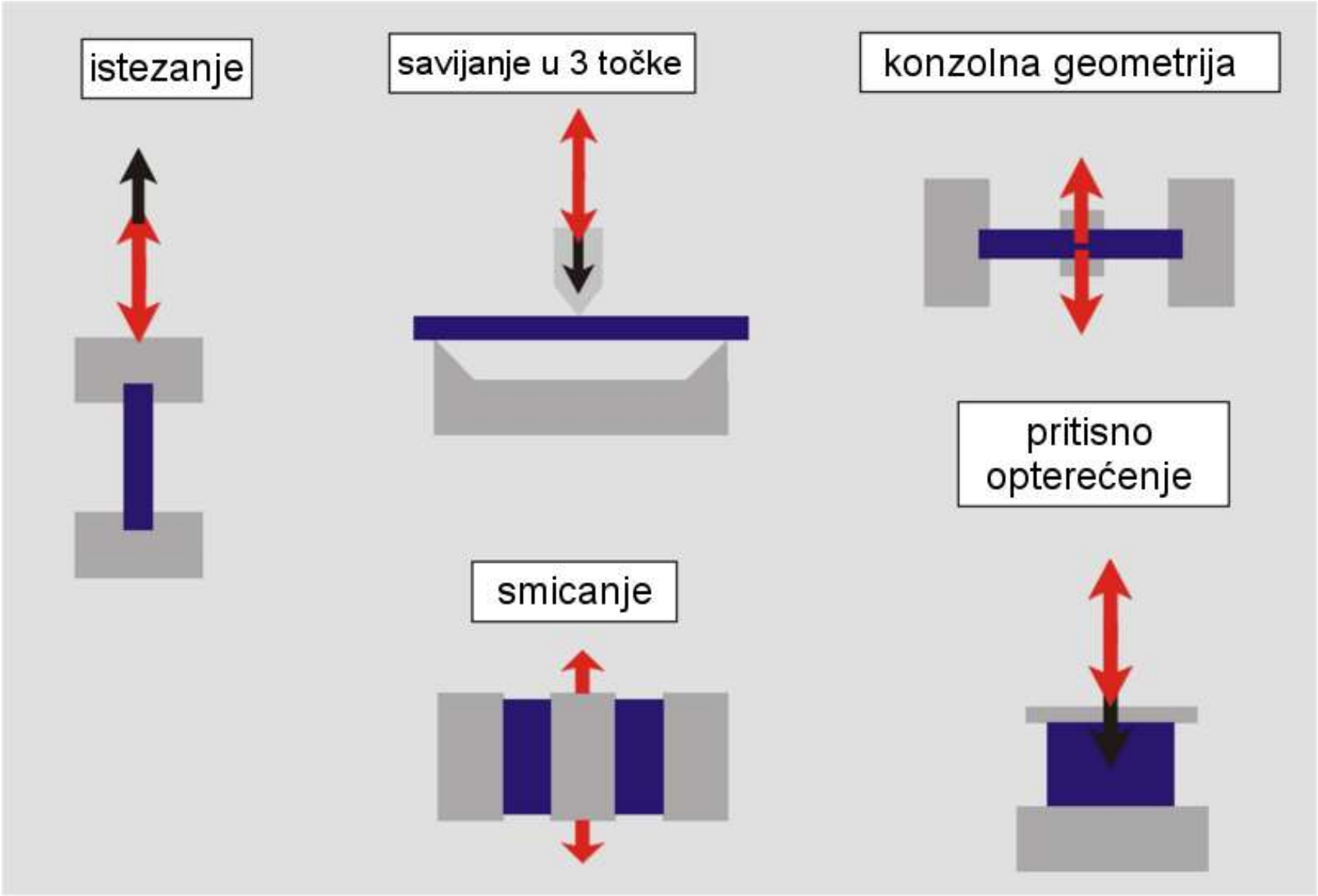
DMA

- Osim pri stalnoj (niskoj) frekvenciji, može i snimanje pri stalnoj temperaturi uz variranje frekvencije / constant or varying frequency
- Kutna frekvencija / Angle frequency:

$$\omega = 2\pi f$$

- Most often tensile and shear stress

DMA


istezanje
savijanje u 3 točke
konzolna geometrija
pritisno opterećenje
smicanje

DMA – applications

- Moduli
- Staklišta / Glass transition
- Međumolekulne interakcije polimera / Intermolecular interactions
- Starenje i toplinska razgradnja / Aging and thermal degradation
- Prigušno ponašanje / Damping
- Otpornost na trošenje / Wear resistance

Prvenstveno za polimere. / Polymers mostly.

TMA or DMA

- Noviji TMA također mogu raditi pod dinamičkim opterećenjem, analogno DMA (*dynamic load* TMA)
- TMA je osjetljiviji na male pomake, DMA može nametnuti jaču deformaciju uzorku
- Instrumenti optimirani za svoj glavni način rada, ali mogu zadovoljiti i u alternativnom

(Thermo)dilatometry

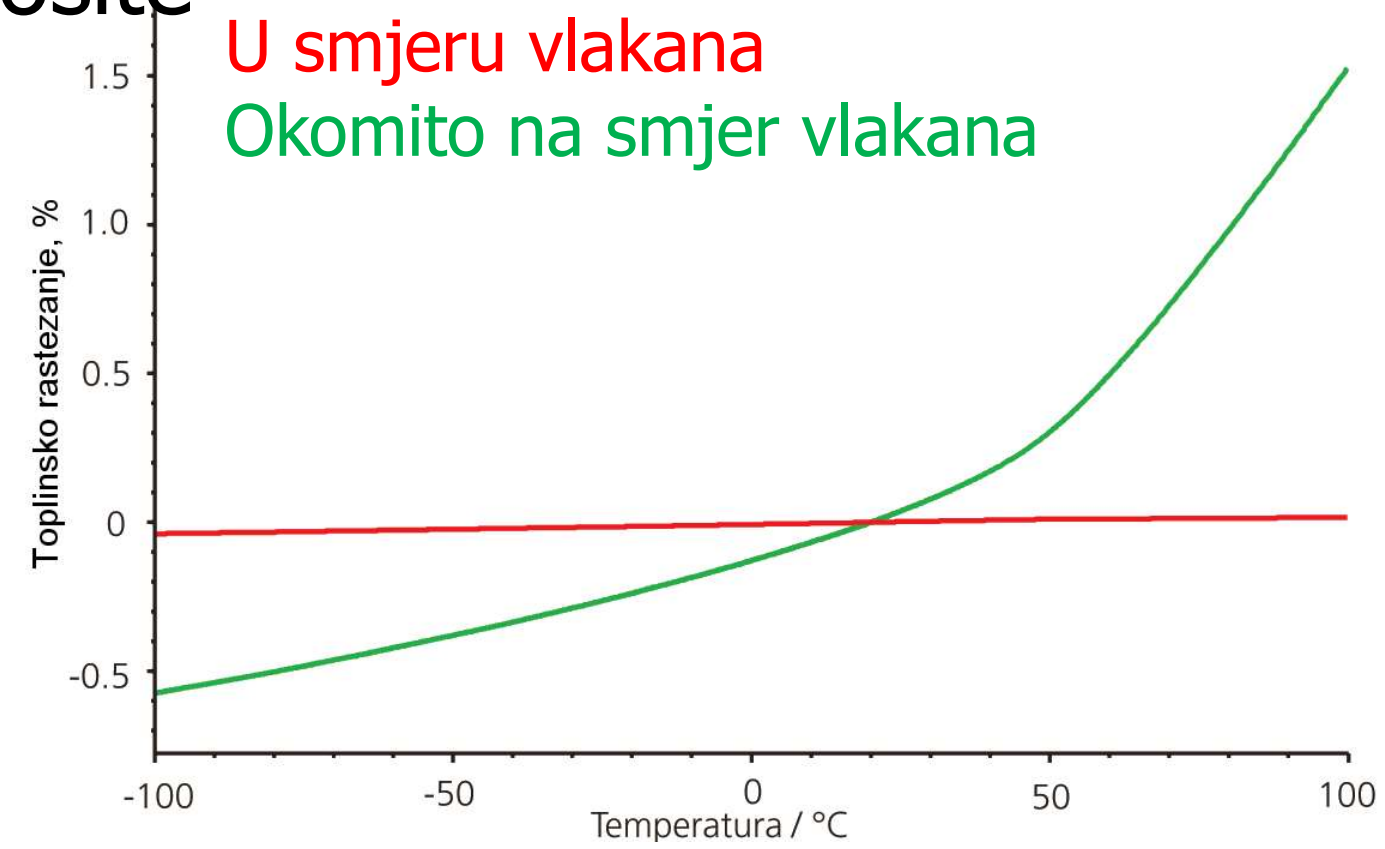
- Promjena volumena ili (češće) duljine uzorka zagrijavanjem / changes in volume or length
- Koeficijent toplinskog rastezanja / Thermal expansion

$$\alpha(T)_{p=\text{konst}} = \frac{1}{L_0} \cdot \frac{\partial L}{\partial T}$$

- Baždarenje materijalom poznatog α pod jednakim uvjetima da se odredi rastezanje nosača / Callibration with known α

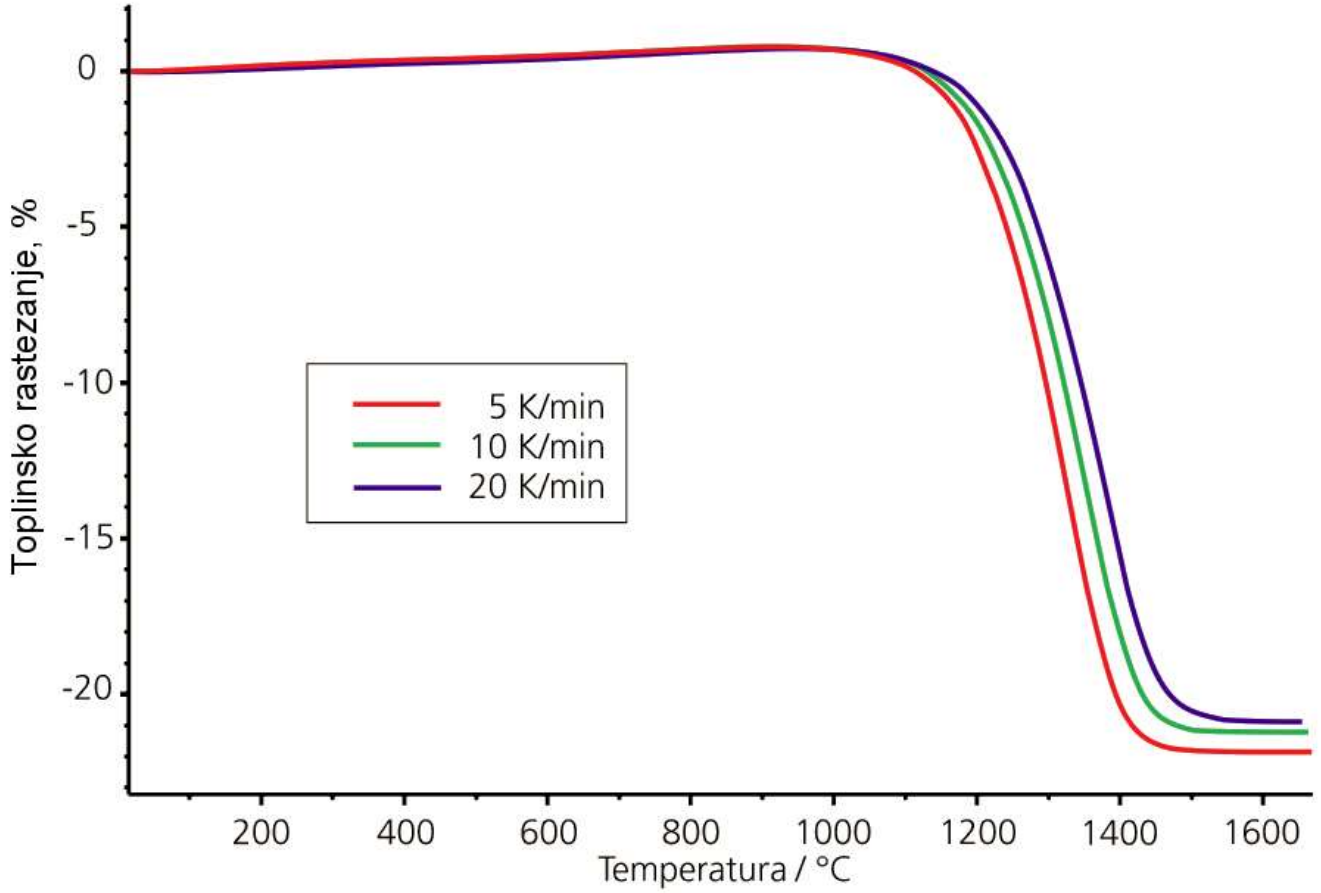
(Thermo)dilatometry

Toplinsko rastezanje vlaknima ojačanog polimernog kompozita / fiber reinforced composite



(Thermo)dilatometry

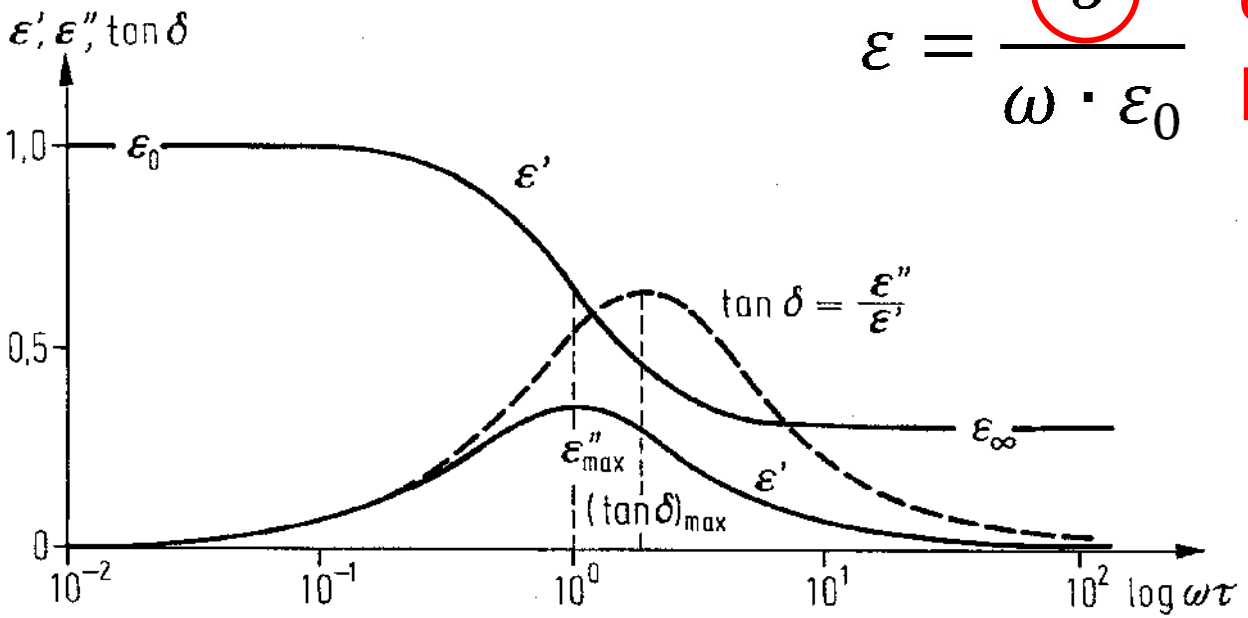
Određivane uvjeta sinteriranja (zgušnjavanja) keramike / ceramic sintering



DEA

DEA – dielectric thermal analysis

- Dobrim dijelom pandan DMA / Parallel to DMA
- Changes in dielectricity in oscillating electric field

