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Modeling of microstructures in dissimilar copper/stainless steel electron beam welds

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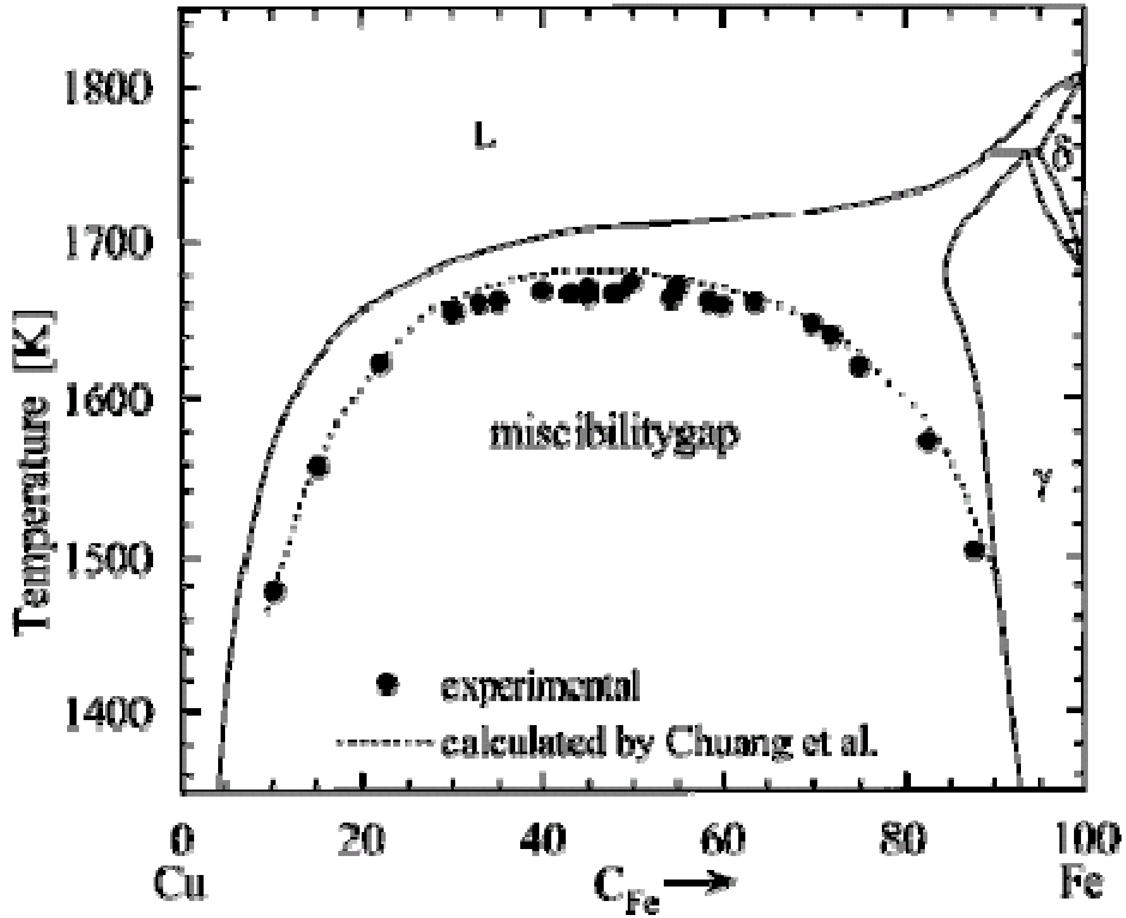
Fe/Cu system

- Limited miscibility under undercooling conditions
- No intermetallics
- Maximal solubility of Cu in austenic Fe matrix is about 15 at.%.



The metals used

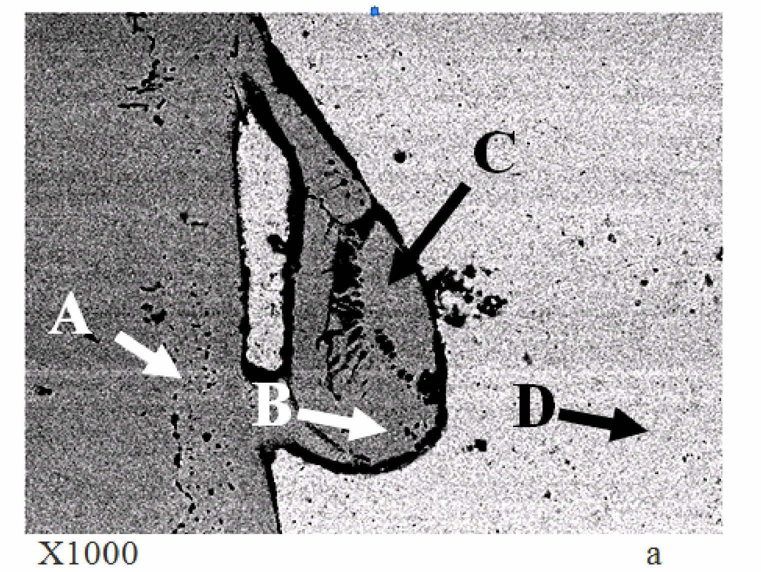
Materials	AISI 316 L austenitic stainless steel					Cu
Element	Si	Cr	Mn	Fe	Ni	Cu
at.%	0.91	20.27	2.09	70.00	6.73	99,99

