Interdiffusion in Aluminum-steel Clad Strip

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Introduction

Why joint of aluminum and steel?

- low density and high thermal conductivity of Al
- high strength and creep resistence of steel
- high corrosion resistance
- low costs

Applications?

- structural elements in car bodies and chases
- aircraft constructions
- shipbuilding
- heat exchangers, smelting production of Al
- household applications

Crucial parameter of overall composite's mechanical properties?

- intermetallic layer (IMC) at the Al-steel interface
- study of diffusion kinetics required!

Aims

- determination of effective interdiffusivity
- simulation of diffusion based on Fick's second law
- in-situ observations

Published values of diffusivities in Al-steel couple

Table 1: Diffusion coefficients of elements from Al-steel couple in Al and Fe [Akramifard et al., 2016]

Guest	Host	$D_{500\,^\circ C}$ [m^2/s]
Al	Fe	$2,77 \cdot 10^{-20}$
Fe	Al	$2,15 \cdot 10^{-15}$
Cr	Al	$3,99 \cdot 10^{-16}$
Ni	Al	$3,09 \cdot 10^{-14}$

- higher diffusivity of Fe in Al than that of Al in Fe
- similar diffusiviy of elements comprising steel

Conclusions in recent articles:

Formation of Al-Fe-intermetallics at the Al-steel interface proceeds towards Al

Studied Al-steel clad composite

Materials

Table 2: Chemical composition given by norm

EN AW-1070	Al	Fe	Si	Zn	Mn	Ti
wt.%	>99.7	<0.25	<0.2	<0.07	<0.03	<0.03
steel 1.4301	Fe	C	Cr	Ni	Mn	Si
wt.%	Balance	0.07	~18.0	~9.3	2	0.75

Twin-roll Casting

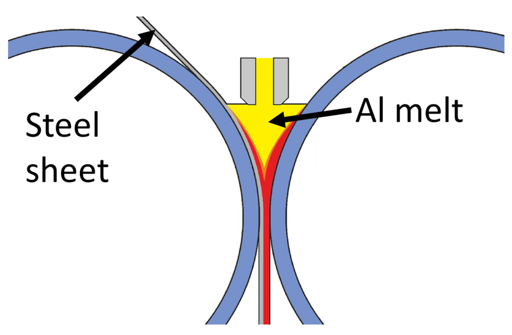


Figure 1: Scheme of twin-roll casting.

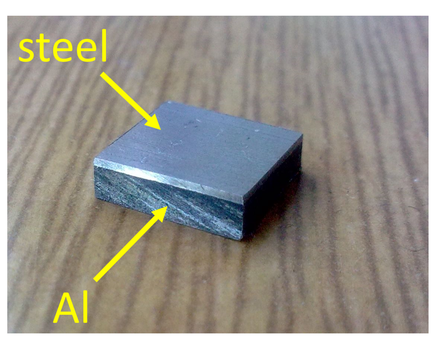
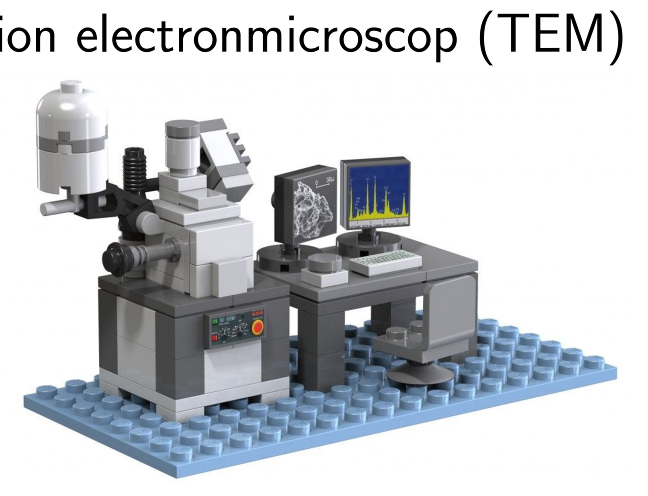


Figure 2: Photo of a piece of studied clad sheet.