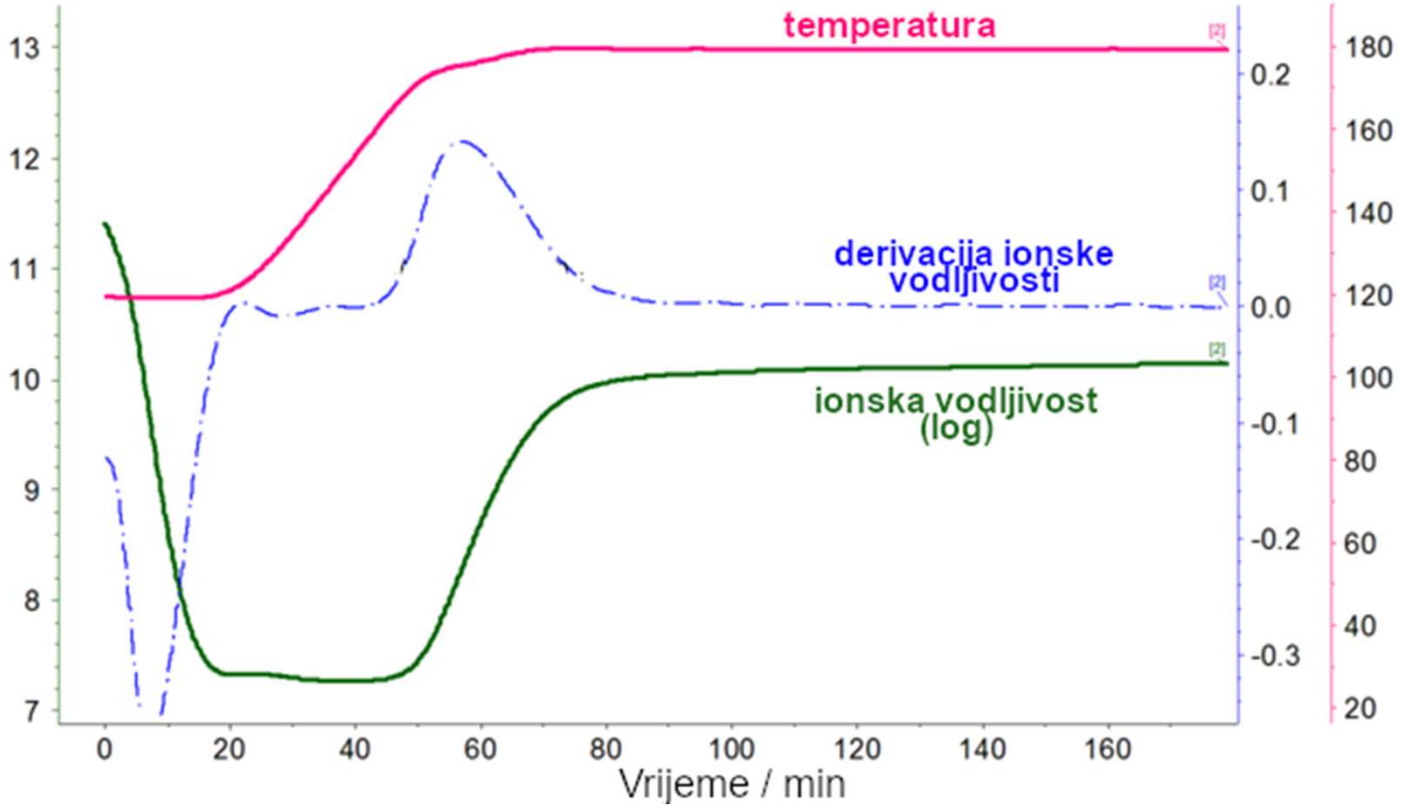


$$\varepsilon = \frac{\sigma}{\omega \cdot \varepsilon_0}$$

električna provodnost

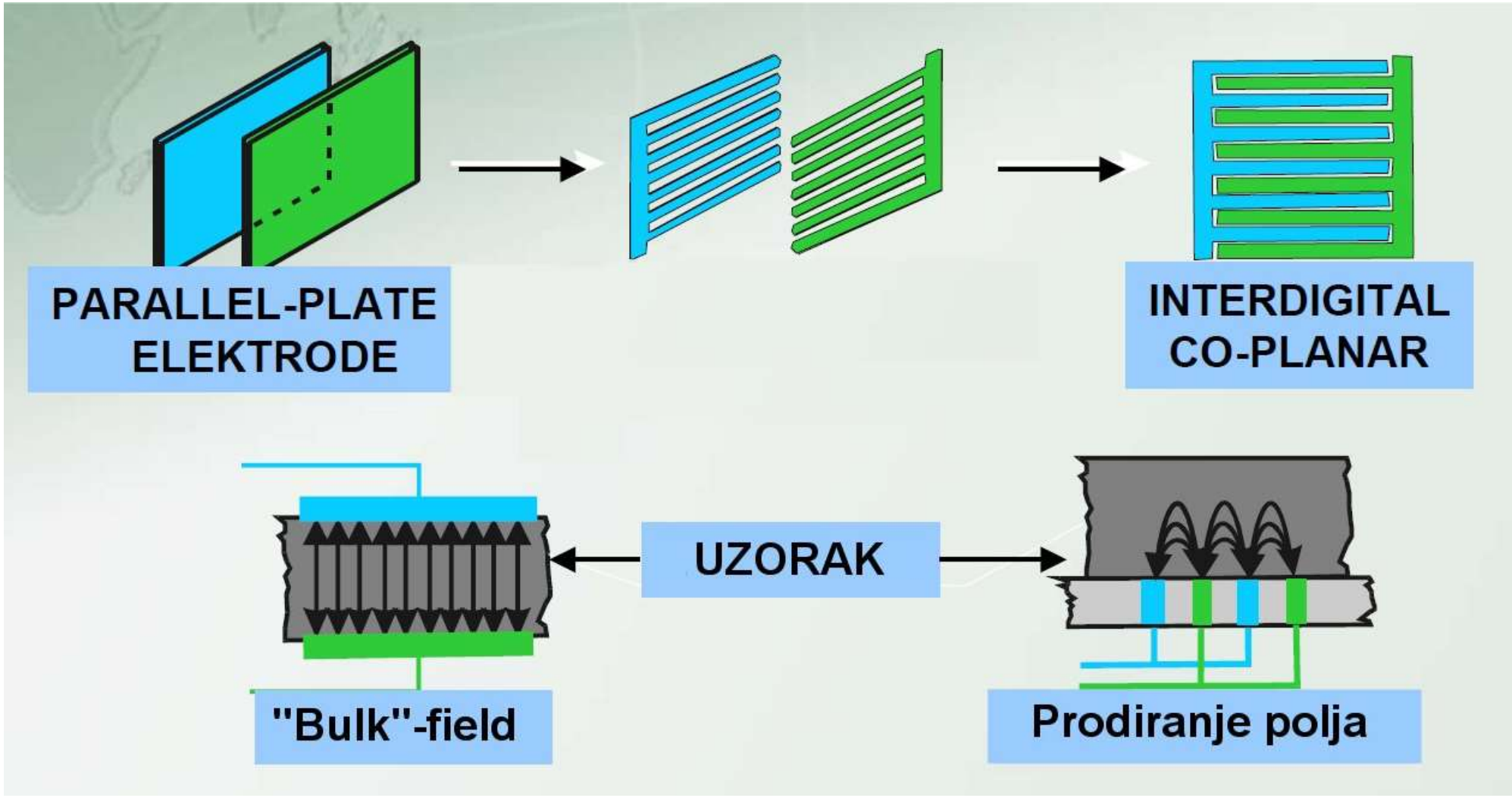
DEA

- Measuring of „ionic viscosity” ($1/\sigma$) while crosslinking, wider range than rheometers



DEA

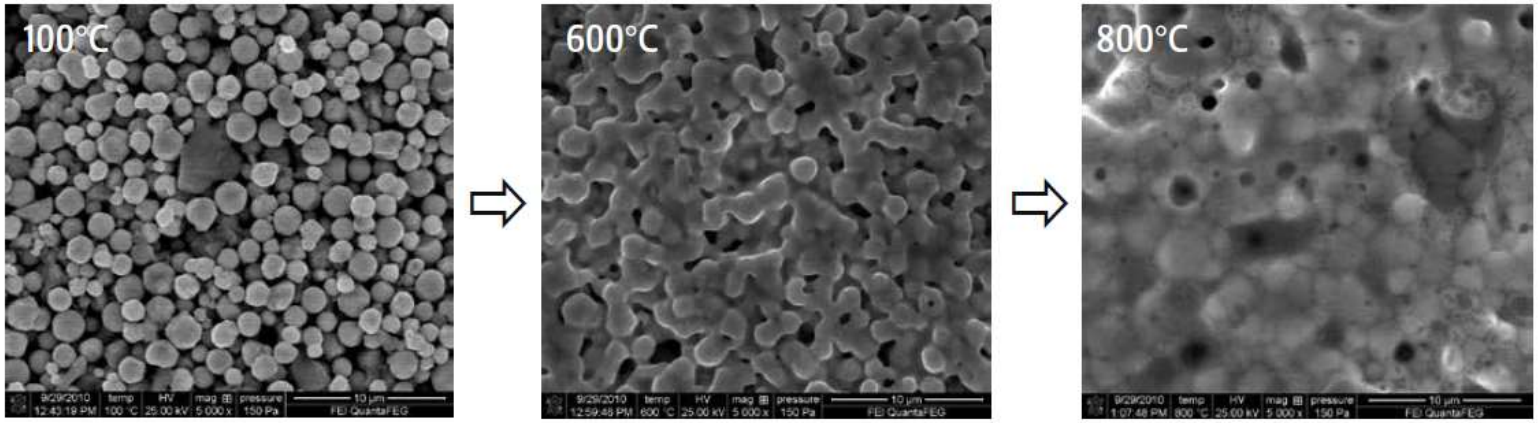
- Izvedbe geometrije elektroda



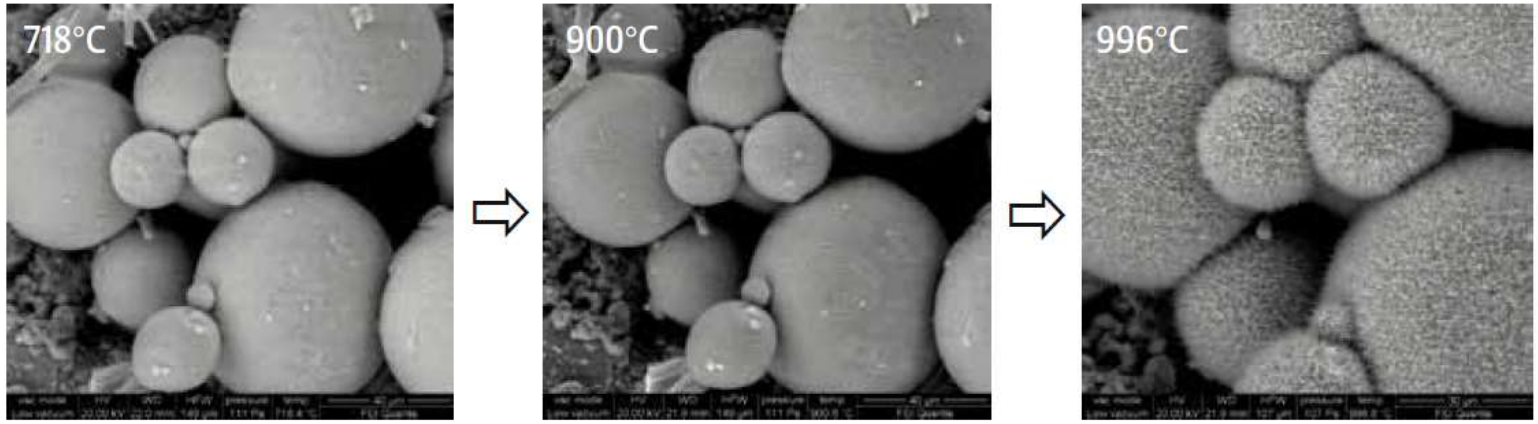
Thermooptometry

- Thermophotometry – emited light
- Thermorefractometry – refraction index
- Thermoluminiscence
- Thermomicroskopy – e.g. in combination with DSC

Heated stages in light and electron microscopy

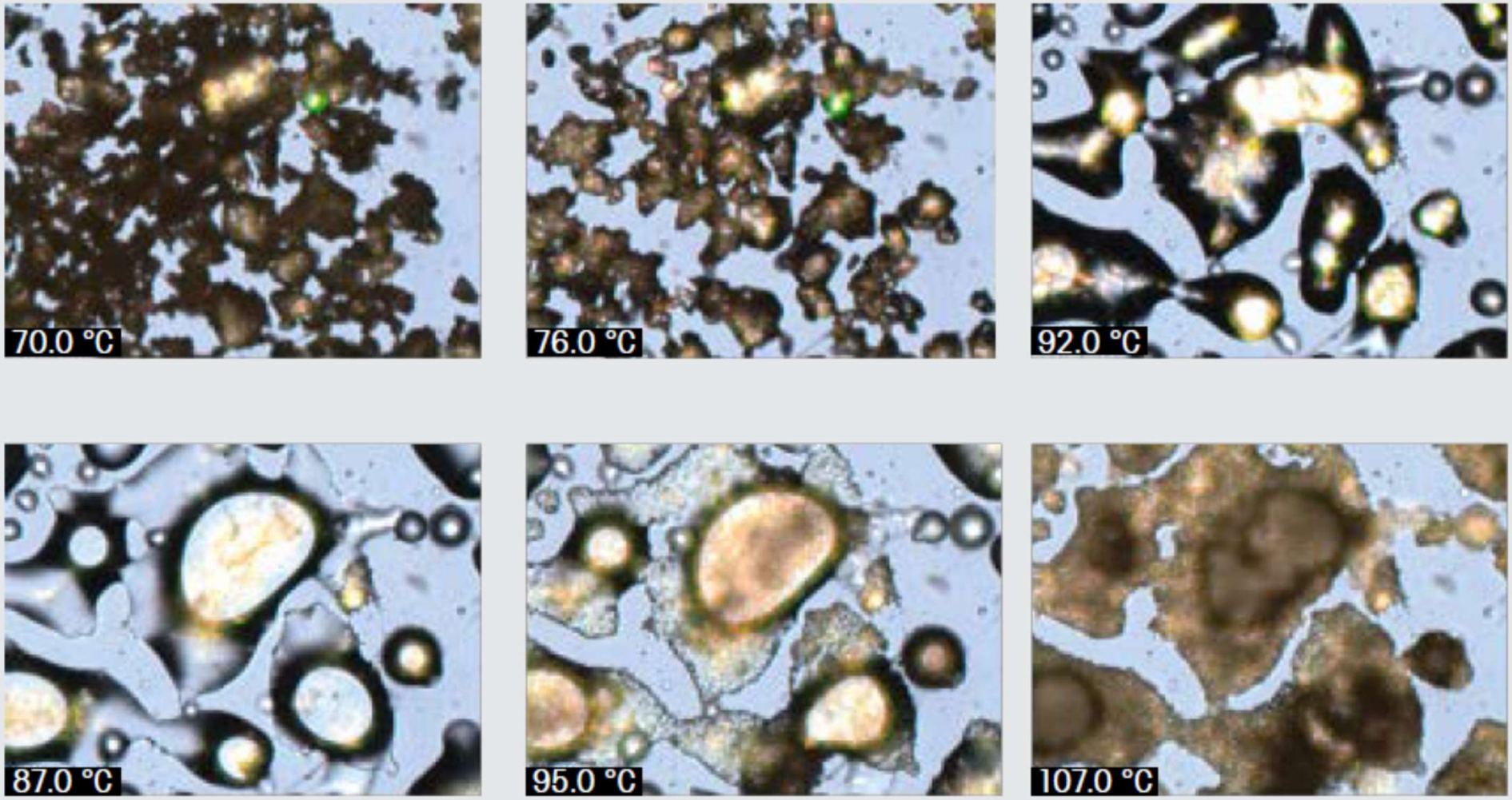


Taljenje srebrne paste



Metalne čestice – promjena površinske morfologije

Zagrijavanje uzoraka u pretražnom elektronskom mikroskopu / Heating in SEM



Zagrijavanje farmaceutika u mikroskopu /
Pharmaceutics heated in microscope

Zagrijavanje farmaceutika, termomikroskopija

Thermooptometry in DSC

- Microscopy: lakša interpretacija i identificiranje artefakata **uslijed pomicanja lončića** (pucanje uzorka, stezanje polimera) / artefact interpretation
- chemiluminiscence: obično kao pomoć u detektiranju oksidativne degradacije organskih tvari (OIT) / aiding in OIT

Simultaneous methods

- DSC-TGA
- TMA-DTA
- TGA-EGA
- DSC-optičke
- DEA-reometar
- DEA-DMA

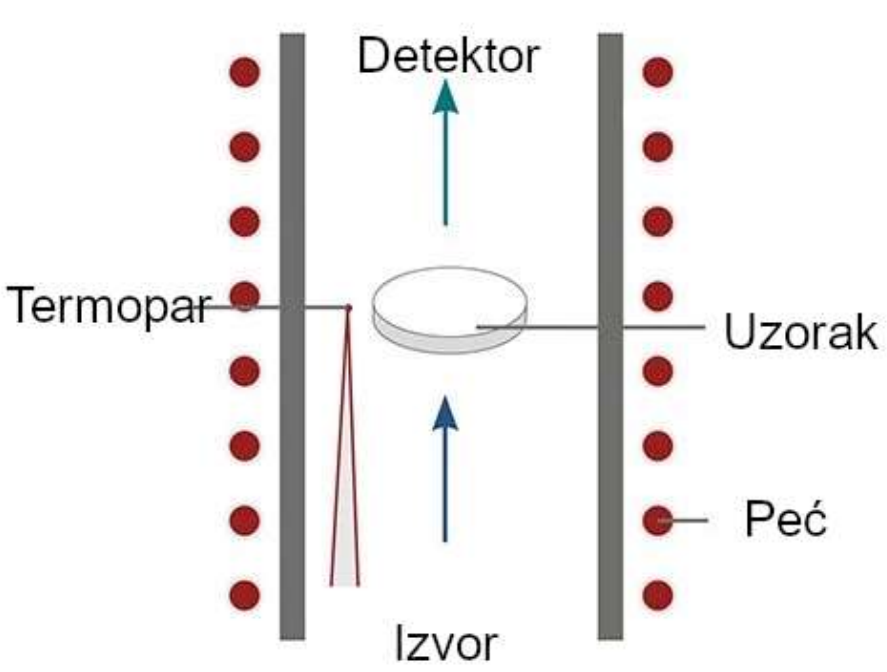
Thermo-phisical properties

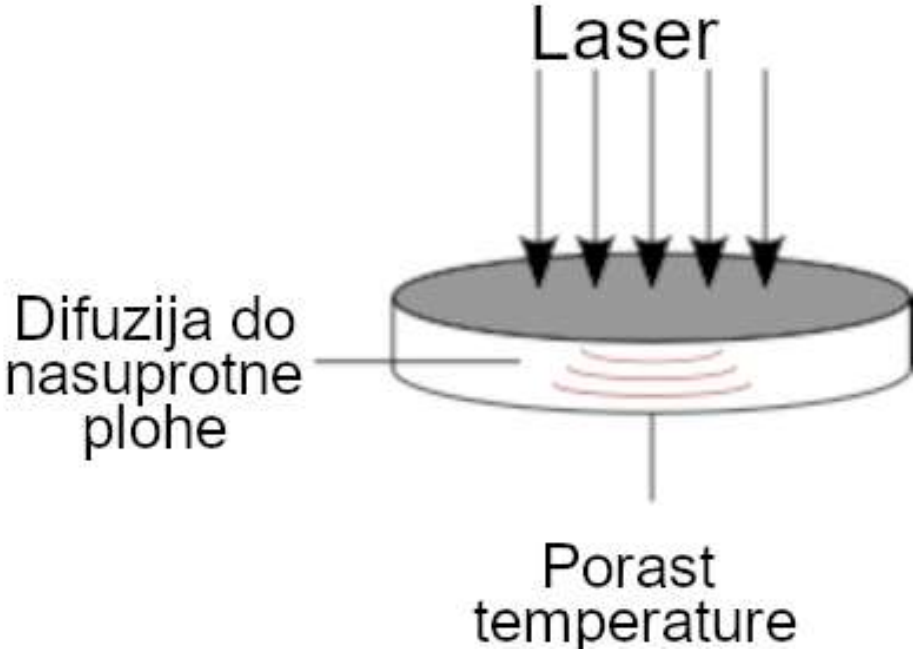
- Razvoj novih instrumenata koji služe određivanju osnovnih toplinskih svojstava materijala (prijenos topline):
  - toplinska provodnost/conductivity, λ
  - toplinska difuznost/diffusivity, a