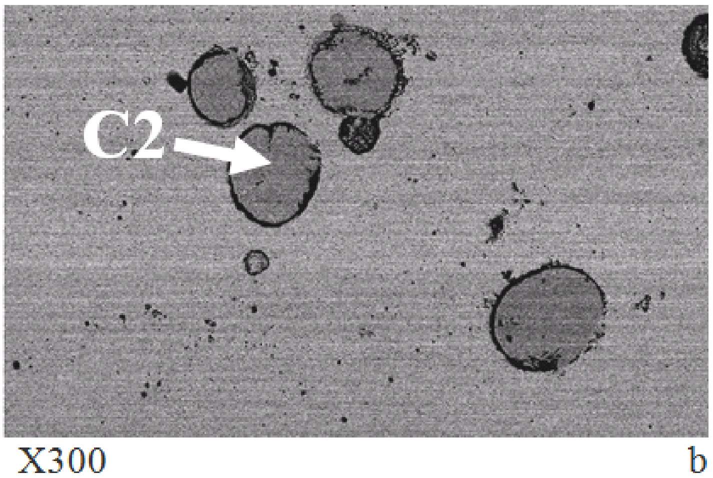
Solubility Cu(austenite) = 18 at.%

Solubility Fe(Cu) = 0.57-2 at.%

Two types of morphology

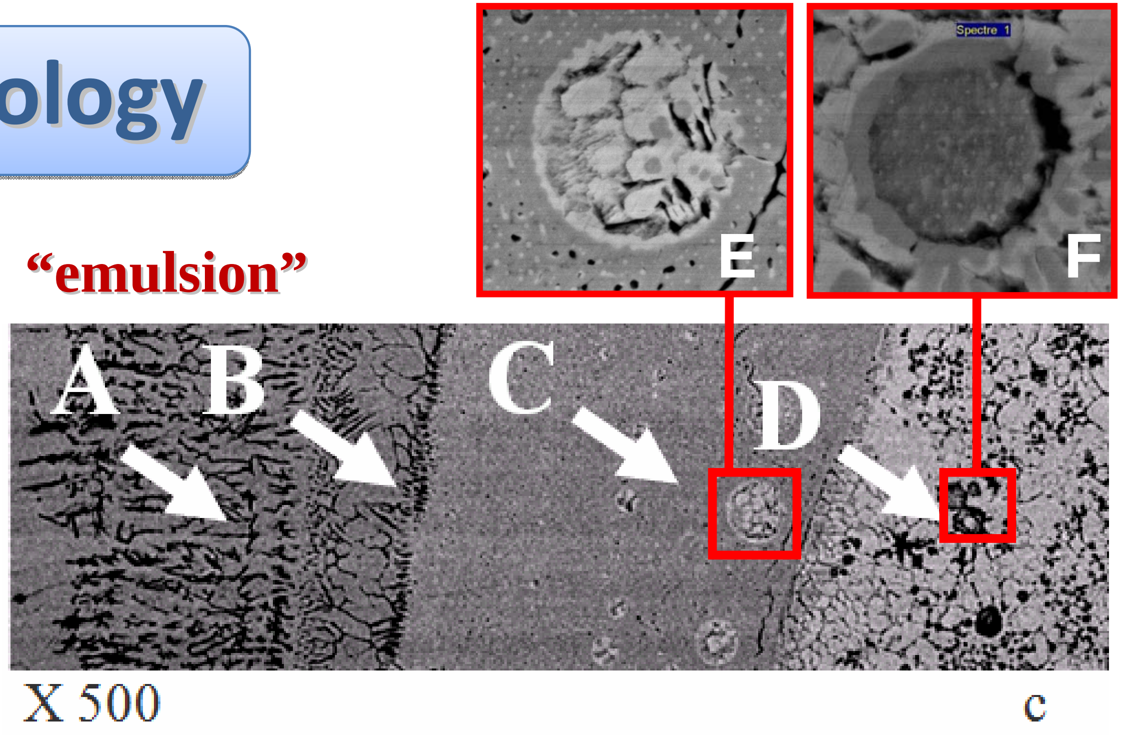
"droplet"





