The model of austenite decomposition kinetics based on CCT curves and its application in 22MnB5 steel

Xiangjun Chen[a,b], Namin Xiao[a], Dianzhong Li[a], Guangyao Li[b]

[a]Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences

[b]State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University

Outline

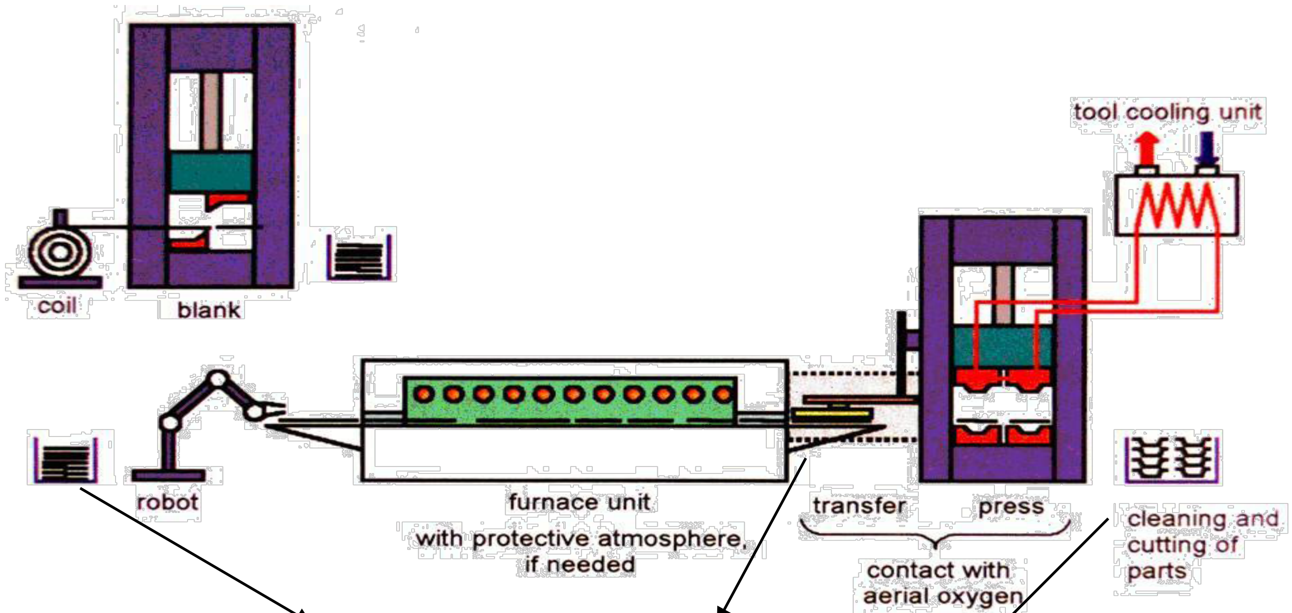
- Introduction to hot stamping
- Thermal-mechanical-metallurgical coupled FEM model
- Theoretical analysis of diffusional austenite decomposition

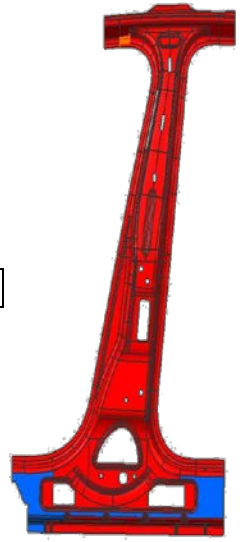
The mathematical relationship between isothermal and non-isothermal transformation