$$a = \frac{\lambda}{\rho \cdot c_p}$$

LFA

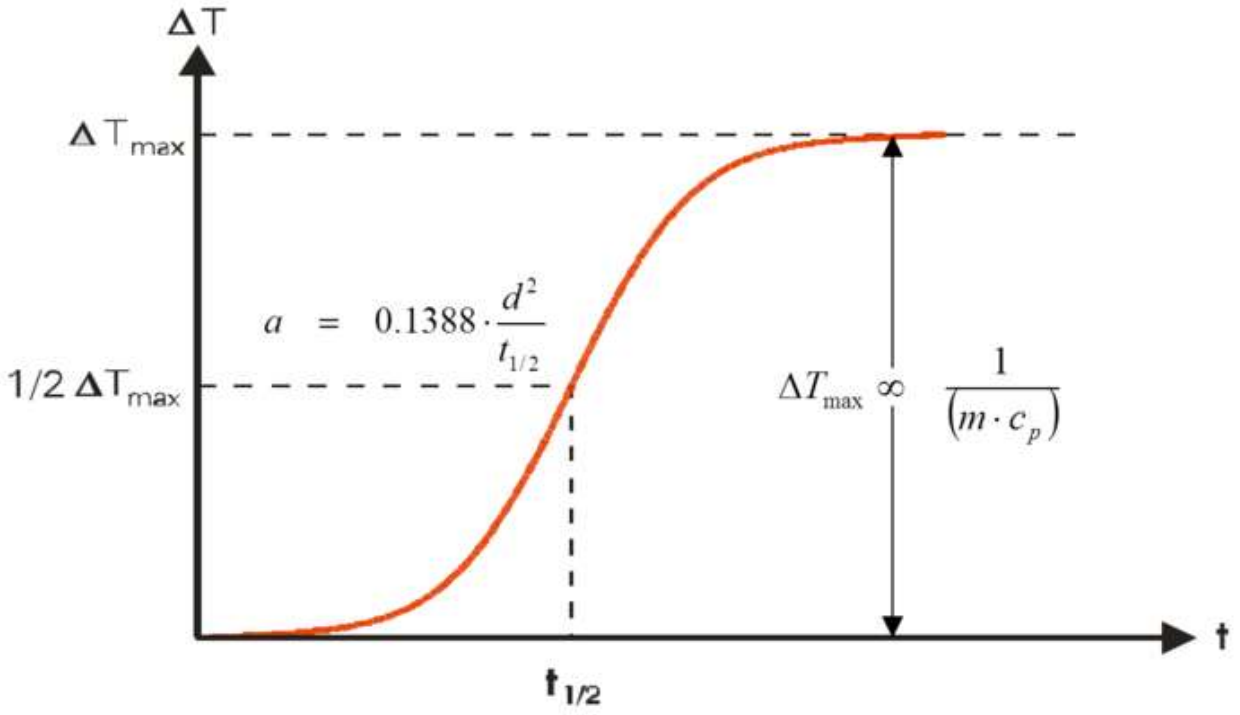
- *Laser Flash Method*: laserskim pulsom se uzorak zagrijava s jedne strane, IR detektor mjeri prolaz topline s druge strane





LFA

- daje a, λ se može izračunati iz poznatih ρ i c_p



- mjerenje do 900 °C / up to 900 °C

LFA

- Radi jednolike apsorpcije energije naparivanje uzorka npr. grafitom ili zlatom, u svakom slučaju nije dobro da bude zrcalno sjajan! / graphite or gold coating for equal energy absorption
- Uz prilagodnu detektora i za male (mikro) uzorke i tanke filmove! / also for micro samples and thin films
- Za tanje ili slabo vodljive uzorke, da se izbjegne pregrijavanje: PLH (*Periodic Laser Heating*), moduliranje pulsa ulazne energije. / for thinner or less conductive samples

LFA variant – HSXD

- Umjesto lasera, izvor je ksenonska lampa (*High Speed Xenon Discharge*, HSXD)
- Znatno jeftinije i jednostavnije od lasera a rezultati adekvatni. / cheaper and simpler than laser, adequate results

Which methods do you find interesting?

~ intermission~

Experimental conditions

Odabir i utjecaj parametara mjerenja

Experimental conditions

- **U**zorak / sample
- **L**ončić / crucible
- **B**rzina (zagrijavanja/hlađenja) / rate
- **A**tmosfera / atmosphere
- **M**asa (i raspodjela) / mass + distribution

Kontrolirano mijenjanje parametara može pomoći u interpretaciji rezultata! / Parameter change can help interpretation

Sample

- Koja atmosfera? / Which atmoshpere?
- Koji lončić? / Which crucible?
- Raspon temperatura / Temp range
- Očekivane pojave / what is expected
- Količina uzorka / Sample quantity

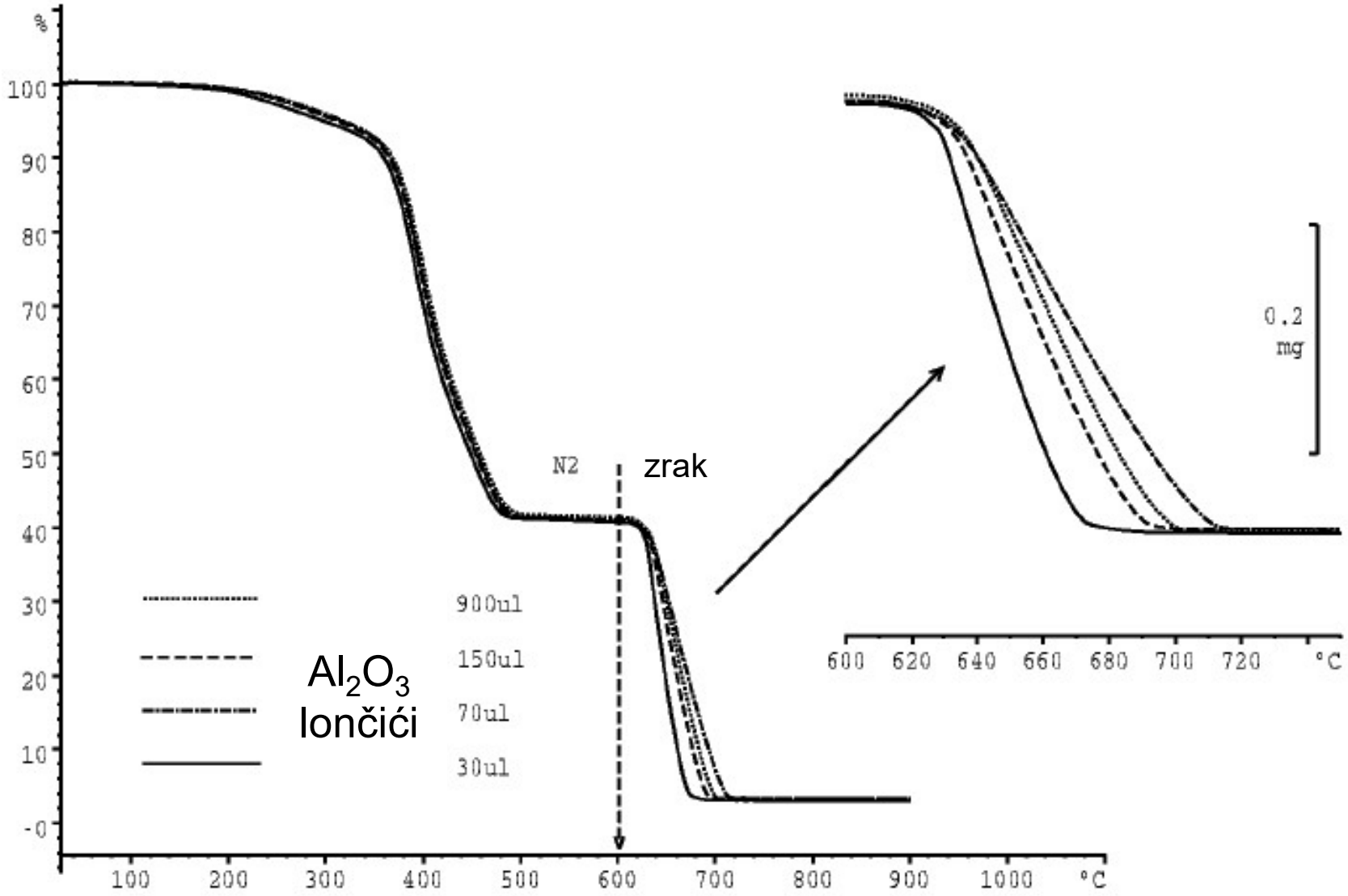
Sample preparation

Za svaku instrumentalnu metodu:

- Najvažnija / The most important
- Prividno jednostavna / Deceptively simple
- Ne može se naučiti teorijski / Can’t be taught theoretically

Crucible

- Samo za neke metode! / Not all methods!
- Utjecaj oblika i C_p kompenzira se kalibracijom / callibration for shape and C_p

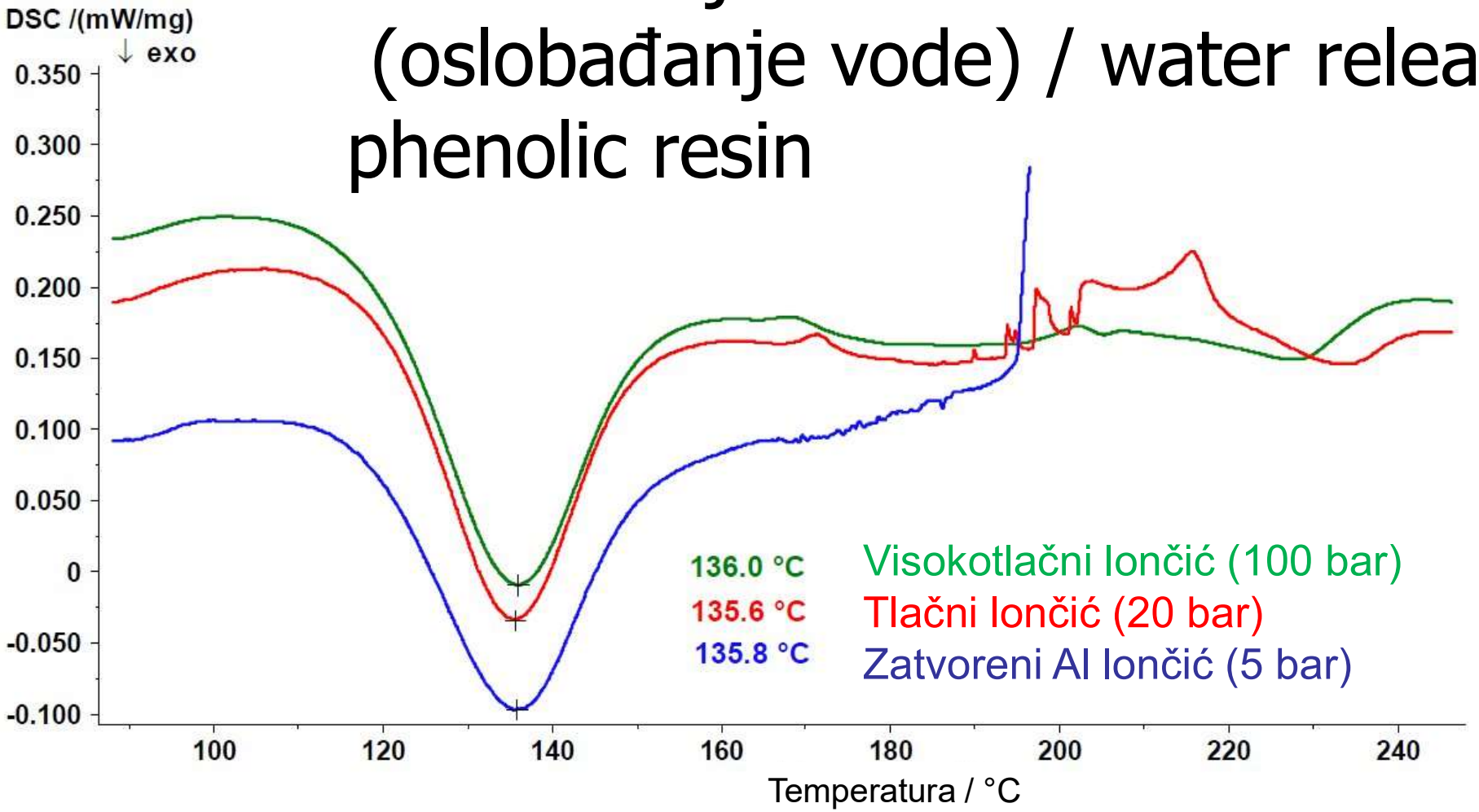

%
100
90
80
70
60
50
40
30
20
10
-0
100
200
300
400
500
600
700
800
900
1000
°C
N2
zrak
900ul
150ul
70ul
30ul
Al_2O_3
lončići
0.2
mg
600
620
640
660
680
700
720
°C

Crucible

- Atmosphere contact:
  - otvoreni / open
  - probušeni poklopac / hole in lid
  - 50 μm otvor (samo-generirana atmosfera) / self-generated atmosphere
  - hermetički zatvoren / hermetical
- Hermetički samo < 200 °C ($p \sim T$!)

Crucible

Očvršćivanje fenolne smole (oslobađanje vode) / water release phenolic resin



Crucible

- Ponekad i TGA bez lončića, radi boljeg dodira s atmosferom (reaktivnim plinom):
  - platforma za uzorak (bez bočnih stijenki)
  - mrežasti držač uzorka da plin može strujati kroz njega!

TGA without crucible – a platform or a grid

Crucible

Izbor materijala / Material choice:

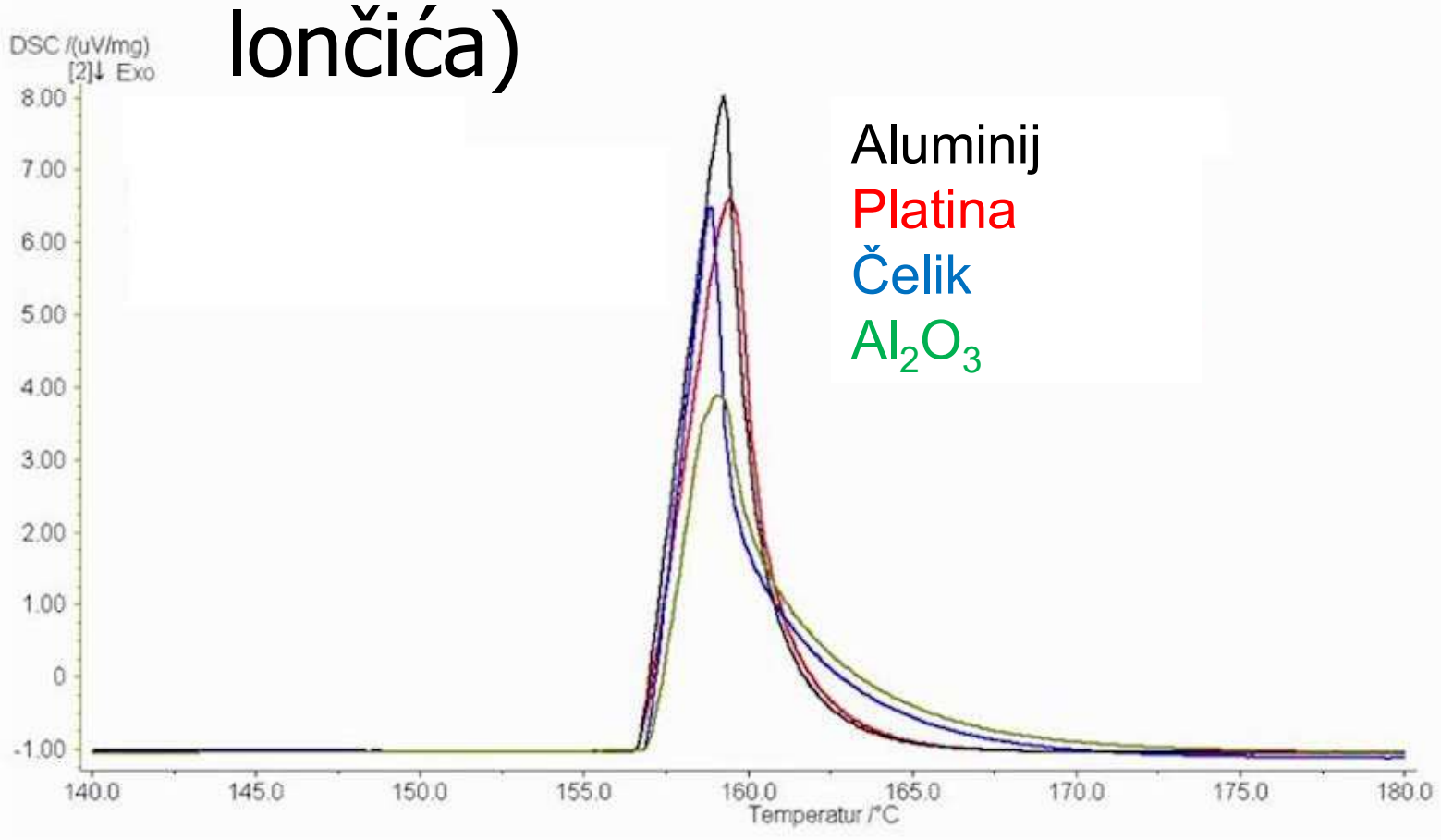
- Inertan! / Inert!
- Katalitička aktivnost: Cu za OIT / Catalytic activity
- Temperaturni raspon / Temp range:

$$T_m(\mathrm{Al}) = 660\ ^\circ\mathrm{C}$$

- Često jednokratni (čišćenje teško) / often single-use (tough to clean)