I = 40 mA, U = 25 kV , P = 1000 W, v =600 mm/min

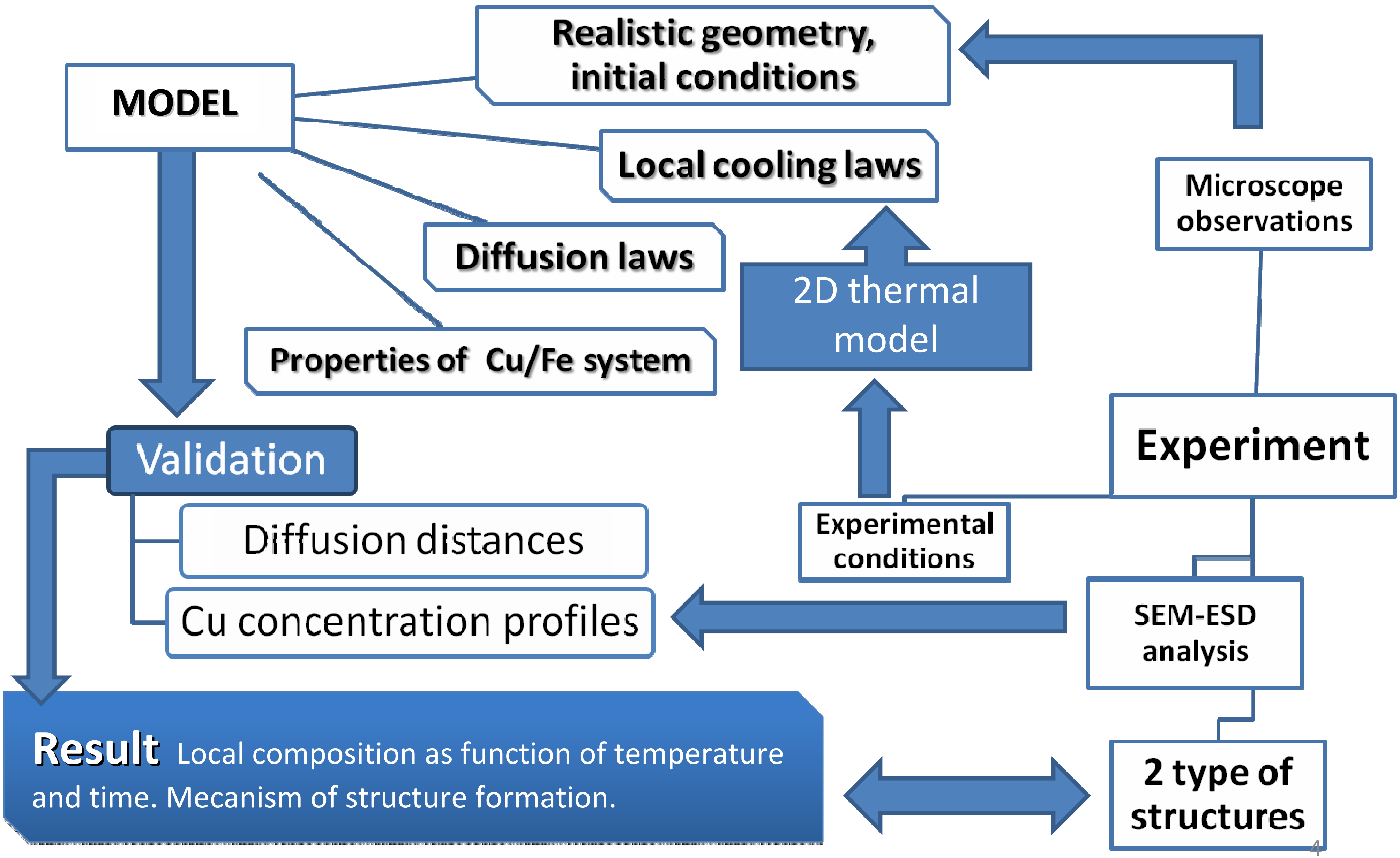
"emulsion"



I=30 mA, U = 37,5 kV , P = 1125 W, v = 600 mm/min

Structure	Element, at. %			
	Cu	Fe	Cr	Ni
"droplet"-like structure				
A	8,0	65,6	20	6,4
B	11,5	63,1	19,2	6,2
C	21,4	56,6	16,6	5,2
D	94	4,5	1,2	0,3
C2	21,3	55,2	17,2	6,3
"emulsion"-like structure				
A	0,5	70,6	20,8	8,1
B	7,9	65,7	20	6,4
C	21,3	56,5	16,5	5,7
D	94	4,5	1,2	0,3
E	91,1	5,6	2,0	1,3
F	14,9	62,5	18,0	4,6

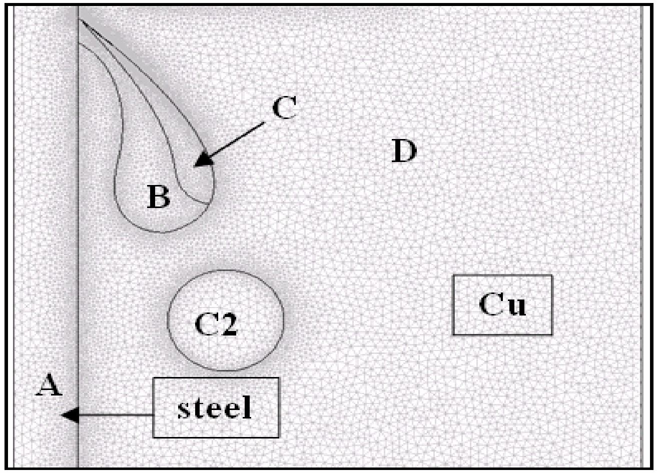
Modeling of microstructures



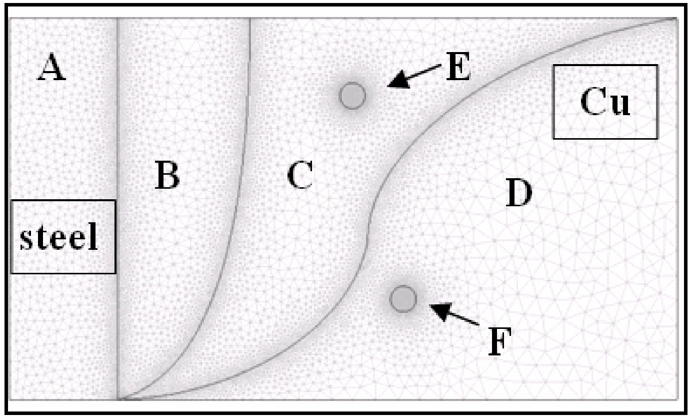
Model description

Realistic geometry

"droplet"



"emulsion"



Hypothesis

- "droplet" structure : the droplets are formed by eroding of steel by copper-rich flux.
- "emulsion" structure: undercooling phenomena with secondary phase separation.