Experimental methods

- Isothermal annealing 500 °C
- Scanning electron microscopy (SEM)
- Energy dispersive X-ray anylysis (EDX)
- Transmision electronmicroscop (TEM)



Numerical analysis

Boltzmann-Matano method (B-M method)

- determination of concentration dependent interdiffusion coefficient $D(c)$ from experimental concentration profile
- based on inversion of Fick's second law of diffusion → explicit relation for $D(c)$, [H. Mehrer, Diffusion in Solids]

$$D(c^*) = -\frac{1}{2t}\frac{\int_{c_L}^{c^*}(x - x_M)dc}{\frac{dc}{dx}|_{c^*}}, \qquad (1)$$

x_m position of Matano plane

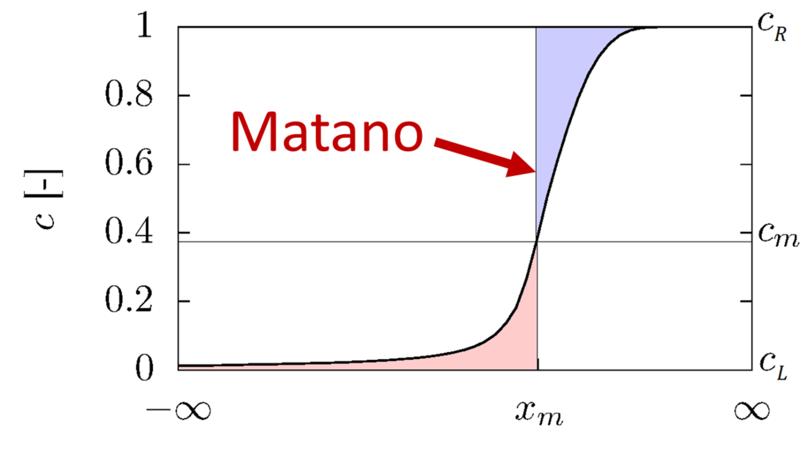


Figure 3: Position of Matano plane.

Finite element method (FEM)

- solution of 1D-diffusion equation

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D(c)\frac{\partial c}{\partial x}\right); \quad \frac{\partial c}{\partial \vec{n}} = 0, \quad c(x, t = 0) = (c_R - c_L)\mathcal{H}(x) \qquad (2)$$

Results

Computational test

- analysis of the error-function profile
- limited precision of B-M method near c = 1 and 0
- D(c); c near 0 and 1 is not taken into an account, piecewise fit is used

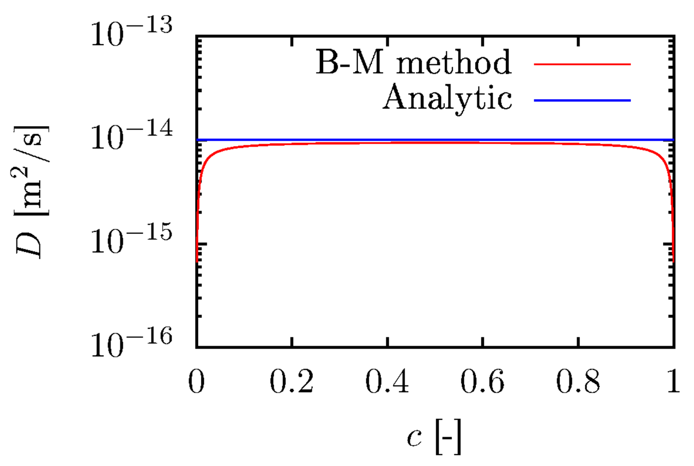


Figure 4: Diffusion coefficient $D(c)$.