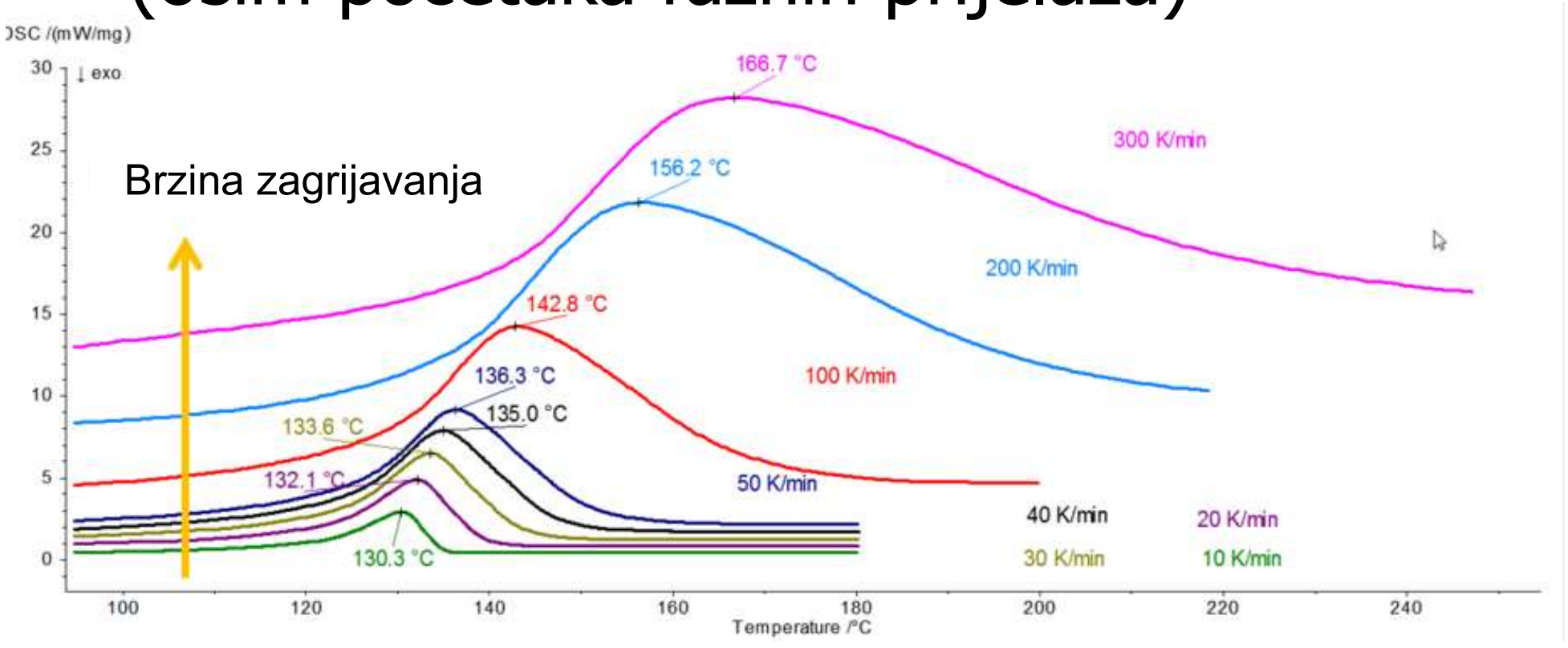
Crucible

Utjecaj na DSC maksimum (toplinska provodnost, toplinski kapacitet i masa lončića)

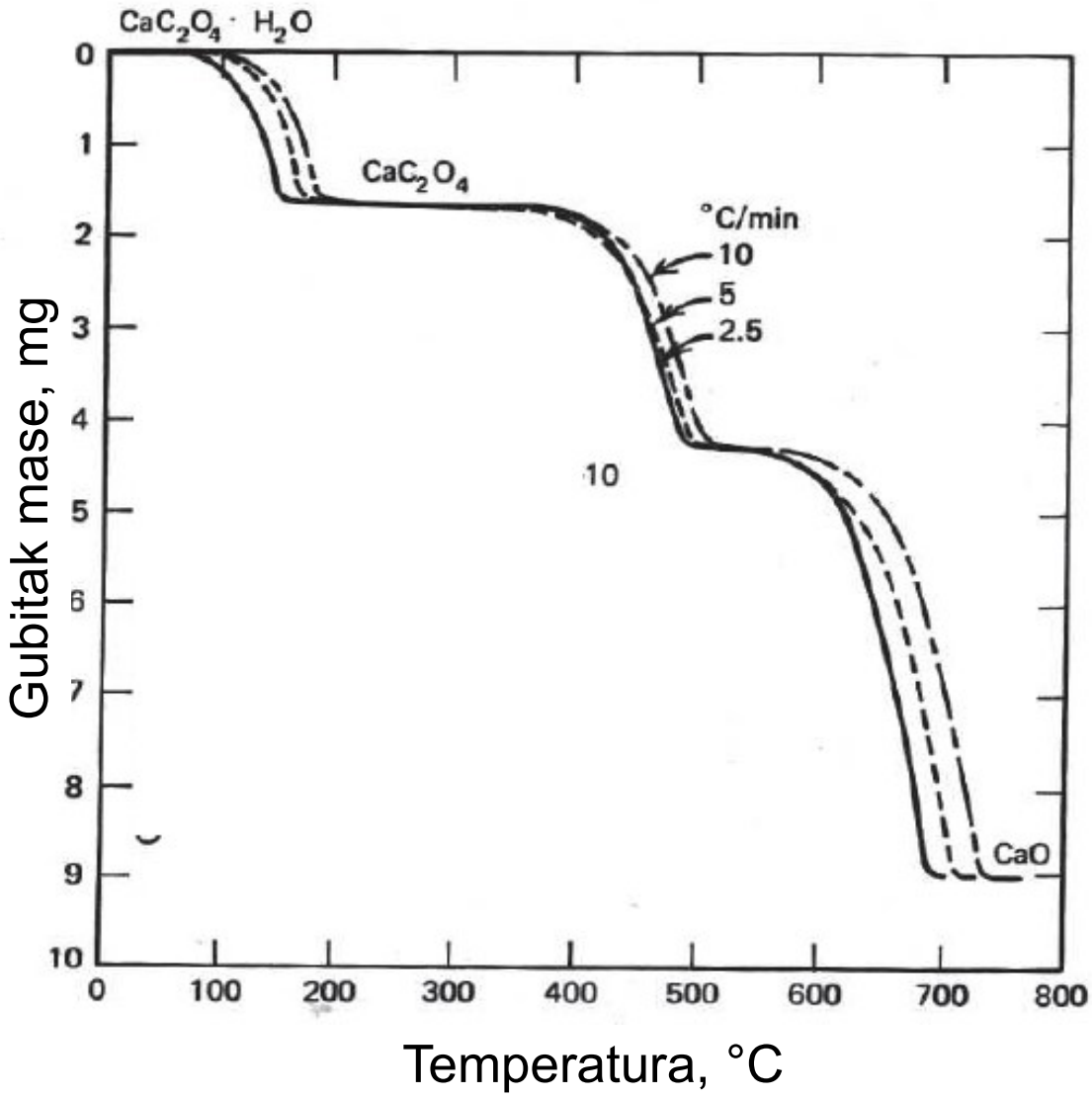


Rate

- Linearne, $\beta = 0{,}1 - 200$ K/min
- Pomak u temperaturama / Temp shift (osim početaka faznih prijelaza)



Rate



Raspad kalcijevog oksalata/ calcium oxalate degradation

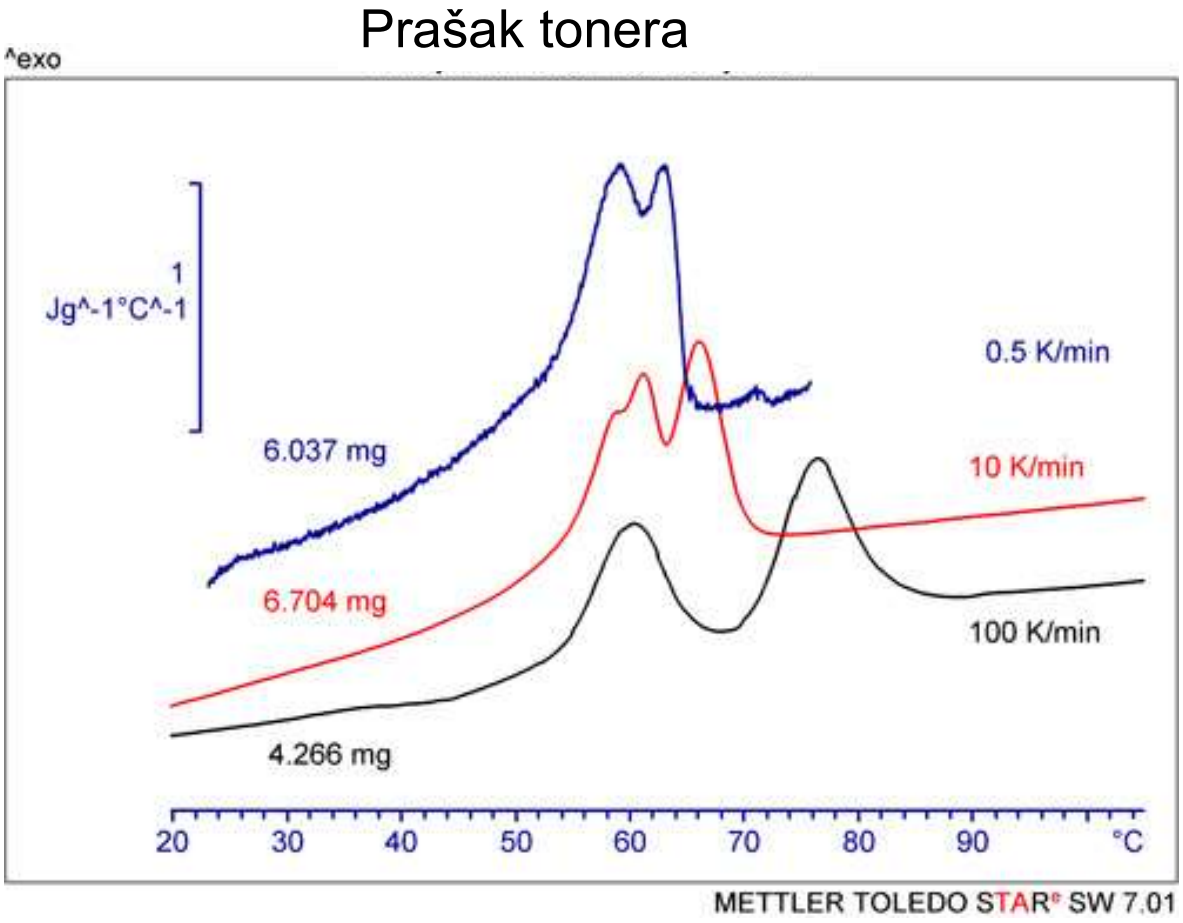
(modelna TGA reakcija)

Rate

Veća brzina daje jači signal i veće preklapanje / higher rate stronger signal and more overlap

ALI

•Pomak na više temperature razdvaja taljenje i degradaciju



Cooling

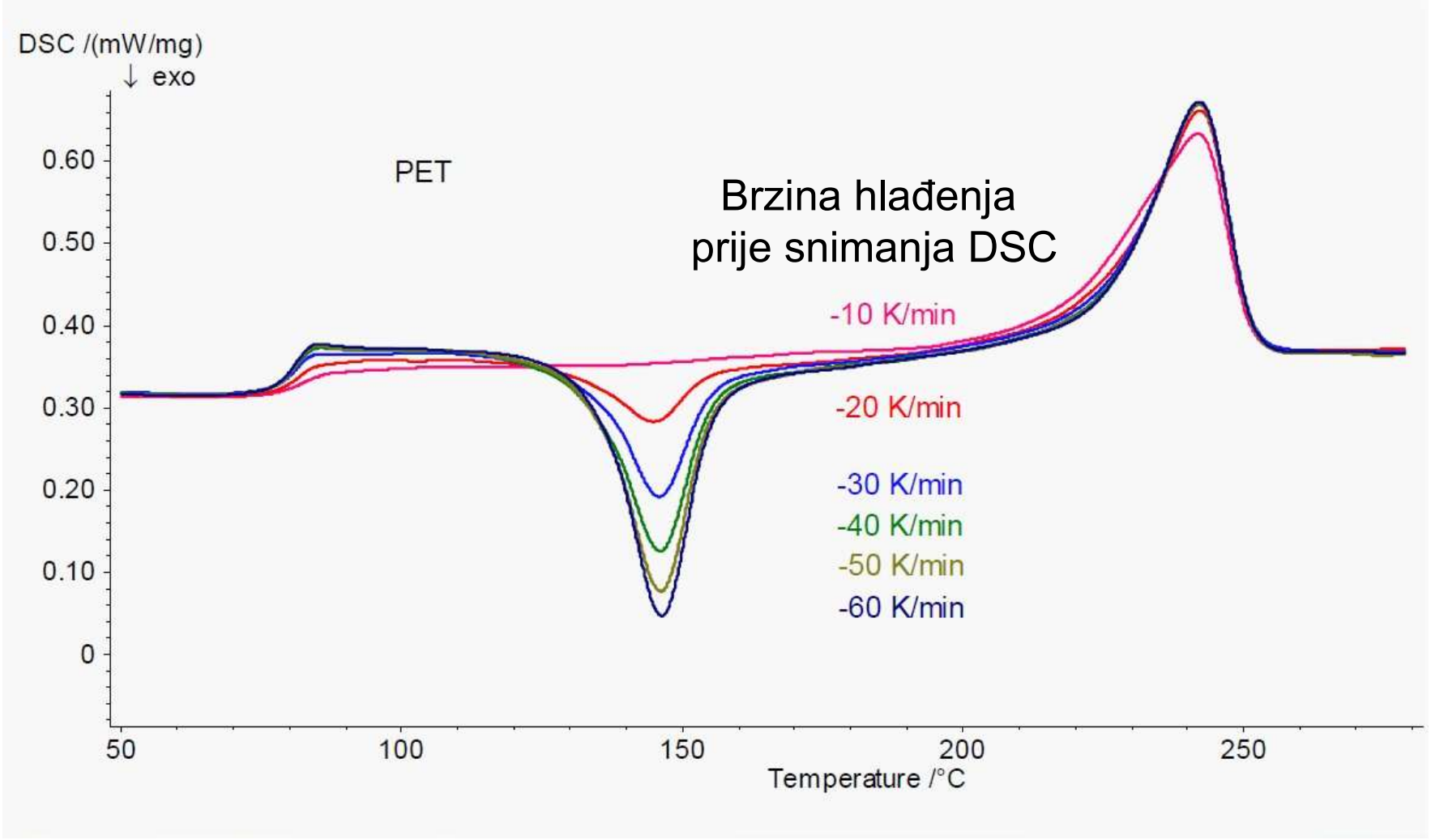
- Jedinica za hlađenje / refrigerating unit
- Kapljeviti dušik / liquid nitrogen
- Termoelektrični Peltierov element / Peltier

Cooling

Brzina hlađenja ovisi o ciljnoj temperaturi (tekući dušik najbrži i najhladniji)