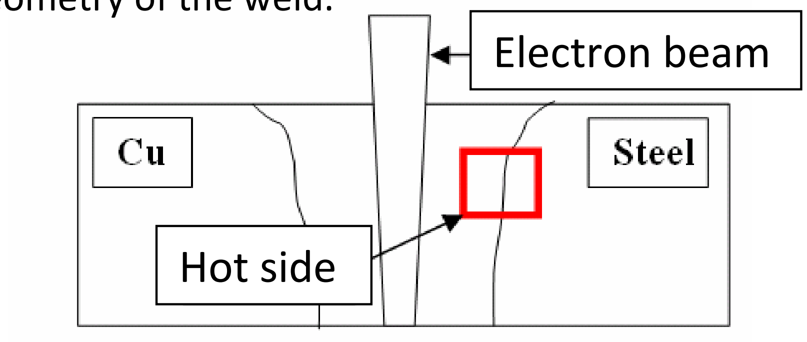
Simplifications

- the model deals only with solidification period of melted zone life ;
- convection is neglected;
- steel is considered as homogeneous material with diffusion coefficient of γ-Fe.

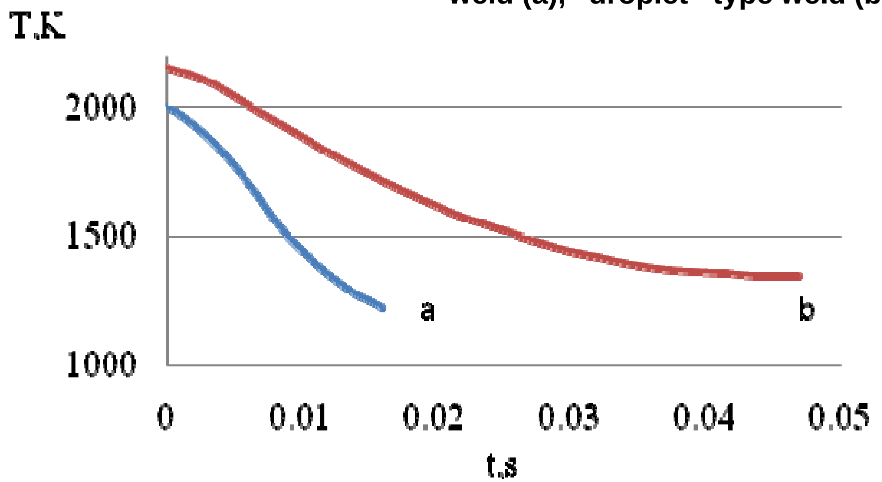
Model description

Heat transfer

The position of modeling zone at global geometry of the weld.



Cooling laws used in calculations: "emulsion"-type weld (a), "droplet"-type weld (b)

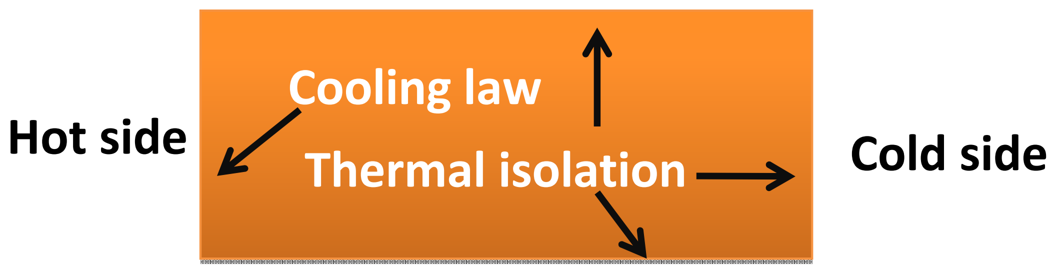


Heat equation: $$\rho c_p \frac{\partial T}{\partial t} = \nabla(-k\nabla T)$$

Discontinuity of properties:

$A=A_{solid} + (A_{liquid} - A_{solid})\cdot flc2hs(T-T_f, \delta T)$, $A = k, \rho, C_p$

Boundary conditions:

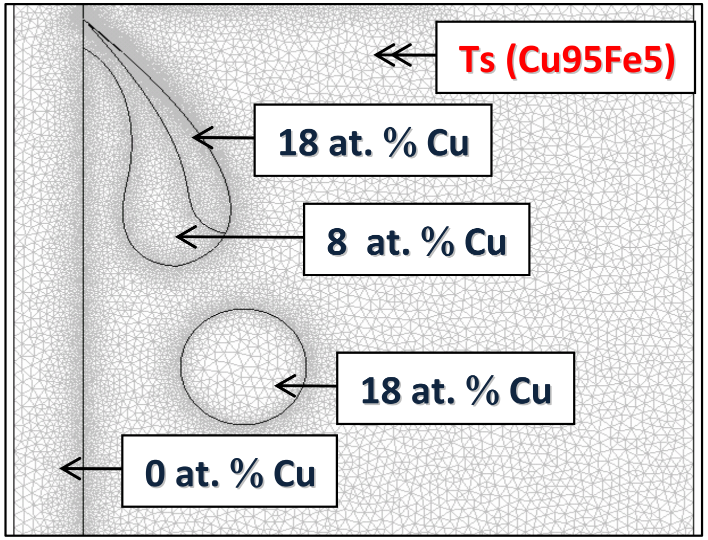


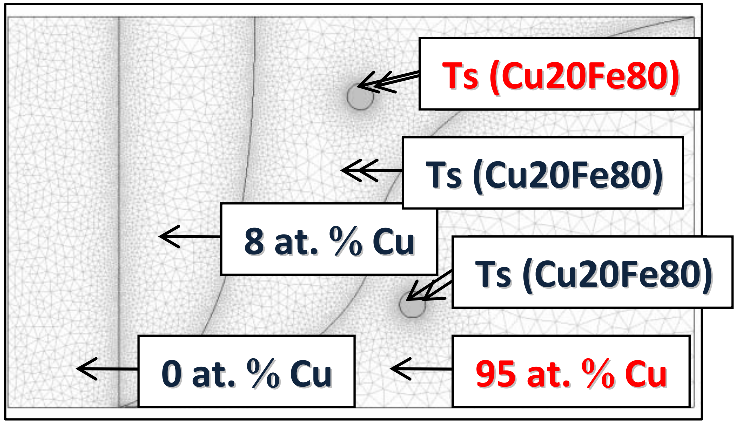
The approximations of cooling laws used in calculations

Joints	"emulsion"	"droplet"
Gauss approximation : T(K) = y0 + (A/(w·sqrt(PI/2)))·exp(-2·(t/w)^2)		
y0	1159,264	1333,8
w	0,01523	0,0367
A	16,2814	42,6
R^2	0,99	0,99

Model description

Initial conditions





Diffusion

System	T, °C	D, m^2/s	E, kJ/mol	Reference
Cu (γ-Fe)	950-1083	$3.0 \cdot 10^{4}$	225	C.J. Smithels(Ed), Metals Reference Book, 4 ed, vol 2, Butterworths, London, 1967
Fe(Cu)		$1.4 \cdot 10^{-4}$	217	

- copper-rich zones $\nabla(-D_{Cu(Fe)} \cdot \nabla c_{Cu}) = 0$
- steel-rich zones $\nabla(-D_{Fe(Cu)} \cdot \nabla c_{Fe}) = 0$

$$D_T = D \cdot \exp(-\frac{E}{R \cdot T})$$

$$D_{domain} = D_T \cdot flc2hs(T_{start} - T, \delta T)$$

Post treatment

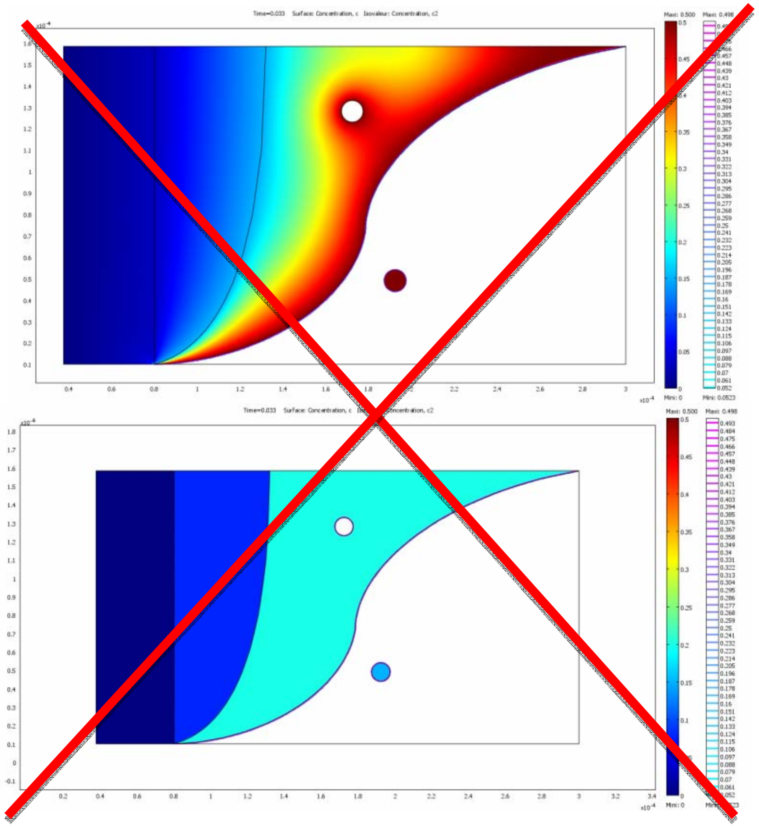
C(M), at. % - ?