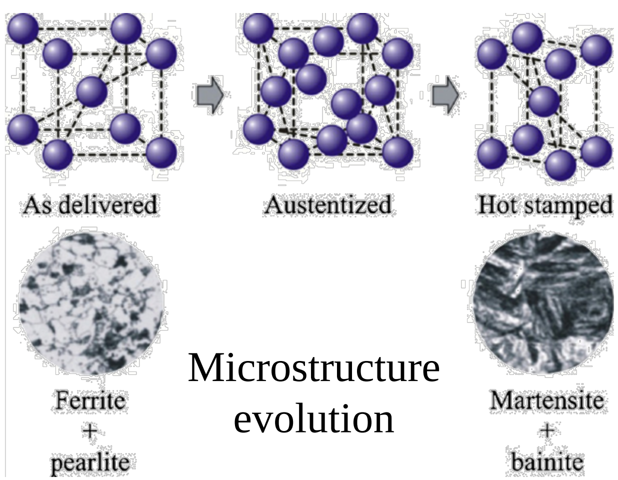
Generalized additive rule

- Summary

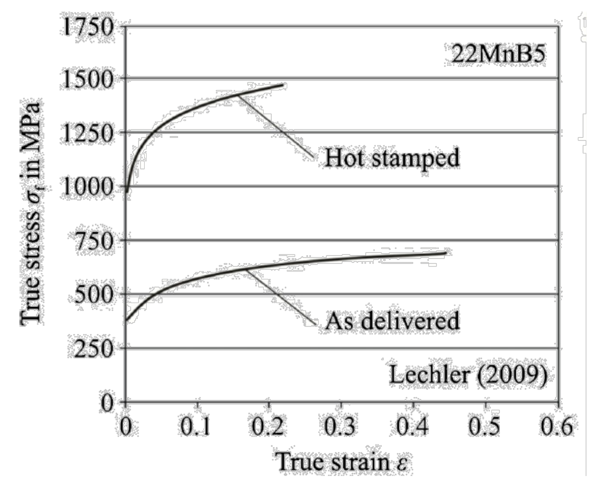
Introduction to Hot Stamping



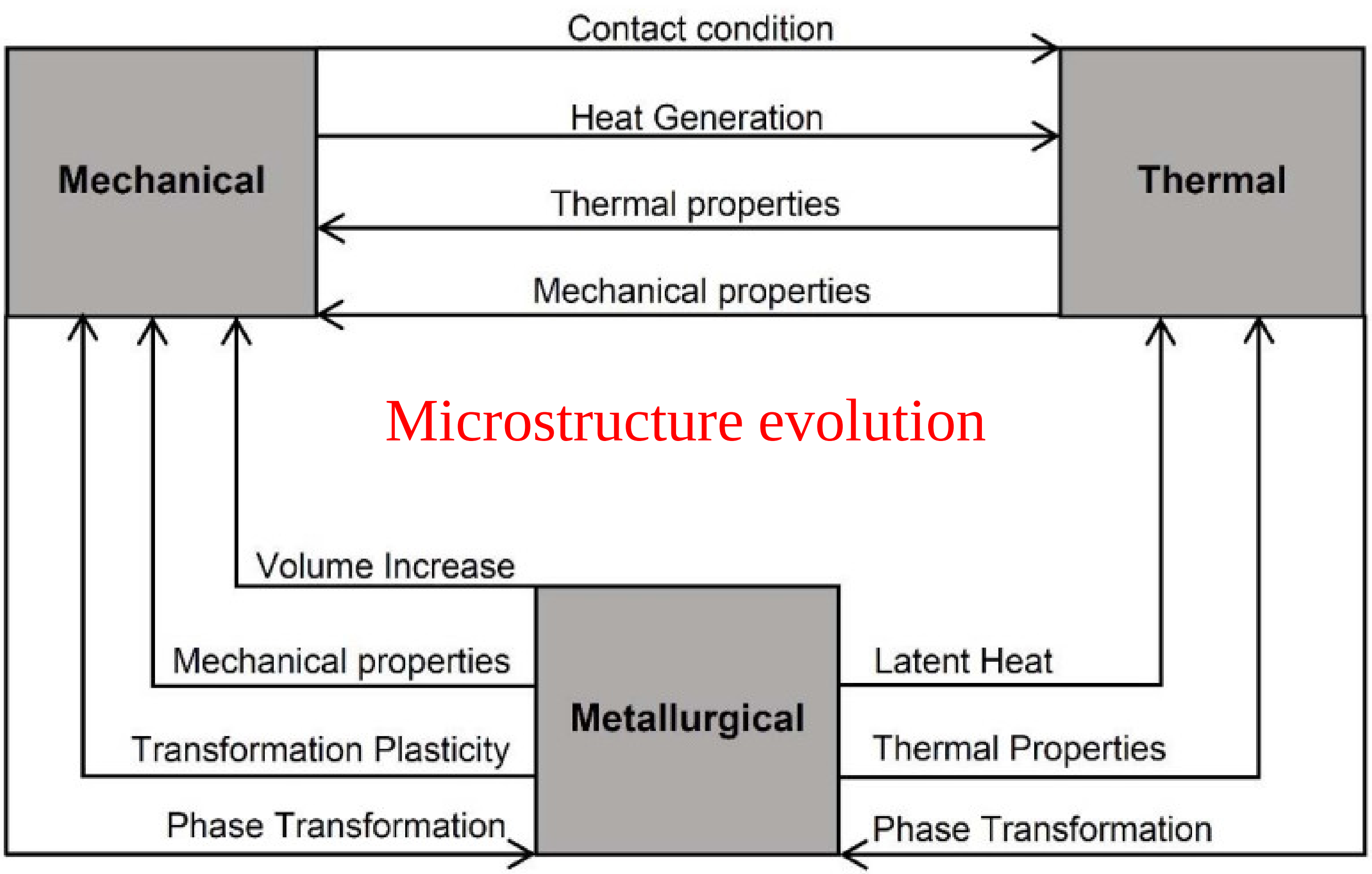




Mechanical properties



Thermal-mechanical-metallurgical coupled FEM model



Thermal-mechanical-metallurgical coupled model during hot stamping

Thermal-mechanical-metallurgical coupled FEM model

Austenite decomposition kinetics

1, Diffusional phase transformation

JMAK type model (1) $$F = 1 - \exp(-b \times t^n)$$

K-V type model (2) $$\frac{\partial F_i}{\partial t} = \frac{f(T)\, f(F_i)}{f(G)\, f(C)}$$

- *T---Temperature*
- *F---Current fraction formed*
- *G---Austenite grain size*
- *C---Alloy composition*

Scheil additivity hypothesis (**Calculating non-isothermal transformation from isothermal kinetics**)

$$\sum_i^m \frac{\Delta t_i}{\tau_i} = 1$$

$$t_j = \Delta t_j + \left[-\frac{\ln(1 - F^{j-1})}{b}\right]^{\frac{1}{n}}$$

2, Diffusionaless phase transformation

Koistinen-Marburger equation

(1) M. Avrami., et al. The Journal of Chemical Physics.1939 (7),1103.
(2) J.S. Kirkaldy, et al. International Conference on Phase Transformations in Ferrous Alloys.1983, 125-148.