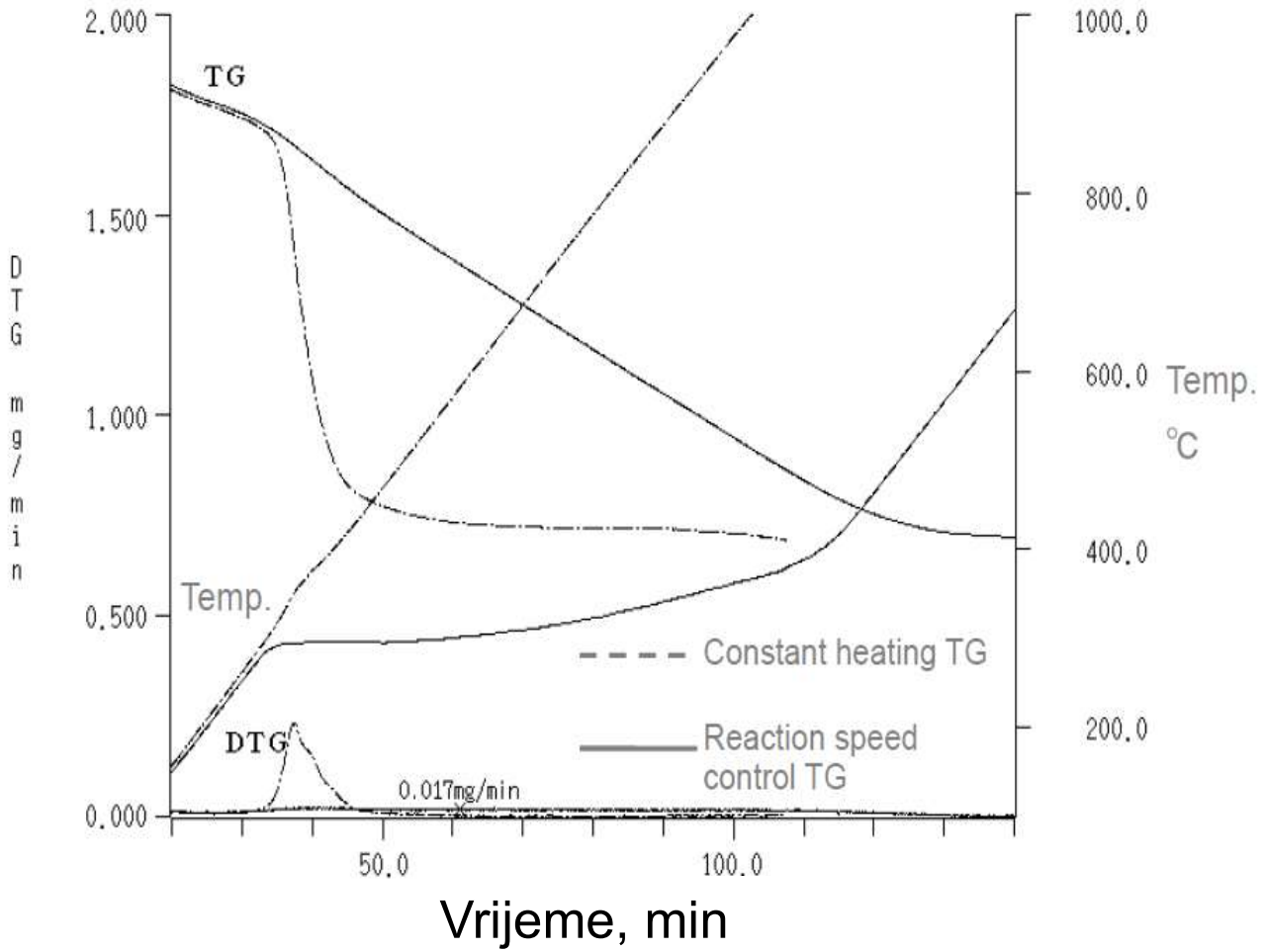
Brzina, K/min	donja granica		
	jednostupanj. hladnjak	dvostupanjski hladnjak	tekući dušik
100		300 °C	200 °C
50	175 °C	120 °C	0 °C
20	40 °C	-20 °C	-100 °C
10	0 °C	-50 °C	-150 °C
5	-15 °C	-75 °C	-165 °C
2	-40 °C	-90 °C	-180 °C

Cooling


DSC /(mW/mg)
↓ exo
0.60
0.50
0.40
0.30
0.20
0.10
0
PET
Brzina hlađenja
prije snimanja DSC
-10 K/min
-20 K/min
-30 K/min
-40 K/min
-50 K/min
-60 K/min
50
100
150
200
250
Temperature /°C

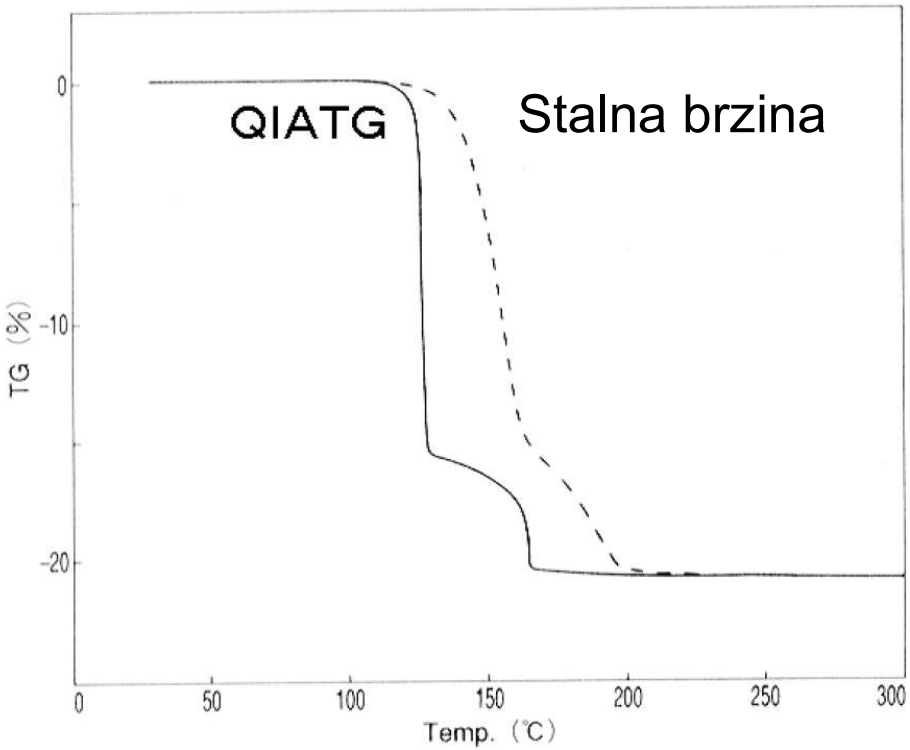
Non-linear rates

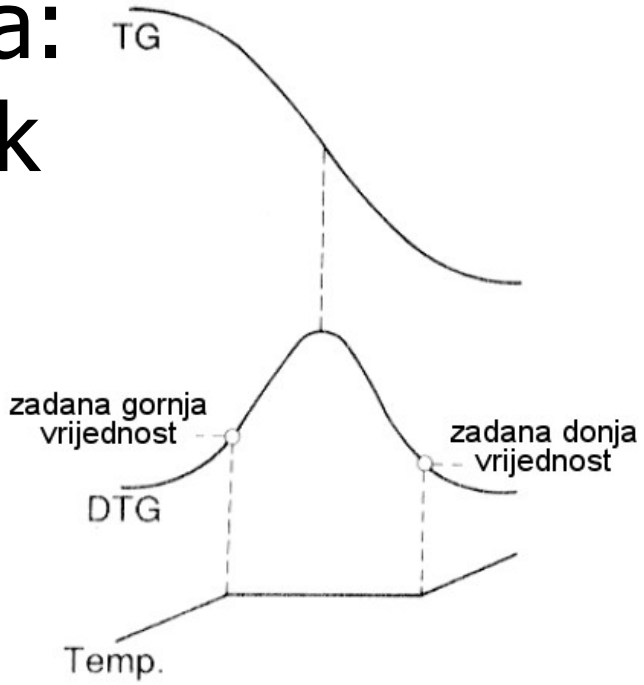
- Izotermno/isothermal
- Stepenasto/ Steps
- Modulirano/ Modulated
- Uzorkom-vođeno/Sampl controlled



Sample-controlled methods

QIA – kvazi-izotermna analiza: zaustavlja se zagrijavanje dok traje promjena svojstva

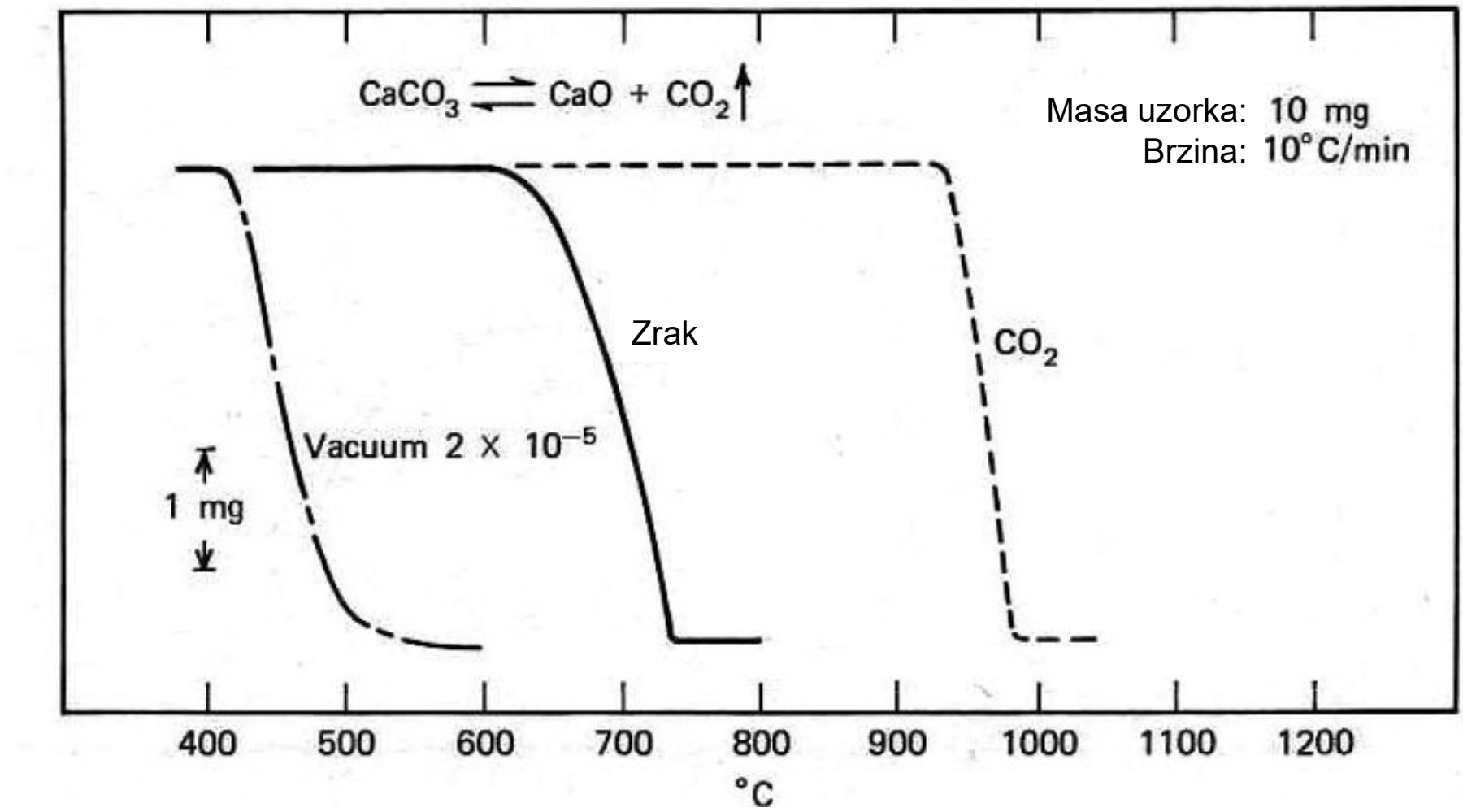




Bolje razdvajanje efekata

Atmosphere

- Reaktivna ili inertna
  - Oksidacijska
  - Redukcijska: H_2 u Ar
- Utjecaj vlage! / humidity!
- Visoki tlak, vakuum / high pressure, vacuum



Utjecaj atmosfere na termolizu $CaCO_3$

Influence of atmosphere on thermolysis

Atmosfera: protok

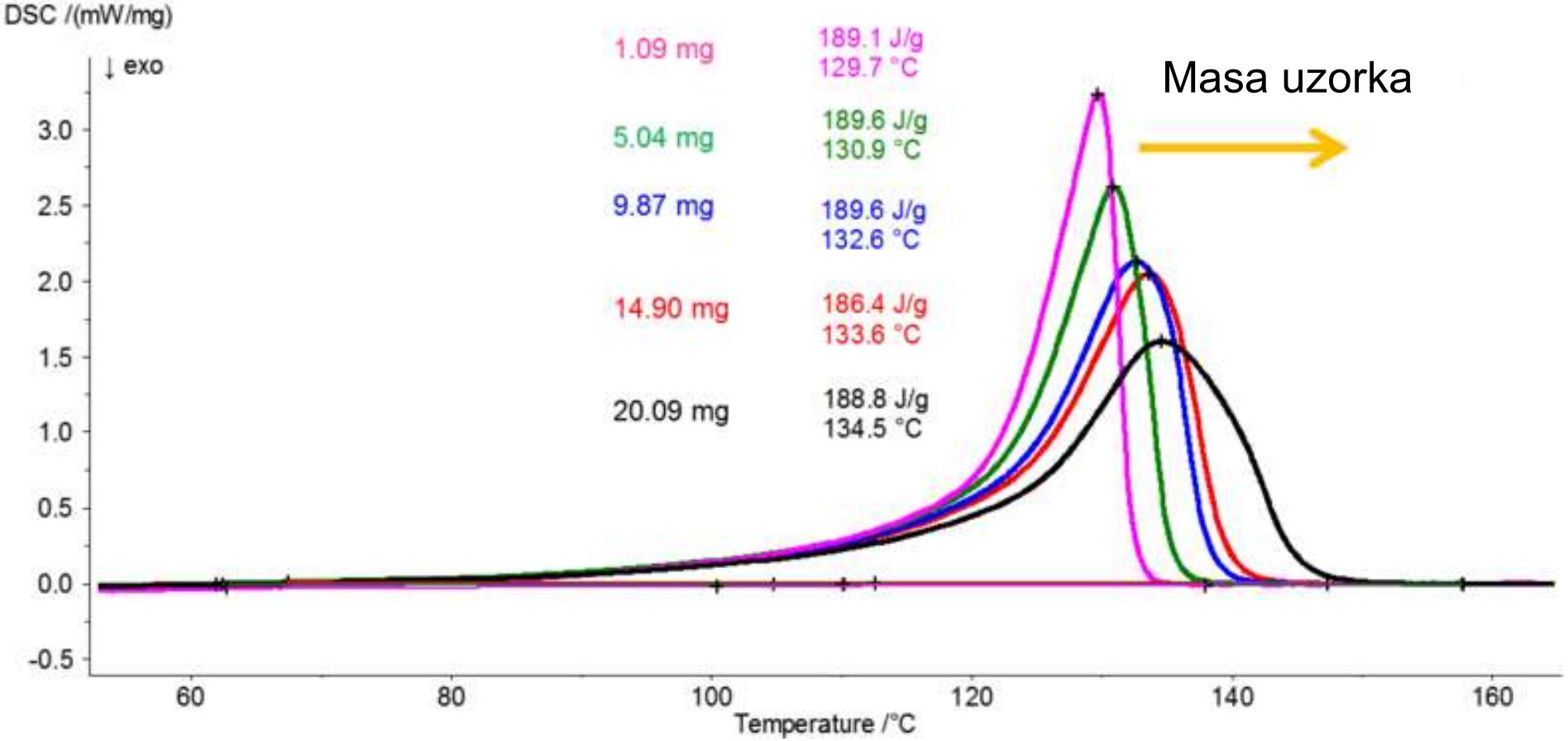
Protok plina (*purge*): održavanje stalnih reakcijskih uvjeta; 20 – 100 mL/min, bez fluktuacija!