$C(M) = C_{steel} \cdot \gamma(M) \cdot 100\ \%$,

M = Fe, Cr,Ni,

$\gamma(M)$ - molar part of M in original steel

Emulsion model: choice of start points of diffusion



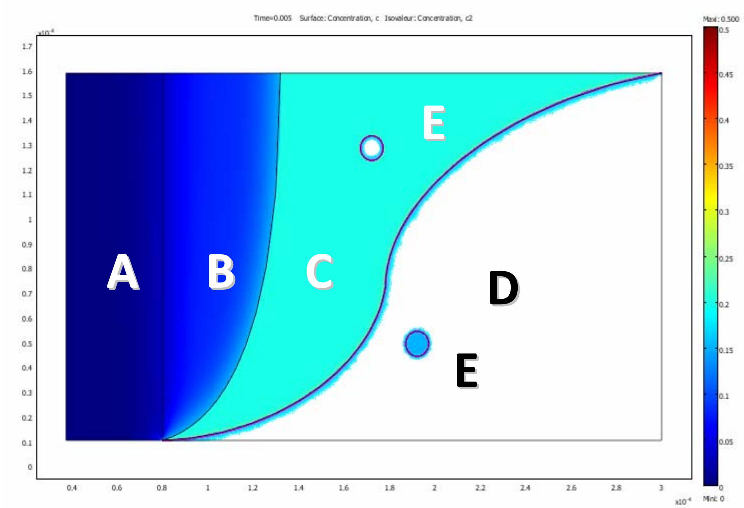
Diffusion starts immediately after beam pass and small globulas do exist:

Small globulas would be dissolved
Front of diffusion is too large

Diffusion starts after solidification of steel and small globulas do exist from beginning:

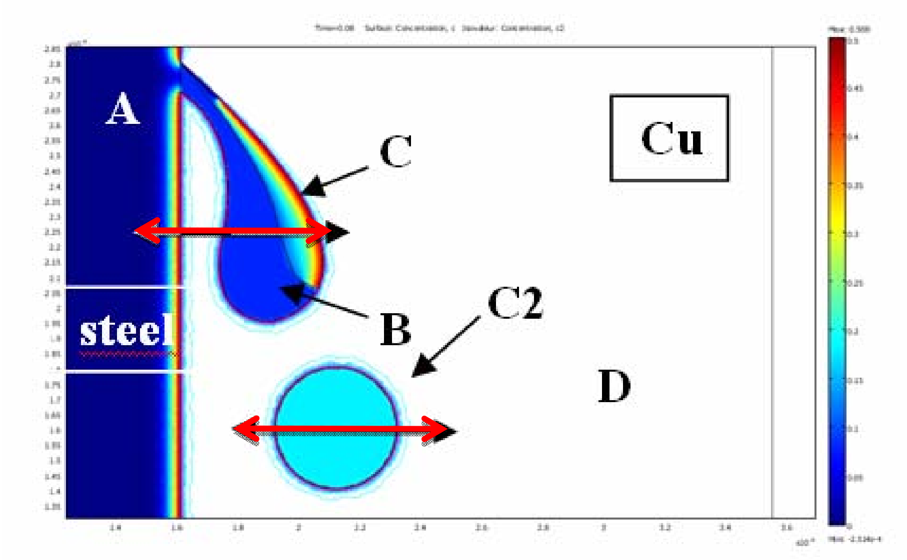
There is no diffusion observed

Diffusion starts after beam pass in A and B and after Ts (Cu20Fe80) at the regions C, D, E ad F (when small globulas are already formed during undercooling of the weld).
Large diffusion front in A,B and small in C,D, E and F.