Thermal-mechanical-metallurgical coupled FEM model

Decomposition of austenite

isothermal ferrite, pearlite and banitic transformation

$$X = 1 - \exp[-b\left(\frac{\mathrm{D}\gamma_{\mathrm{TTT}}}{\mathrm{D}\gamma}\right)^{m}(t-\tau_o)^n]$$

Martensitic transformation

$$F_m = F_a \times \{1 - \exp[-0.011 \times (M_s - T)]\}$$

Heat transfer model

$$\rho c_p \frac{\partial T}{\partial t} = \lambda \nabla T + Q \qquad Q^{th} = \Delta H_i \frac{\Delta F_i}{\Delta t}$$

Mechanical response

$$\boxed{d\varepsilon_{ij} = d\varepsilon_{ij}^{e} + d\varepsilon_{ij}^{p} + d\varepsilon_{ij}^{th} + d\varepsilon_{ij}^{tr} + d\varepsilon_{ij}^{tp}}$$

$$\begin{cases} d\varepsilon_{ij}^{th} \rightarrow \mathit{Thermal\ strain\ increment} \\ d\varepsilon_{ij}^{tr} \rightarrow \mathit{Transformation\ strain\ increment} \\ d\varepsilon_{ij}^{th} \rightarrow \mathit{Transformation\ induced\ plasticity} \end{cases}$$

$$d\varepsilon_{ij}^{th} = \tilde{\alpha}\delta_{ij}dT + \frac{\partial\tilde{\alpha}}{\partial T}\delta_{ij}TdT + \sum_{I=0}^{N}\frac{\partial\tilde{\alpha}}{\partial\xi_I}\delta_{ij}Td\xi_I$$

Volume change due to the thermal process

$$d\varepsilon_{ij}^{tr} = -\sum_{I=0}^{N}\left(\frac{\partial\tilde{D}_{ijkl}^{-1}}{\partial\xi_I}\sigma_{kl} + \beta_I\delta_{ij} + \frac{\partial\tilde{\alpha}}{\partial\xi_I}\delta_{ij}T\right)d\xi_I$$

Volume change due to phase transformation

$$d\varepsilon_{ij}^{tp} = -\sum_{I=0}^{N}3K_I s_{ij}(1-\xi_I)d\xi_I$$

Local plastic flow below the yield stress, Greenwood-Johnson model

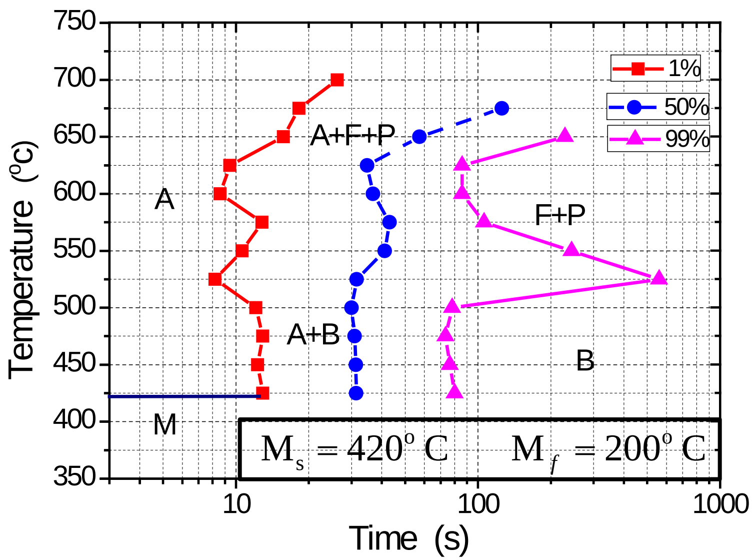
Chen, XJ., Xiao, NM., Li, DZ., Li, GY. Model Simul Mater Sci Eng 2014, **22**(6) 065005:.

Thermal-mechanical-metallurgical coupled FEM model

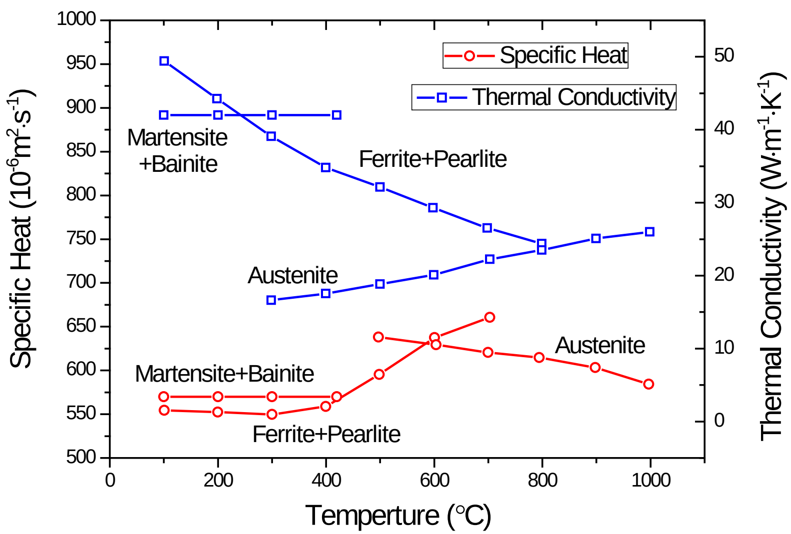
Calculation parameters

Chemical composition for 22MnB5 in weight percent

	C (%)	Si (%)	Mn (%)	P (%)	S (%)	Cr (%)	Ni(%)	B(ppm)
Measured	0.27	0.29	1.25	0.007	<0.005	0.22	0.013	39