Zaštitni plin *(protective):* odnosi korozivne tvari i zagađivala

Vlastita atmosfera: najbolje zatvaranjem lončića s uzorkom

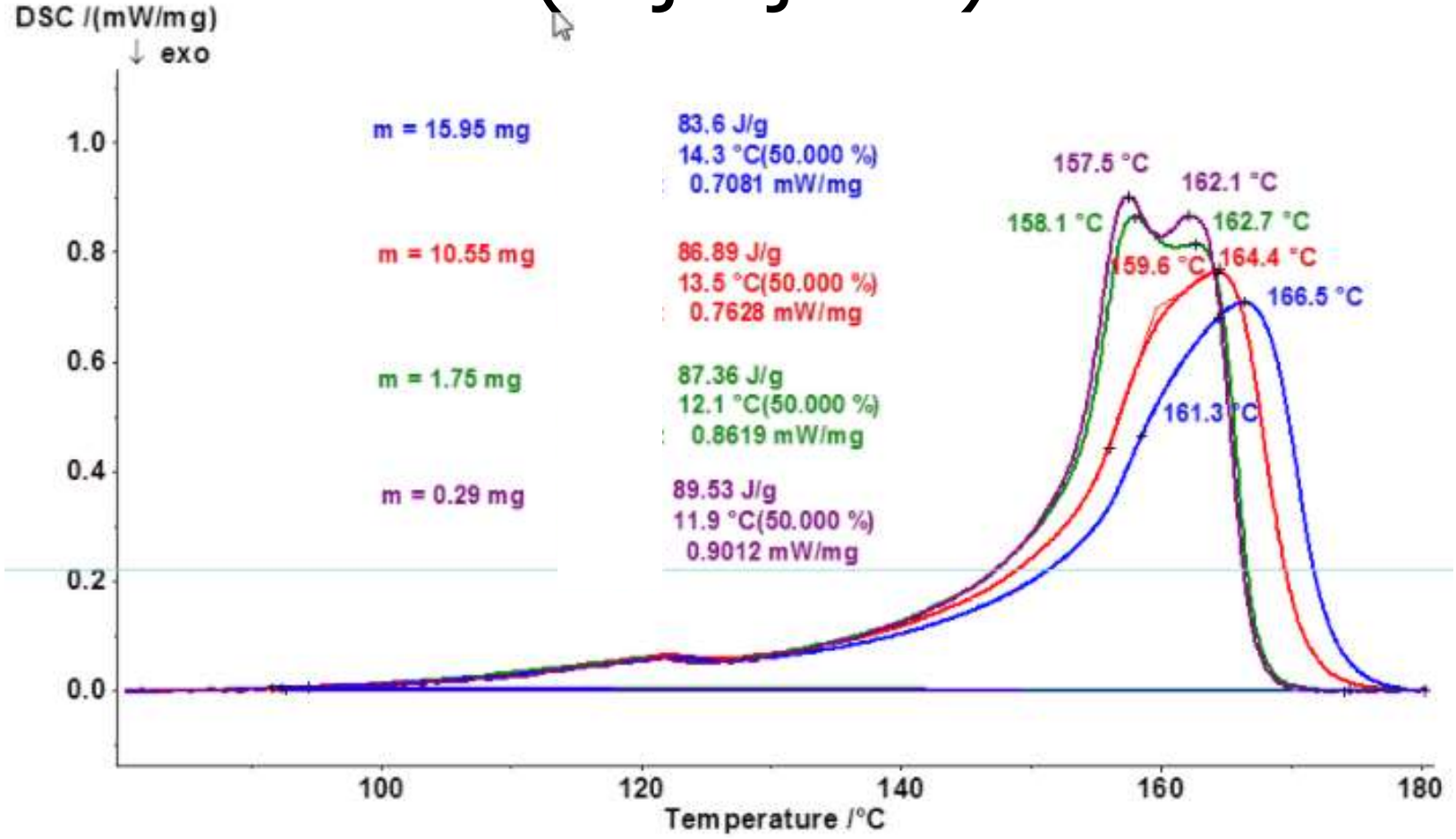
Mass

- Small mass: diffusion is negligible
- Increase has similar effect as rate



Mass

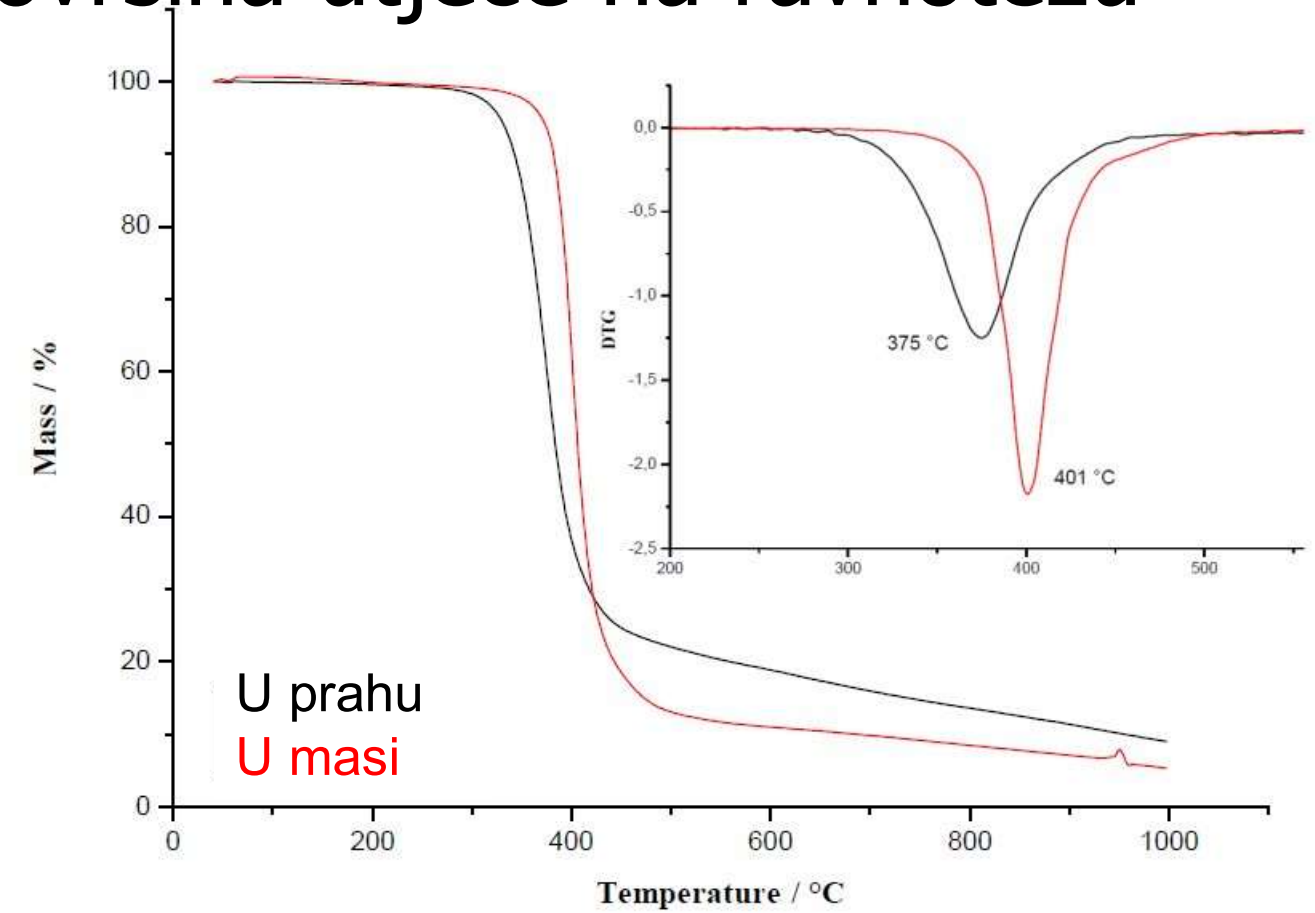
- Veća masa – gubitak razlučivanja / resolution loss (taljenje PP)



...and distribution

BULK vs. POWDER – specific surface

- Specifična površina utječe na ravnotežu S-G
- Nasipna gustoća!

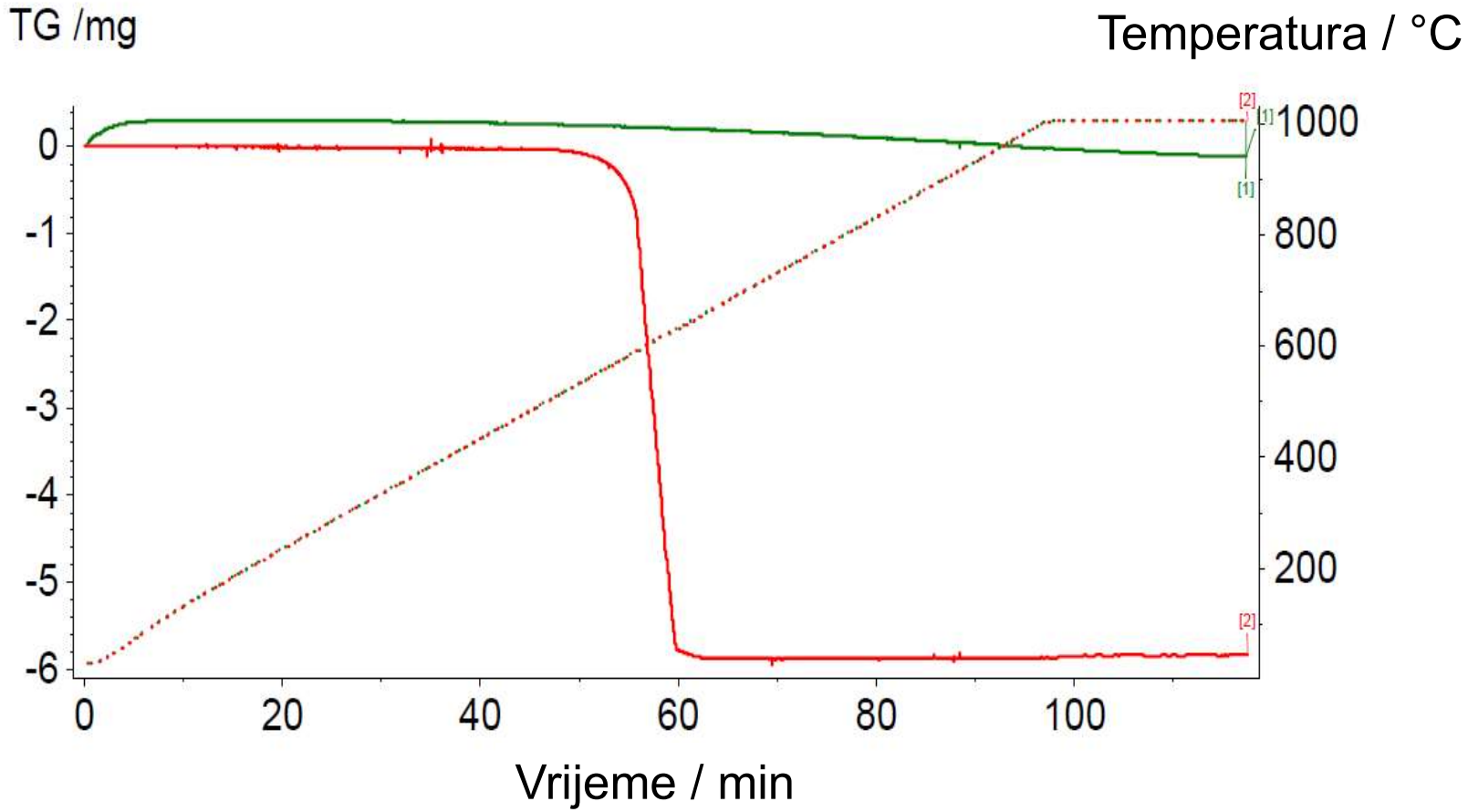


Instrument callibration

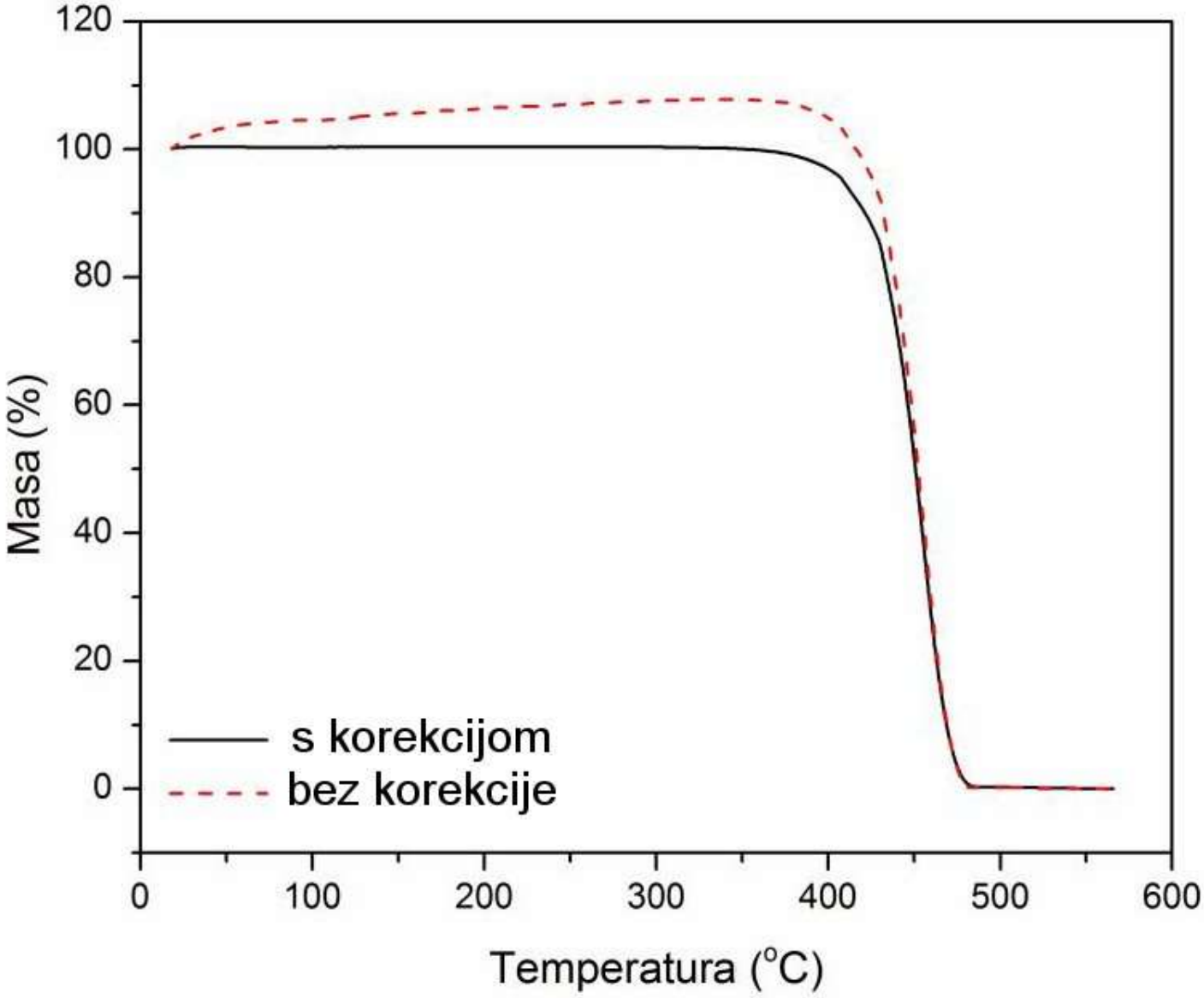
- Utjecaj konstrukcije instrumenta
- Utjecaj lončića, atmosfere itd.
- Zaostajanje temperature uzorka za onom u peći (*thermal lag*)
- Za TGA – feromagnetični materijali (T_C) u magnetskom polju
- Za DSC – niz čistih tvari poznatih tališta i entalpija (istovremeno T i ΔH)

Correction curves

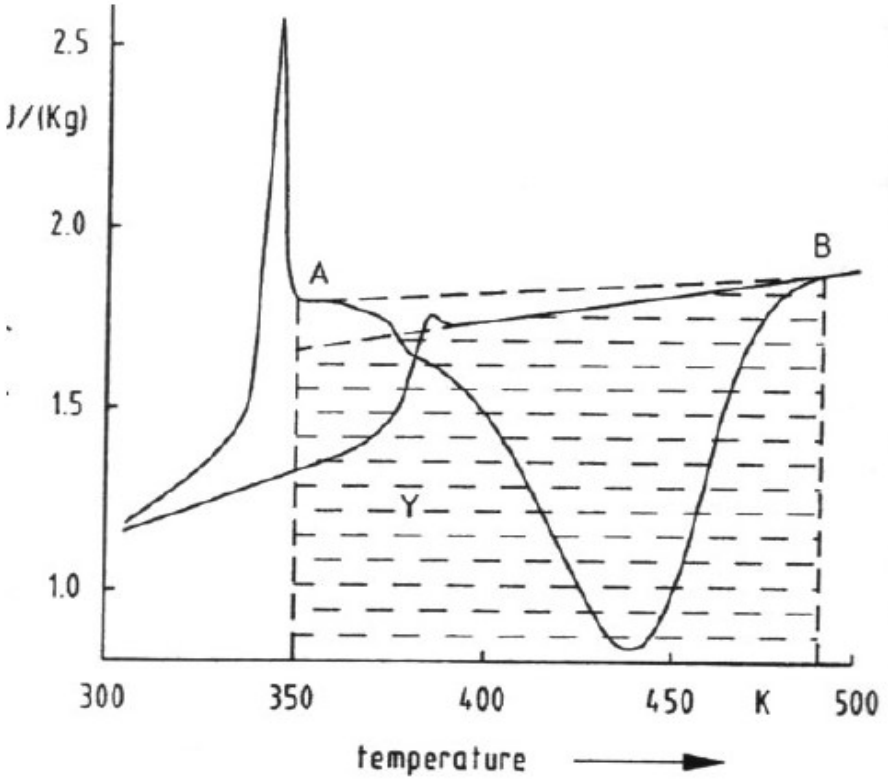
- Mostly TGA (buoyancy correction)

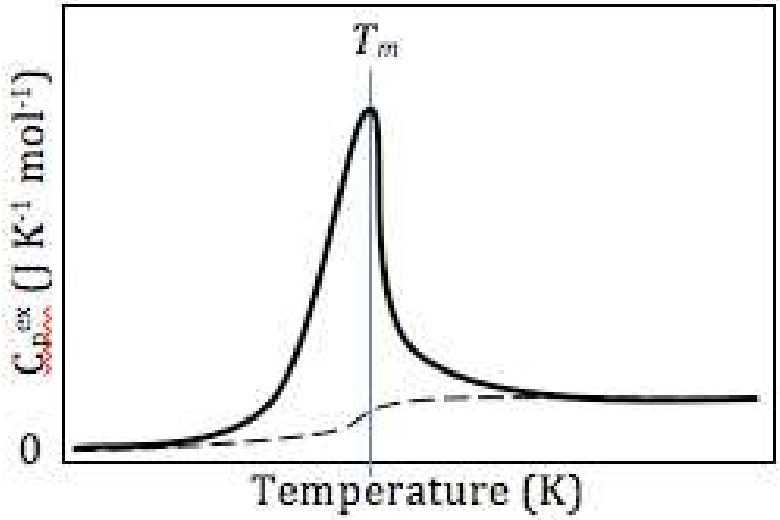


Correction curves



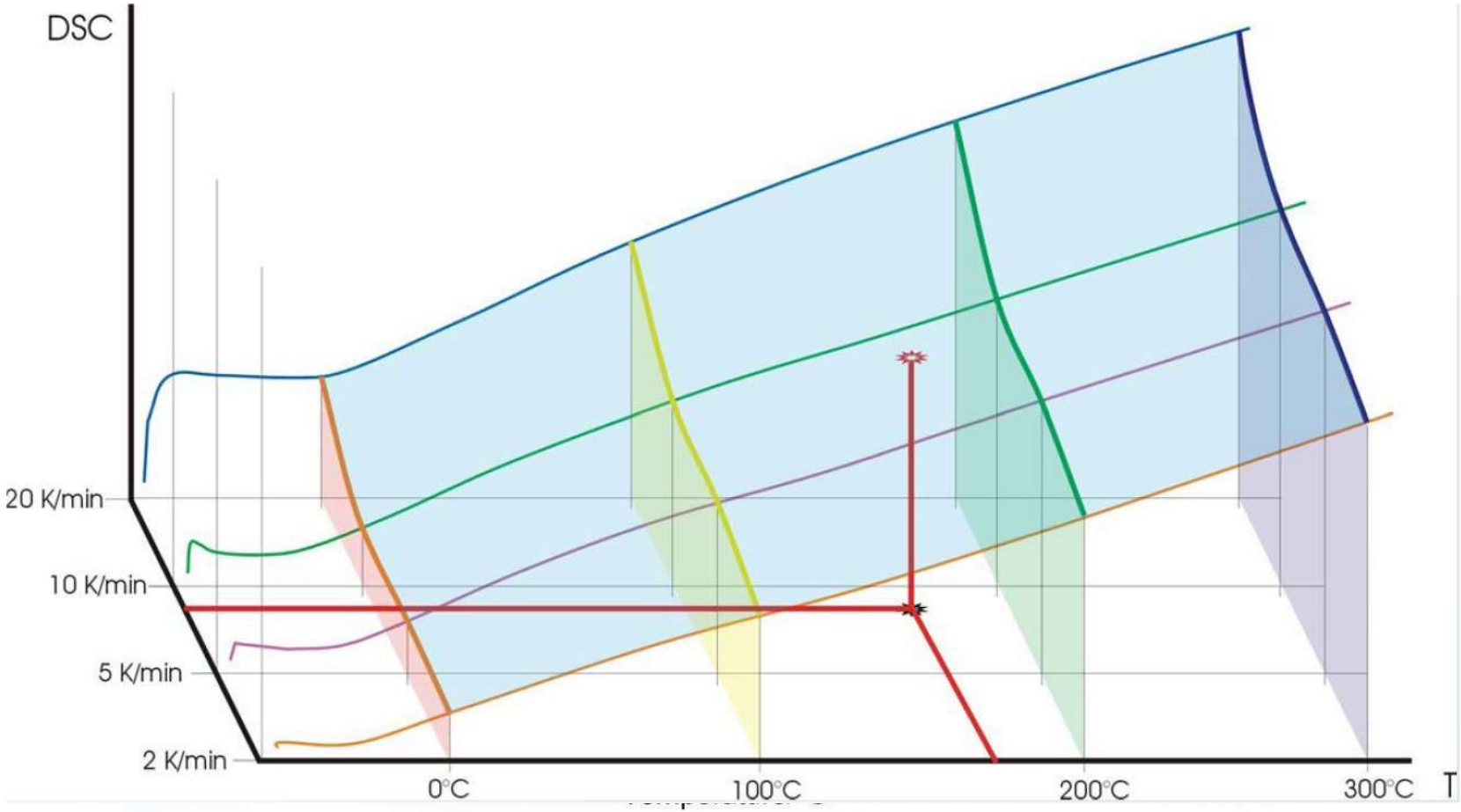
Baseline





Ponekad vrlo složeno provući odgovarajuću baznu liniju… / Can be difficult

Baseline



Softversko „peglanje” stvarne bazne linije (Netzschov BeFlat) / Software corrections