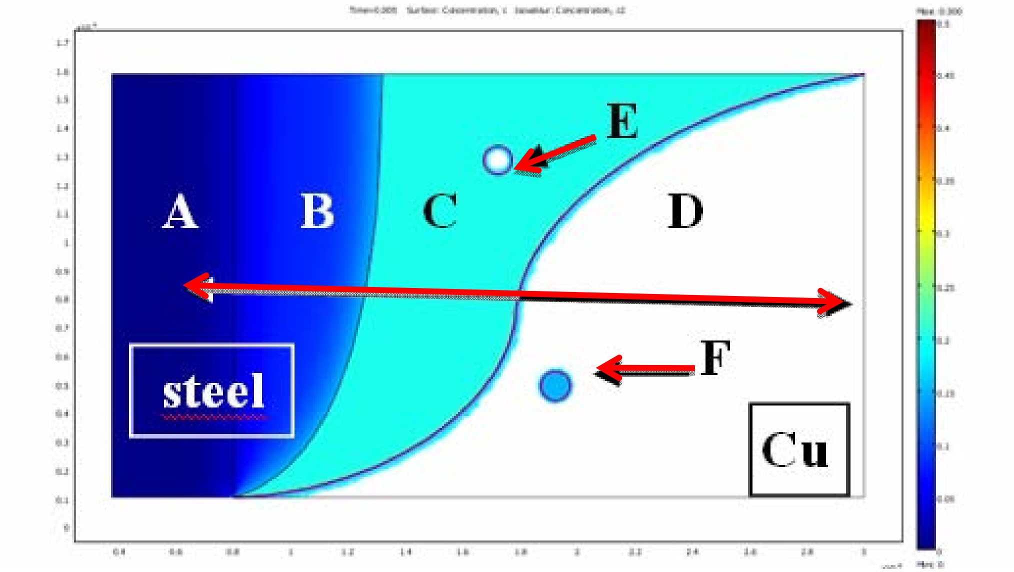


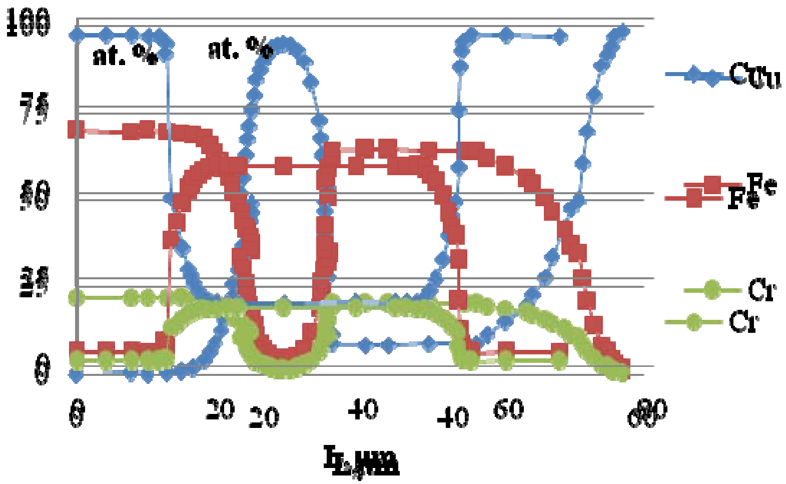
Results

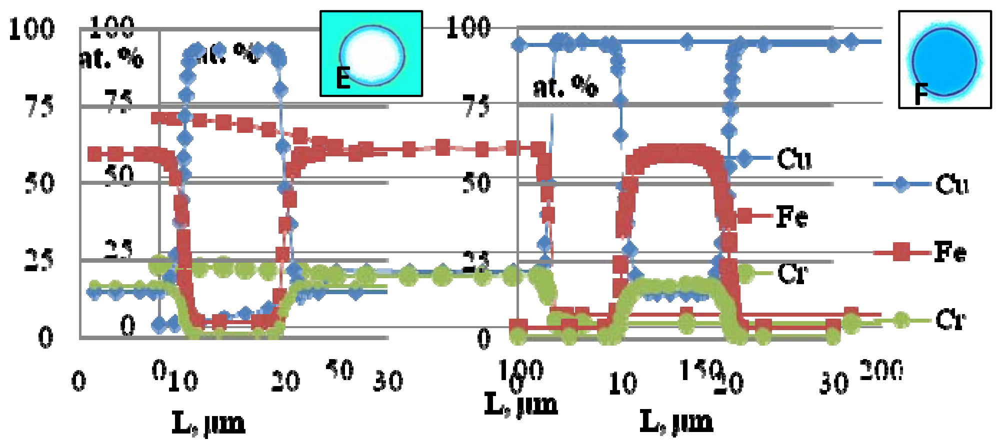
"droplet"



"emulsion"