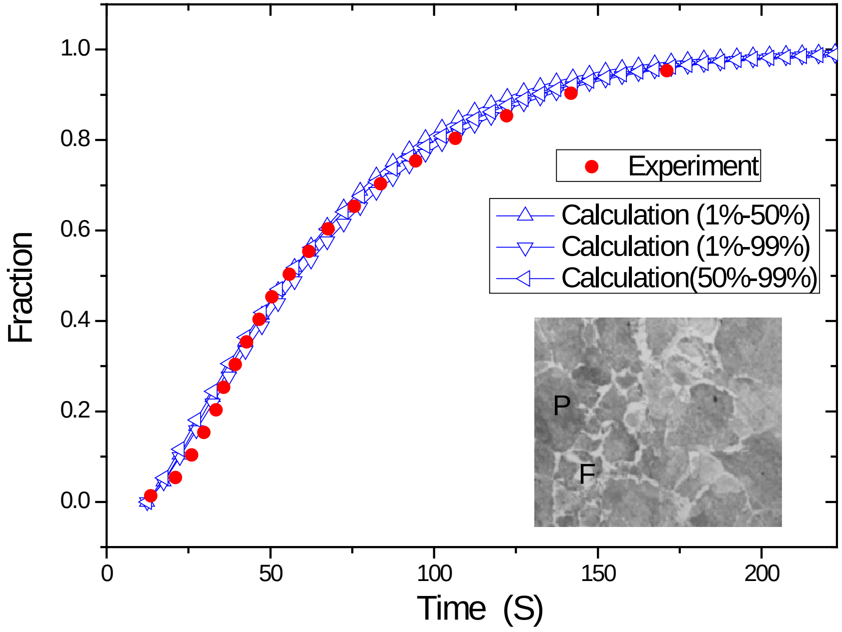
The TTT diagram for the 22MnB5



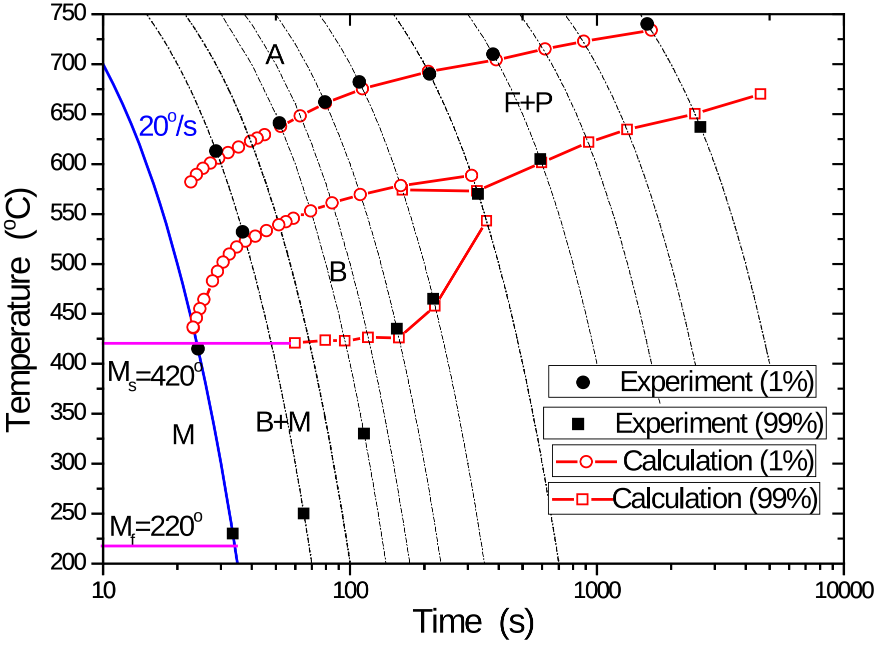
The Thermal conductivity and specific heat for the 22MnB5

Thermal conductivity, specific heat and heat transfer coefficient are experimentally measured as the function of temperature.

Thermal-mechanical-metallurgical coupled FEM model



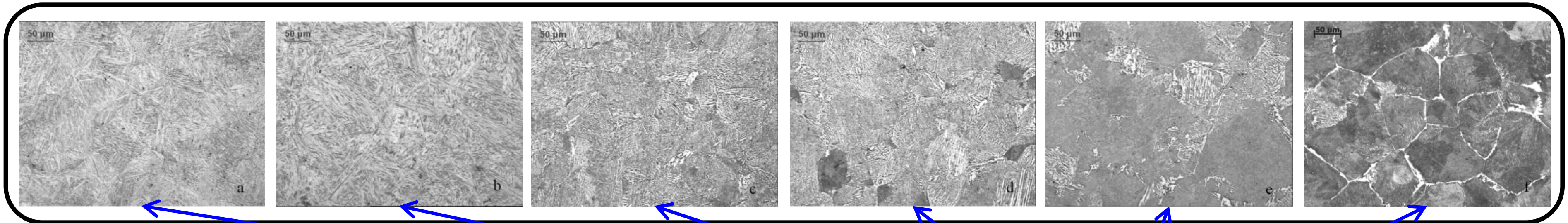
The phase transformation kinetics considering incubation time in JMAK equation and the corresponding microstructure metallograph (F: ferrite, P: pearlite)