~ intermission ~

Examples of applications and analyses

primjeri

Applications

- Znanost o materijalima / Materials sci
- Farmakologija / Pharmacology
- Kontrola kvalitete / Quality control
- Biologija / Biology

Lake za korištenje, **ALI** treba biti pažljiv u interpretaciji! / difficult to interpret

Destruktivne metode / Destructive methods

Applications

- Kristalnost, talište, fazni prijelazi (**nije** termodinamički ravnotežno!)
- Reakcije, konverzija, kinetika
- Staklište, mekšanje
- Toplinsko širenje, bubrenje, sinteriranje
- Modul i viskoelastično ponašanje (polimera)
- Udio punila/pepela
- Toplinska/oksidacijska postojanost

Your application examples?

Personal experience or seen in literature

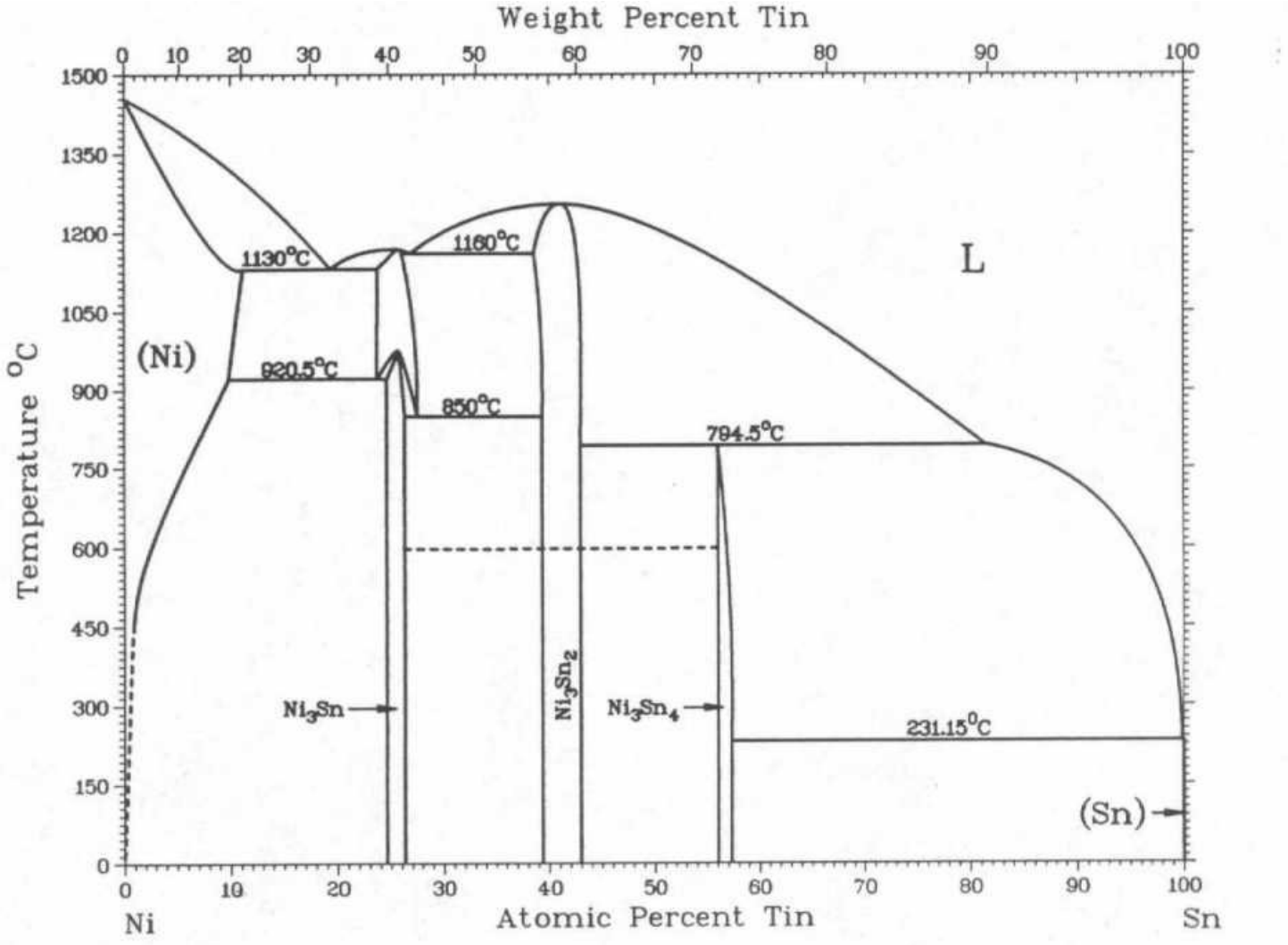
Odabir metode

	DSC	DTA	TGA	TMA	DMA	TOA	TCL	EGA
talište	+	°	-	°	°	+	-	-
kristalizacija i taljenje	+	°	-	°	-	+	-	-
fazni prijelazi čvrsto-čvrsto, polimorfizam	+	+	-	°	-	+	-	-
staklište	+	°	-	+	+	°	-	-
ispitivanje toplinske prošlosti	+	-	-	+	+	-	-	-
mekšište	-	-	-	+	°	-	-	-
toplinsko rastezanje/stezanje, bubrenje u otapalima	-	-	-	+	-	-	-	-
viskoelastično i prigušno ponašanje, Youngov modul	-	-	-	°	+	-	-	-
specifični toplinski kapacitet, entalpijske promjene	+	°	-	-	-	-	-	-

	DSC	DTA	TGA	TMA	DMA	TOA	TCL	EGA
sastav	+	-	+	-	-	-	-	+
sadržaj punila	o	-	+	-	-	-	-	-
sublimacija, hlapljenje, desorpcija	+	o	+	-	-	+	-	+
toplinska postojanost/degradacija piroliza	o	o	+	o	-	o	-	+
oksidacijska postojanost	+	+	+	o	-	-	+	-
reakcija (npr. polimerizacija)	+	o	o	+	+	-	o	-
čistoća kristalnih nepolimernih tvari	+	-	+	-	-	o	-	-
kinetika i modeliranje	+	o	+	-	-	-	-	o
osiguranje kvalitete, odabir proizvoda	+	o	+	o	o	+	o	+

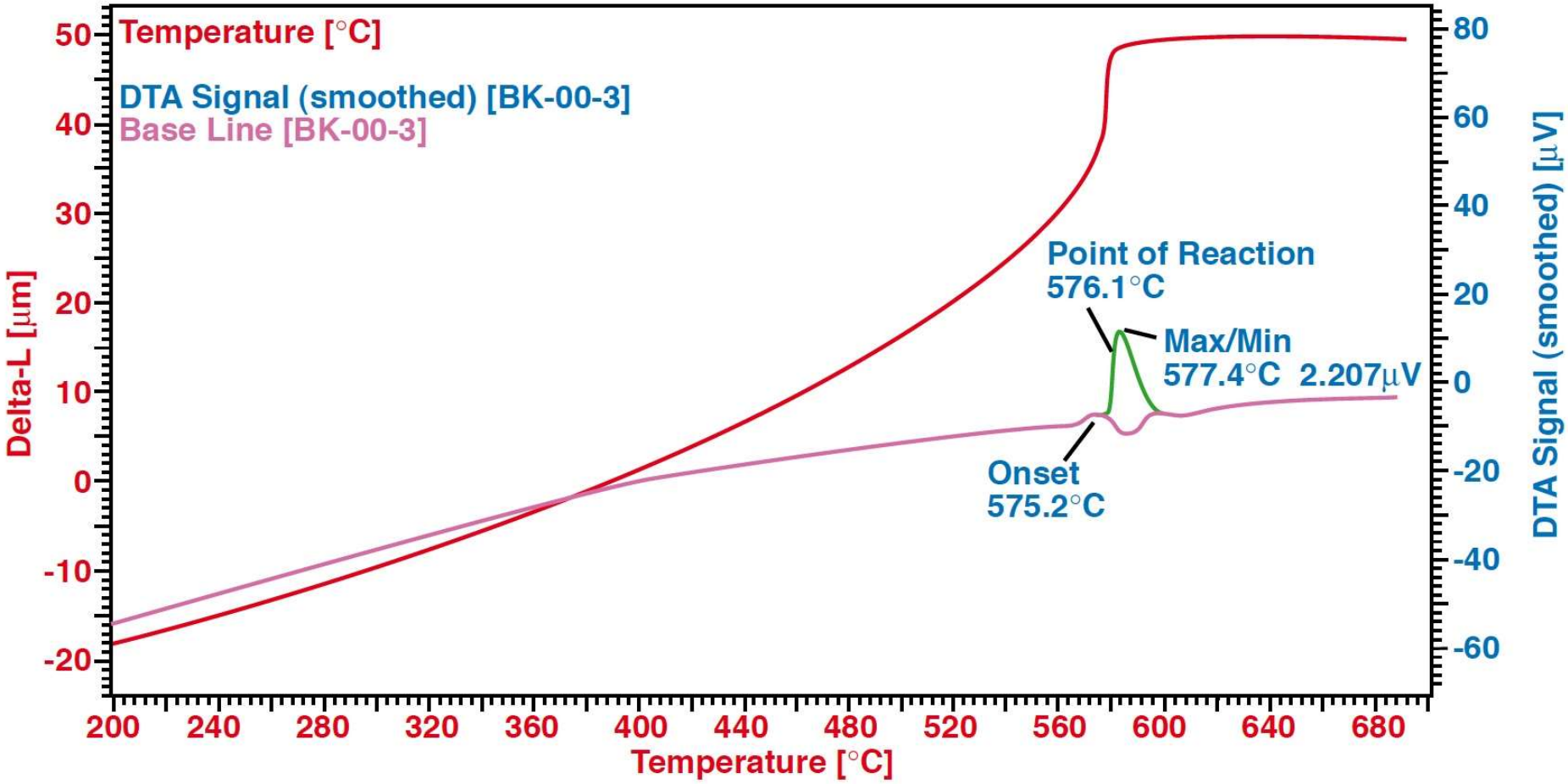
Phase diagrams

- Većinom u metalurgiji (slitine), ali i za keramiku



Ceramic sintering

- Kombinacija dilatometrije i DTA



Pharmaceutics

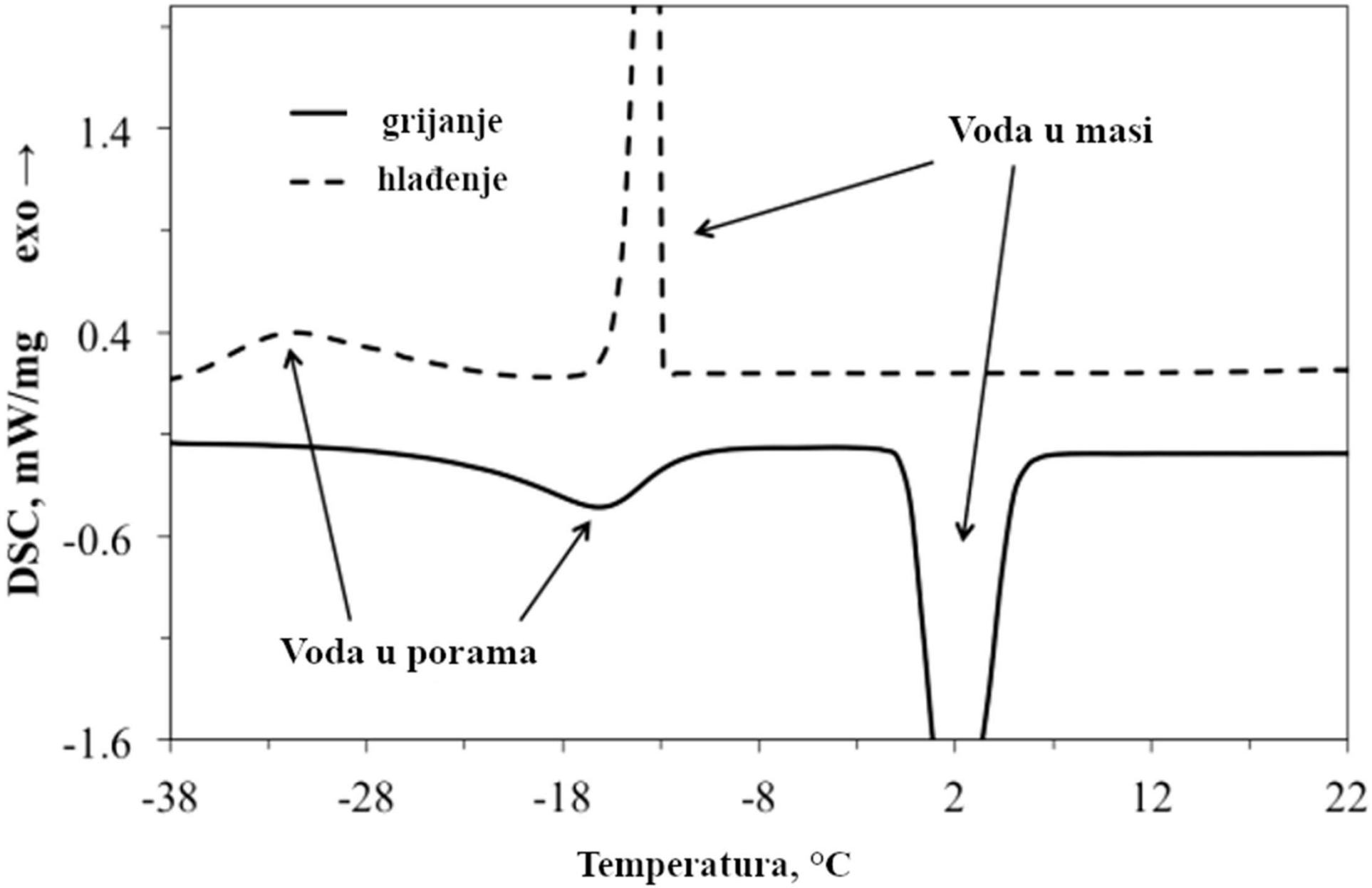
- Većinom kalorimterijska određivanja: mikrokalorimetrija, izotermna titracijska kalorimetrija
- Kemija složenih molekula i njihova međudjelovanja

Classical thermodynamics

- Klasična kalorimetrija – entalpija sagorijevanja, entalpija otapanja i solvatacije, entalpija miješanja
- Proračuni entalpijskih i entropijskih promjena

DSC for porosity determination

- Thermoporosimety or thermoporometry
- Teže taljenje kapljevine (obično voda) adsorbirane u porama/uz stijenke pora / adsorbed water has shift in melting
- Zahtijeva baždarenje (npr. BET), ima prednost tamo gdje porozna struktura kolabira sušenjem/vakuumiranjem / must be callibrated but can be used „wet”


grijanje
hlađenje
Voda u masi
Voda u porama
DSC, mW/mg exo →
1.4
0.4
-0.6
-1.6
-38
-28
-18
-8
2
12
22
Temperatura, °C

Kinetics from DSC and TGA

- Još uvijek dosta teorijskih rasprava i problema
- Slijepa primjena metoda na promjene (npr. staklište) koji ne odgovaraju teorijskim pretpostavkama
- Rezultati jako ovisni o načinu rada – daleko od “istinitih” podataka