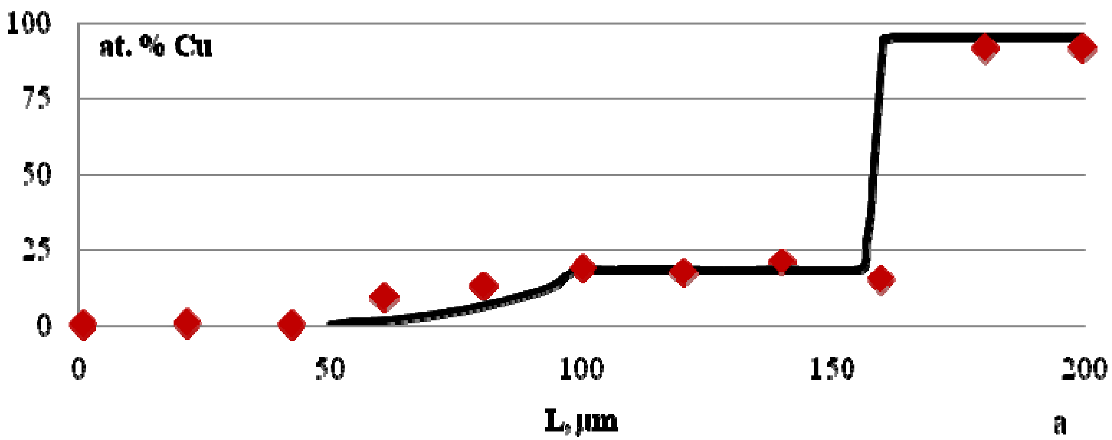


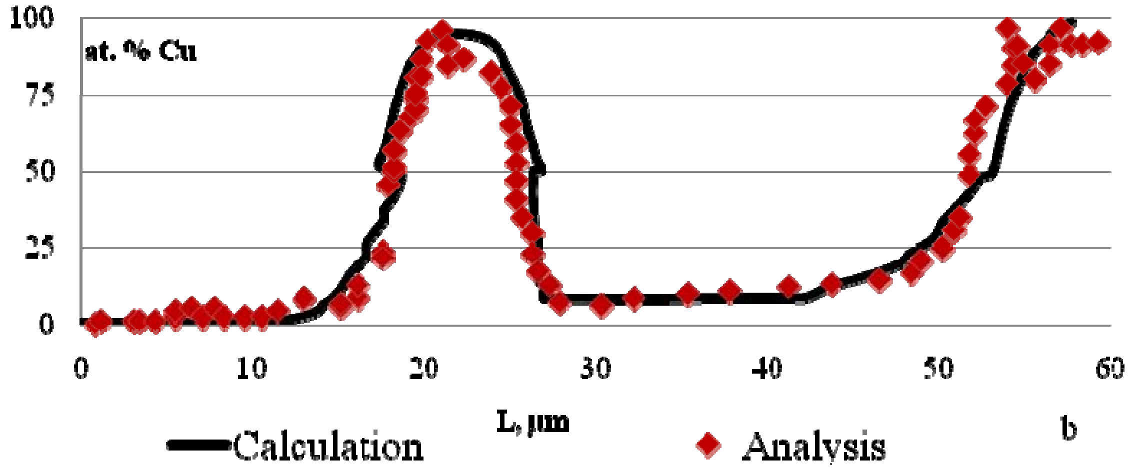


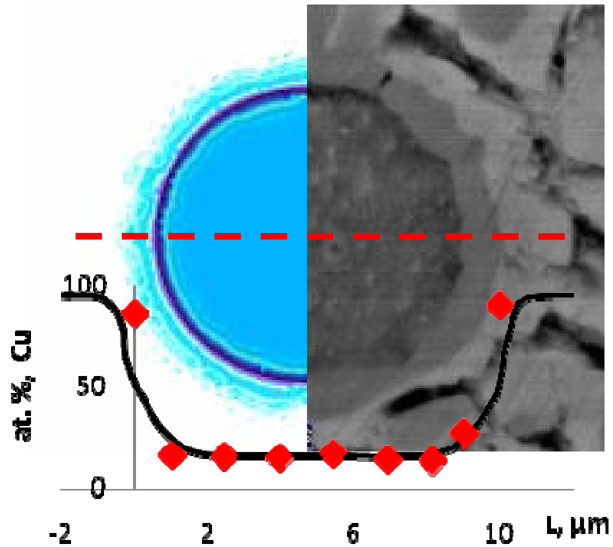


Validation

Comparison between calculated profiles and real copper concentration founded by SEM-ESD analysis in “emulsion”-like (a) and “droplet”-like (b) microstructures.



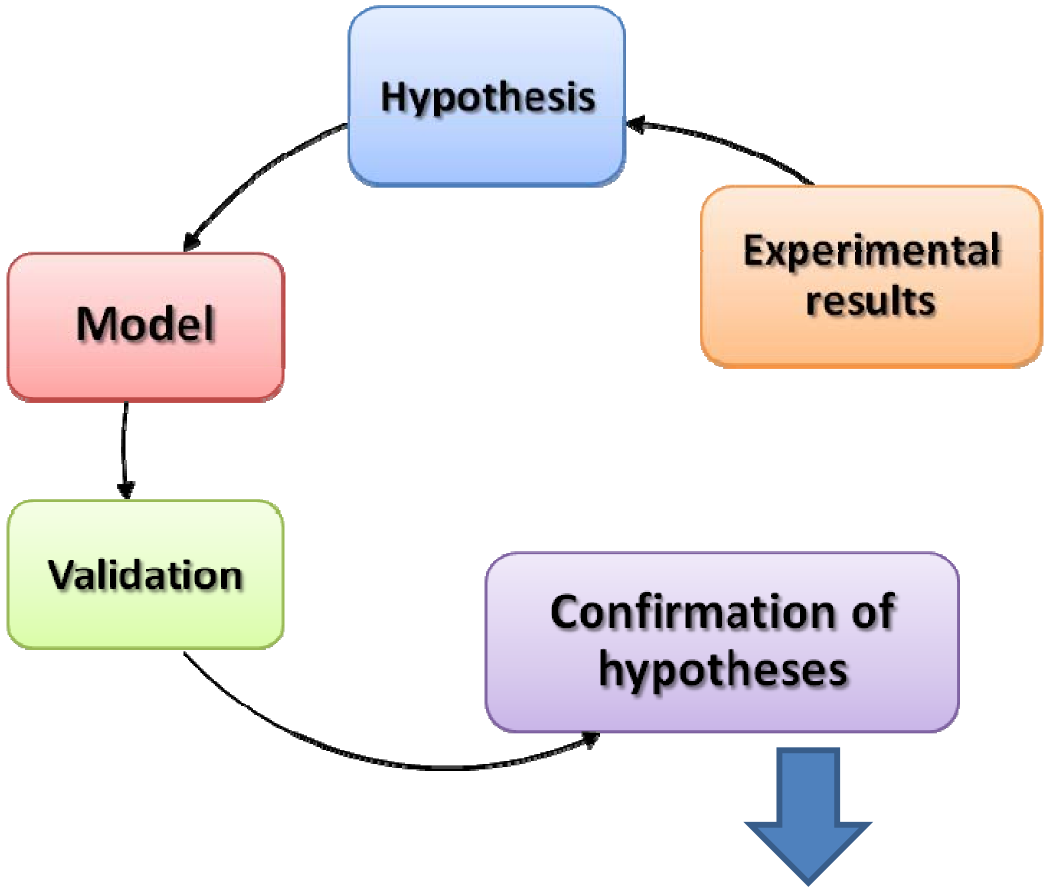




Comparison of diffusion distances on different interfaces

Interface	Distance, μm	
	“droplet”	
	calculated	observed
A/D	14	17
B/D	4	3
C/D	4	3
C2/D	2,4	1,8
	“emulsion”	
	calculated	observed
A/B	31	29
C/D	1,7	1,4
C/E	1,3	1,1
D/F	1,7	2,3

Conclusions



➢Present numerical models of microstructures development are in good correspondence with SEM images and the results of local ESD analysis.

➢The temperature evolution is realistic.

➢The results confirm our hypothesis on the way of microstructure formation under different welding conditions.

➢There are two mechanisms of microstructures formation depending on operational parametens.

- « droplet» structure is formed by eroding of steel surface by copper flux.
- « emulsion» structure is formed under undercooling conditions.