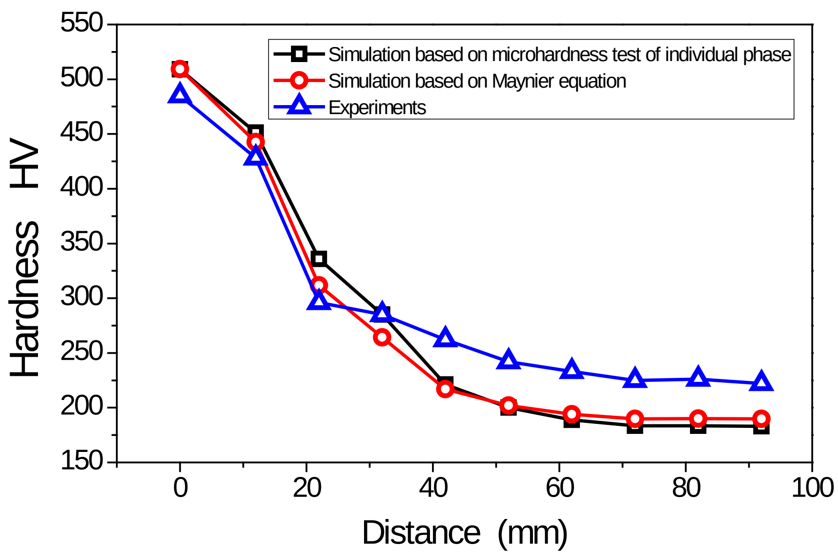


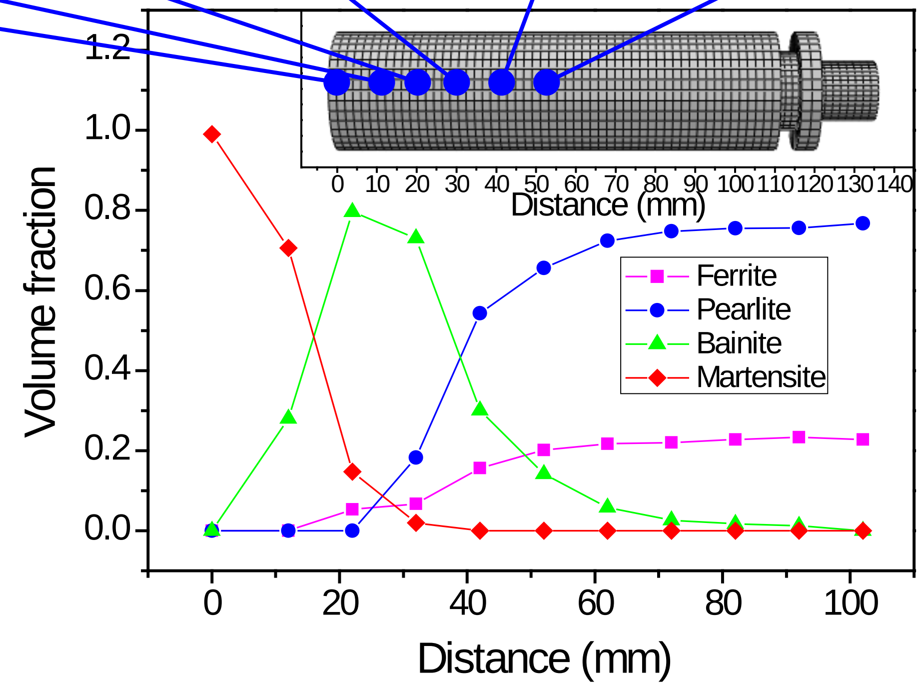
The CCT diagram prediction and comparison with dilatational experiments

Thermal-mechanical-metallurgical coupled FEM model

The Jominy end-quenching test and the microstructure prediction





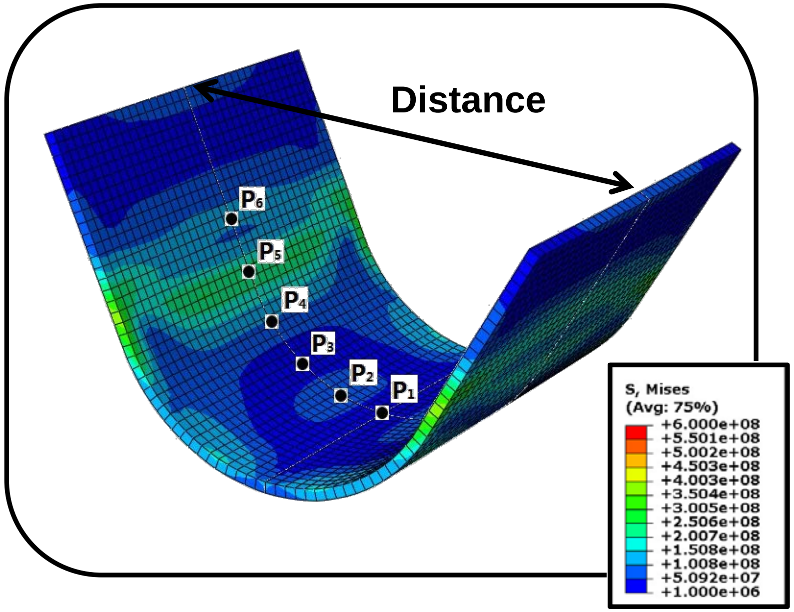


Measured and calculated hardness as function of distance from the quenched end

The simulated final microstructure components and the corresponding fraction along the Jominy bar

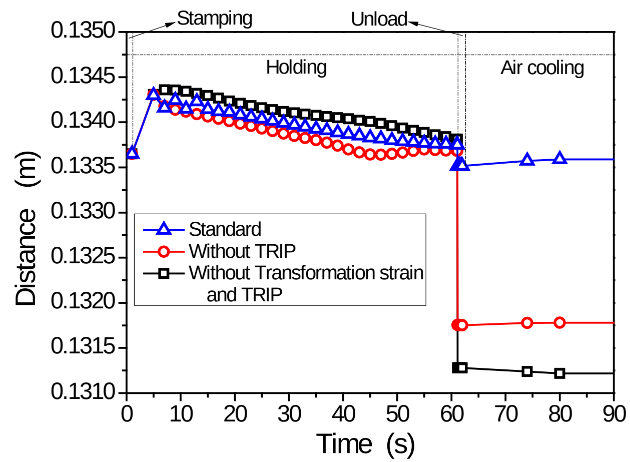
Thermal-mechanical-metallurgical coupled FEM model

Unloading spring-back and Residual stress

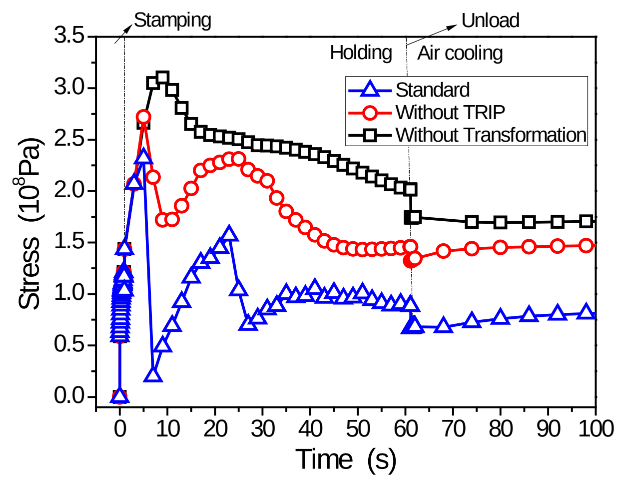


The expansion due to martensitic transformation is benefit for controlling the unloading spring-back.