Kinetic analysis

- Brzina reakcije i energija aktivacije:

$$r_A = \frac{d\alpha}{dt} = k(T) f(\alpha)$$

$f(\alpha)$ – kinetički model; mehanicistički ili (češće) empirijski

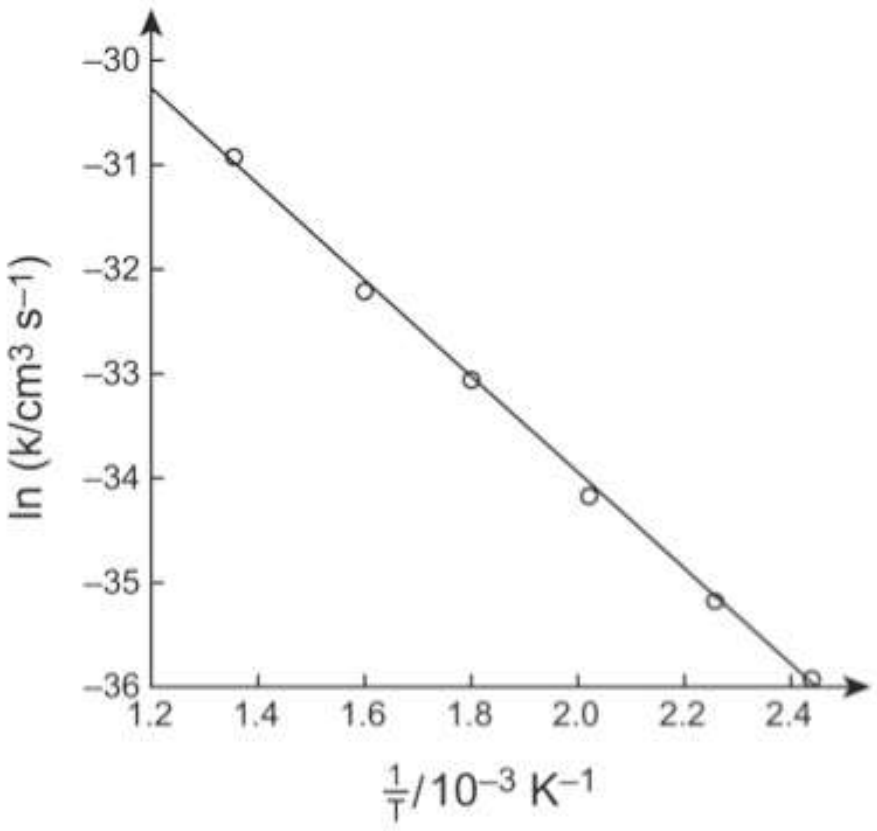
$$k = k_0 \exp\left(\frac{-E_a}{RT}\right)$$ Niz izotermnih mjerenja

Arrhenius

$$k = k_0 \exp\left(\frac{-E_a}{RT}\right)$$

Odsječak: k_0

Nagib: E_a

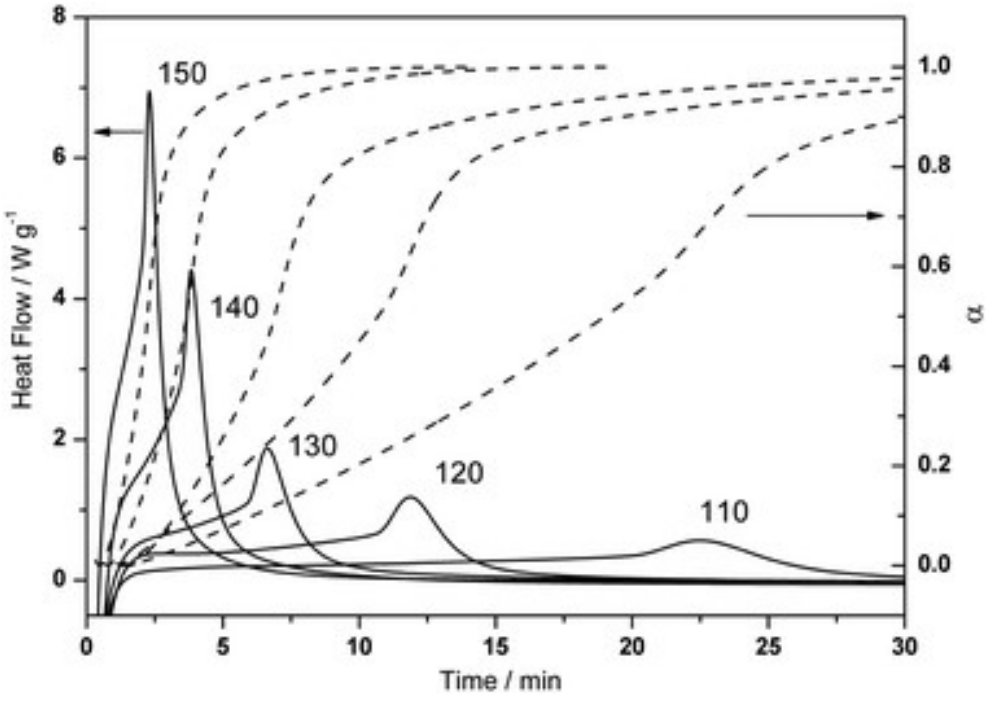


Kinetic analysis – DSC

- Povezivanje konverzije, α, s oslobođenom toplinom:

$$\frac{d\alpha}{dt} = \frac{1}{\Delta H}\frac{dH}{dt}$$

$$\alpha(t) = \frac{1}{\Delta H}\int_0^t \frac{dH}{dt}$$



Pretpostavka **jedne/iste** reakcije! / Assumption of one/same reaction!

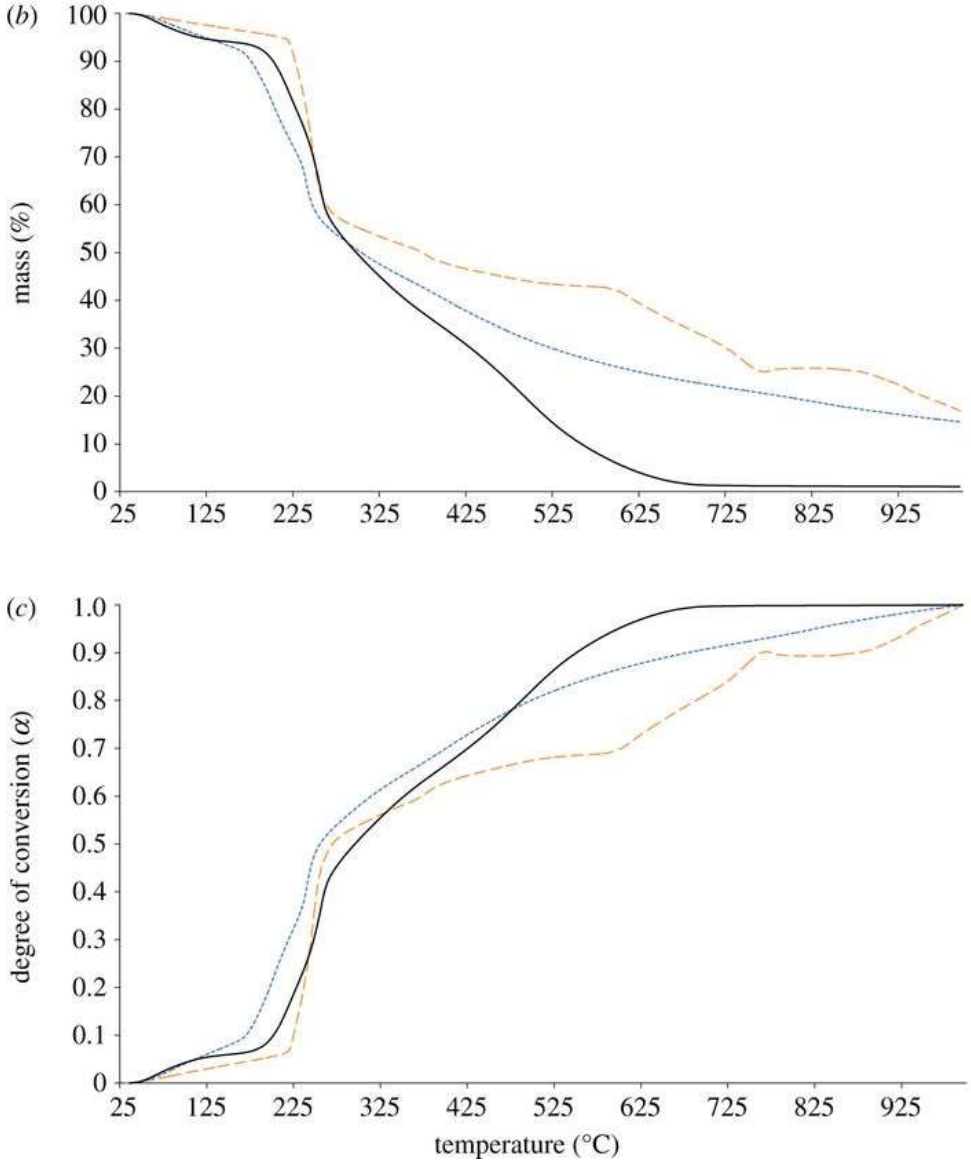
Kinetic analysis – TGA

- Analogno za TGA:

$$\alpha(T) = \frac{m_0 - m(T)}{m_0 - m_\infty}$$

Brzina reakcije vremenskom derivacijom konverzije

Same assumptions!



Isoconversion methods

- Iz niza neizotermnih mjerenja različitih brzina zagrijavanja (pomak maksimuma!)
- Određivanje temperature pri kojoj se postigne ista konverzija za različite brzine
- Ovisnost prividne energije aktivacije o konverziji
- Više metoda (KAS, FWO, Friedman)

Isoconversion methods

- Diferencijalna – Friedman

$$\ln\left(d\alpha/dt\right) = -\frac{E_a}{R}\frac{1}{T} + \ln\left[k_0 f(\alpha)\right]$$

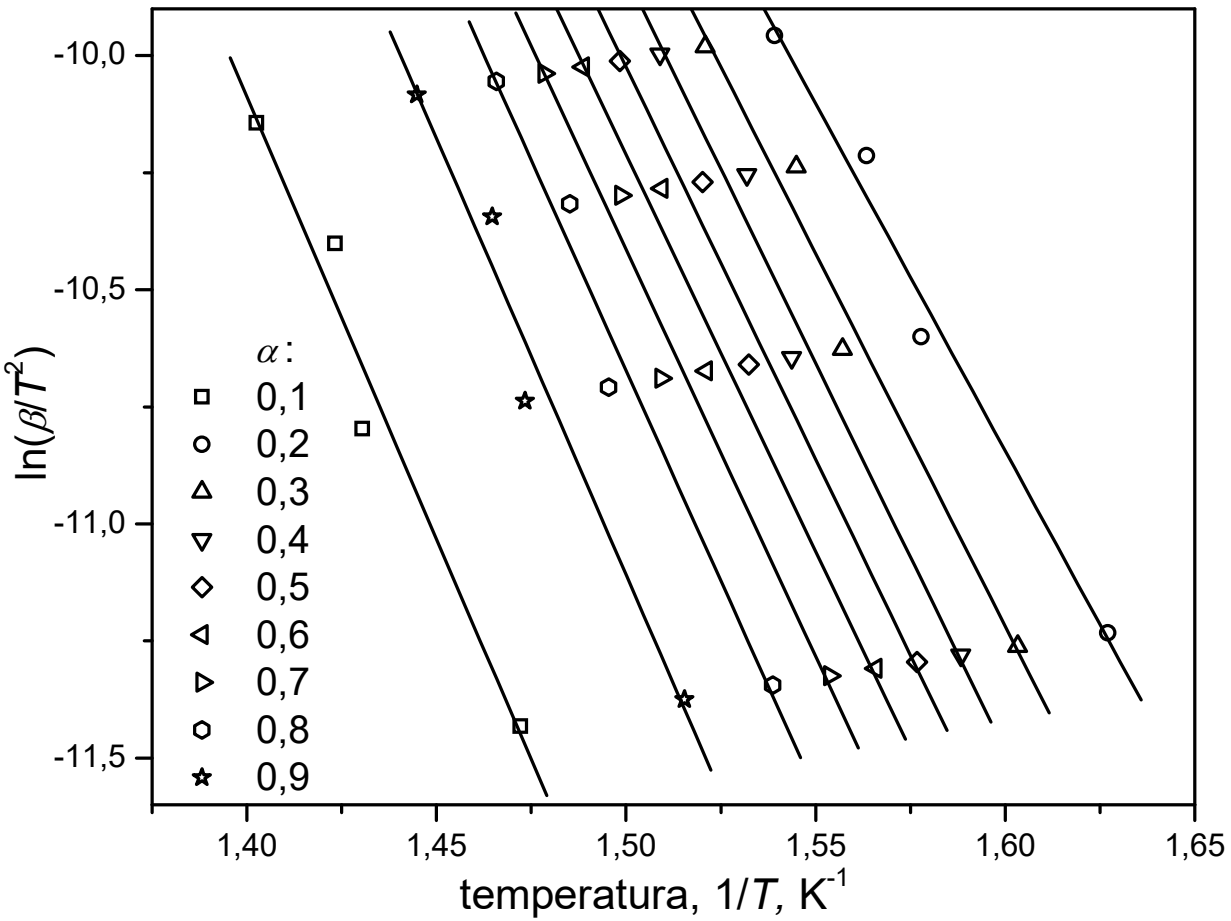
- Integralne:
  - Flynn-Wall-Ozawa

$$\ln\beta = \ln\left[\frac{0{,}0048 k_0 E_a}{R G(\alpha)}\right] - 1{,}0516\frac{E_a}{R}\frac{1}{T}$$

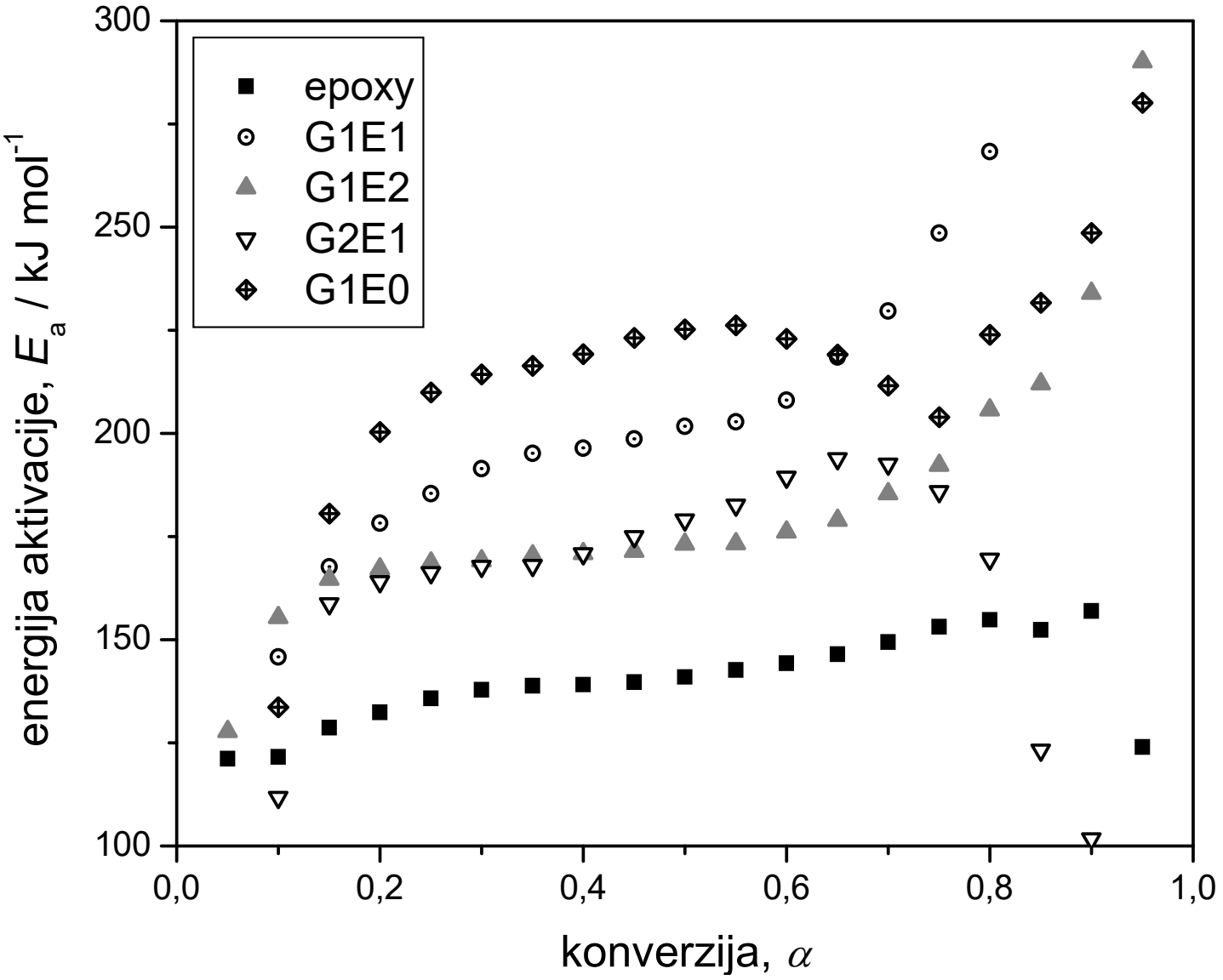
  - Kissinger-Akahira-Sunose

$$\ln\left(\frac{\beta}{T^2}\right) = \left[\ln\left(k_0 R/E_a\right) - \ln G(\alpha)\right] - \frac{E_a}{R}\frac{1}{T}$$

Isoconversion methods



Isoconversion methods



Additional information

Mrežne stranice proizvođača:

NETZSCH

METTLER TOLEDO

webinari, brošure, UserCom (MT)