The expansion due to martensitic transformation results in the smaller distribution of residual stress.



The effect of transformation strain and transformation plasticity on the opening distance



The effect of transformation strain and transformation plasticity on the residual stress

Chen, XJ., Xiao, NM., Li, DZ., Li, GY. NUMISHEET 2014.

Theoretical analysis of diffusional austenite decomposition

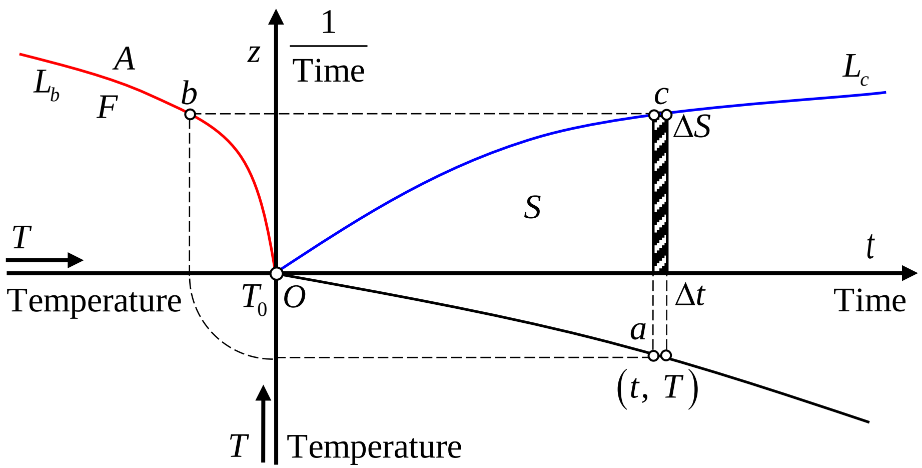
- The CCT curves are easily to be obtained in most industrial design
- The isothermal kinetics curves are hard to be obtained When considering the influence of the deformation as well as the heating process

Is it possible to calculate the transformation kinetics undergoing arbitrary thermal path from CCT curves?

- The mathematical relationship between isothermal and non-isothermal transformation
- Generalized additivity rule of transformation kinetics based on the CCT curves

Theoretical analysis of diffusional austenite decomposition

The mathematical relationship between isothermal and non-isothermal transformation – incubation time



L_a: The non-isothermal path curve

L_b: The isothermal transformation curve (f(x) = 0)

L_c: The incubation contribution curve

$$\sum_{i}^{m}\frac{\Delta t_i}{\tau_i}=1$$

$$\Delta S=\frac{1}{\tau_{\mathrm{TTT}}(T)}\Delta t$$

$$S=\int_0^t\frac{1}{\tau_{\mathrm{TTT}}(T)}dt \quad \leftarrow \quad T=T_0+v(t)\cdot t$$

Incubation contribution

$$S=\int_{T_0}^{T}\frac{1}{\tau_{\mathrm{TTT}}\left(T\right)\times[v'(t)\cdot t+v(t)]}dT$$

For CCT, V=constant

$$\int_{T_0}^{T_{CCT}}\frac{1}{\tau_{\mathrm{TTT}}\left(T\right)\cdot v}dT=1$$

$$\tau_{\mathrm{TTT}}\left(T\right)=\left.\frac{\partial T_{CCT}(v)}{\partial v}\right|_T$$

The calculation of TTT incubation time from non-isothermal curves

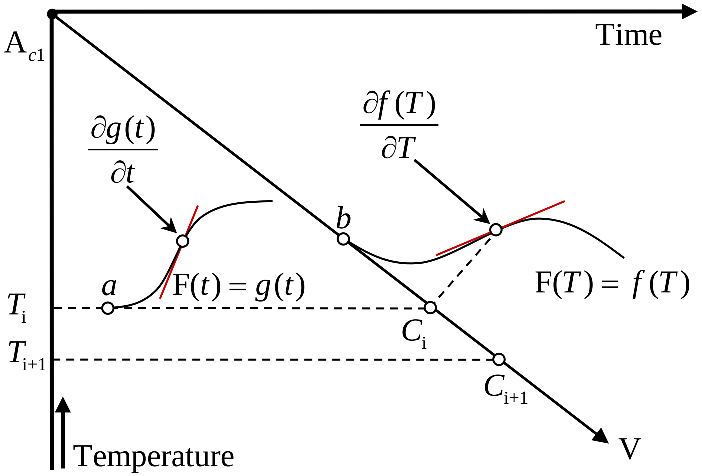
Theoretical analysis of diffusional austenite decomposition

The mathematical relationship between isothermal and non-isothermal transformation – growth kinetics

DO NOT consider incubation time in JMAK equation: only for constant cooling rate (Rios P R. *Acta Materialia* 2005)

$$F(t,T)=1-\exp[k(T)\times t^{n(T)}] \longrightarrow t(F,T)=\left.\frac{\partial T_{CCT}(F,v)}{\partial v}\right|_{F,T}=\left\{\frac{\ln[\frac{1}{1-F(t,T)}]}{k(T)}\right\}^{\frac{1}{n(T)}} \longrightarrow k(T)=\frac{\ln[\frac{1}{1-F(t,T)}]}{\left[\left.\frac{\partial T_{CCT}(F,v)}{\partial v}\right|_{F,T}\right]^{n(T)}}$$

CONSIDER incubation time in JMAK equation: for arbitrary cooling path



Schematic mathematical method of transition from CCT to TTT

$$g(t)|_T=1-\exp[k(T)\times(t-\tau)^{n(T)}]$$

$$\downarrow$$

$$\left.\frac{\partial g(t)}{\partial t}\right|_{t=g^{-1}[f(T_i)]}=\left.\frac{\partial f(T)}{\partial T}\right|_{T=T_i}\times v$$

K(T), *n(T)* and τ can be obtained

f(*T*) and *g*(*T*) are the non-isothermal and isothermal transformation functions respectively

Theoretical analysis of diffusional austenite decomposition

The generalized additivity rule of CCT curve

$$T = T_0 + v(t)\cdot t$$

$$\downarrow$$

$$T_{\mathrm{CCT}}(v) = T_0 + v\cdot\tau_{\mathrm{CCT}}(v)$$

$$\downarrow$$

$$v = \frac{\tau_{\mathrm{CCT}}(v)}{T_{\mathrm{CCT}}(v) - T_0}$$

$$\longleftarrow$$

$$S = \int_{T_0}^{T} \frac{1}{\tau_{\mathrm{TTT}}(T)\times v}\,dT$$

$$\downarrow$$

$$\tau_{\mathrm{TTT}}(T) = \left.\frac{\partial T_{\mathrm{CCT}}(v)}{\partial v}\right|_T$$

$$\longleftarrow$$

$$\Delta S = \int_{T}^{T+\Delta T} \frac{\tau_{\mathrm{CCT}}(v)}{\tau_{\mathrm{TTT}}(T)} \times \frac{dT}{T_{\mathrm{CCT}}(v) - T_0}$$

$$\downarrow$$

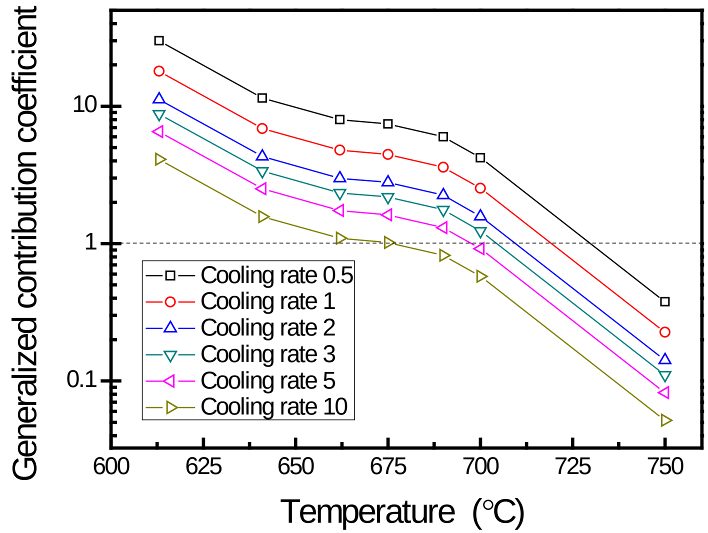
$$\int_{T_0}^{T_f}\left[K(T,v)\times\frac{dT}{T_{\mathrm{CCT}}(v)-T_0}\right] = 1 \longleftrightarrow K(T,v) = \frac{\tau_{\mathrm{CCT}}(v)}{\left.\left(\frac{\partial T_{\mathrm{CCT}}(v)}{\partial v}\right)\right|_T}$$

Kinetics contribution coefficient

$$\downarrow$$

$$\int_{T_0}^{T_f}\left[K(T,v)\times\frac{dT}{T_{\mathrm{CCT}}(v)-T_0} + \frac{\Delta t}{\left.\left(\frac{\partial T(v)}{\partial v}\right)\right|_T}\right] = 1$$

Generalized additivity rule



Kinetics contribution coefficient as the function of temperature

Kinetics contribution coefficient increases with the decreasing transformation temperature, implying that higher cooling degree results in the shorter incubation time.

Theoretical analysis of diffusional austenite decomposition

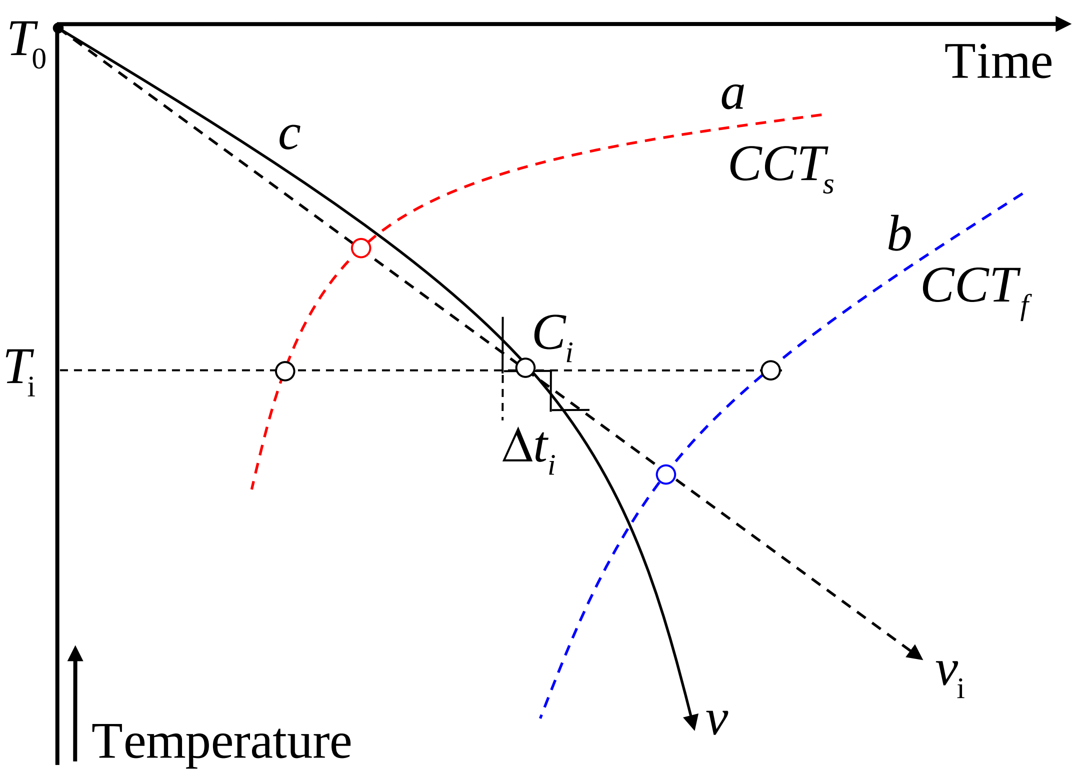
The generalized additivity rule of CCT curve

$$\left.\frac{\partial g(t)}{\partial t}\right|_{t=g^{-1}[f(T_i)]} = \left.\frac{\partial f(T)}{\partial T}\right|_{T=T_i} \times v$$

$$\Delta F_i = \left.\frac{\partial F}{\partial t}\right|_{F_i, T_i} \times \Delta t_i$$

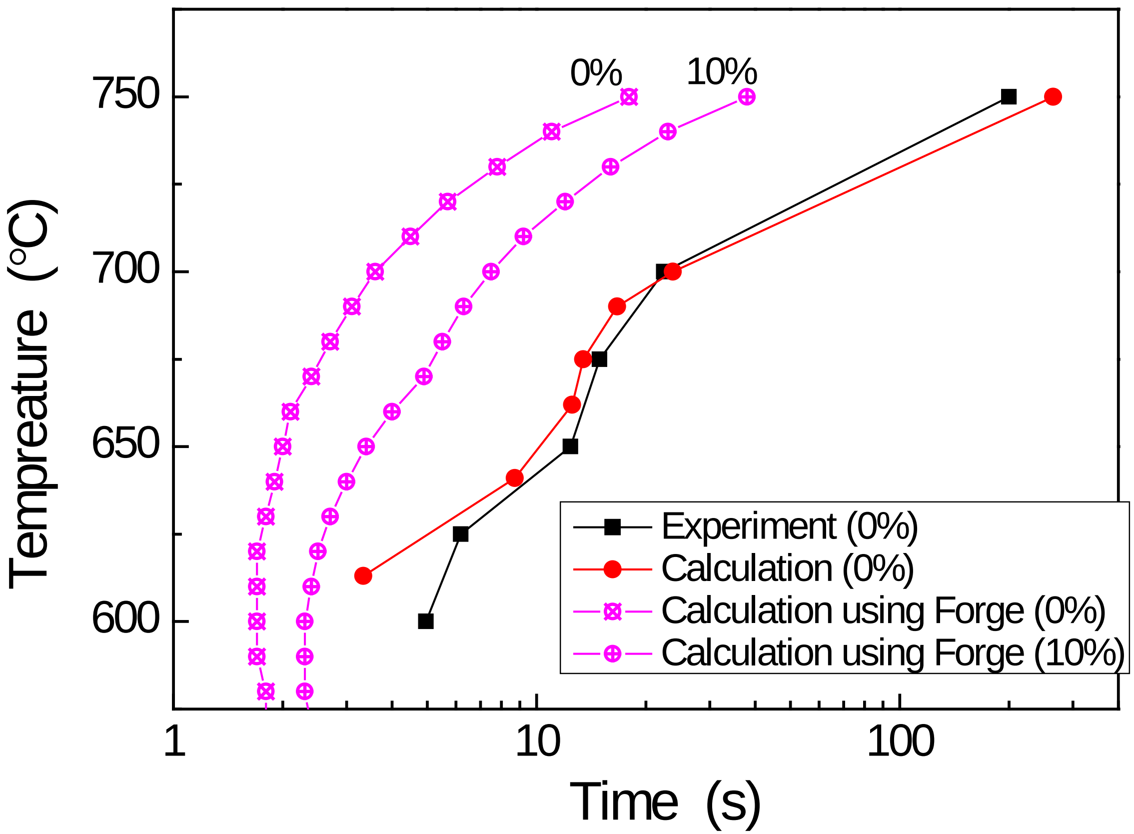
$$\Delta F_i = \left.\frac{\partial f(T)}{\partial T}\right|_{T_i} \times v_i \cdot \Delta t_i$$

$$F_{i+1} = F_i + \Delta F_i$$



Schematic generalized additivity rule using CCT curves

Results



The calculated TTT incubation time using CCT data and comparison with experiments

Brief summary

- A computational model which describes the interactive influence of thermal history, phase transformation and its mechanical responses is developed for simulating hot stamping high strength boron steel.
- The introduction of incubation time in JMAK type equations provide the more reasonable simulation results of phase transformation kinetics.The hardness prediction agrees well with the Jominy test, especially at the range of middle and high cooling rate.
- A theoretical relationship between the isothermal and non-isothermal transformation kinetics and the generalized additivity rule for CCT curve are built.
- This generalized model can be used to calculate the transformation kinetics undergoing arbitrary thermal path (including the cooling and heating) using the experimental CCT or CHT curves.

Thank you for your attention!