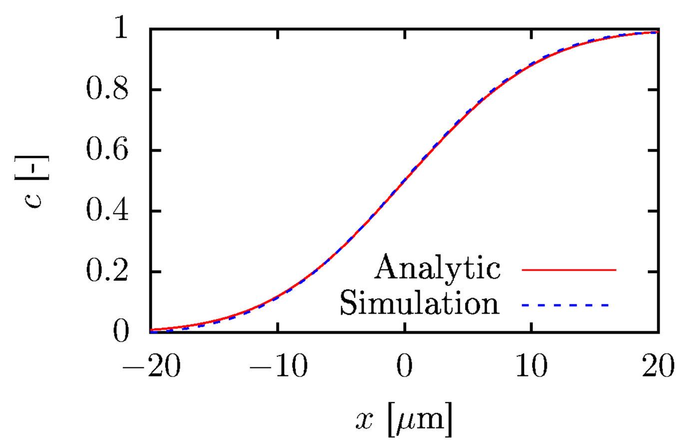


Figure 5: Analytical and simulated c profile.

Analysis of experimental concentration profiles

1. EDX line analysis through Al-steel interface
2. simplification to a binar system – introducing „steel atoms"
3. smoothing of the concentration profile (Savitsky-Golay filter)
4. determination of effective diffusion coefficient using B-M method and inserting of its piecewise fit to diffusion equation → solution by FEM

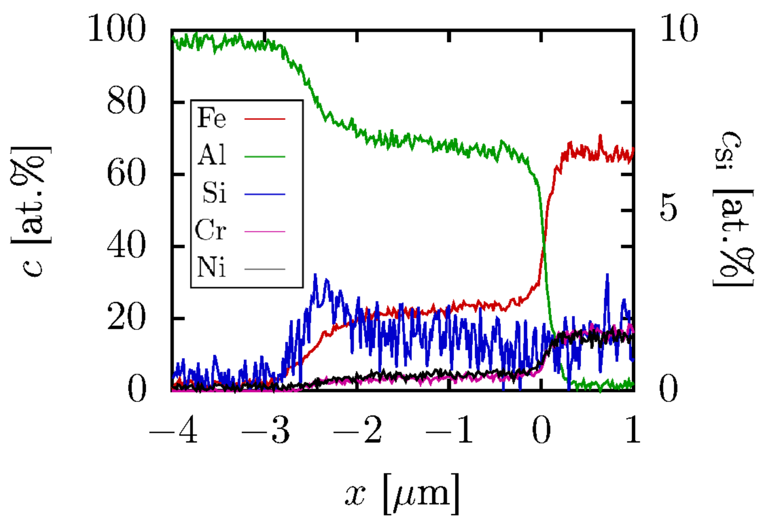


Figure 6: Diffusion coefficient $D(c)$.

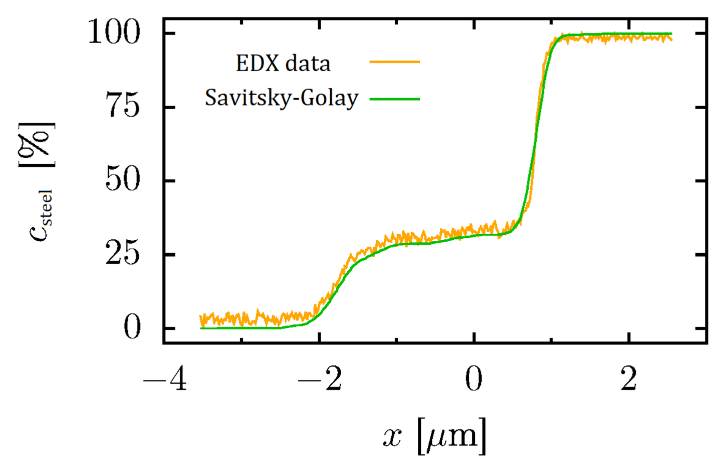


Figure 7: Analytical and simulated c profile.

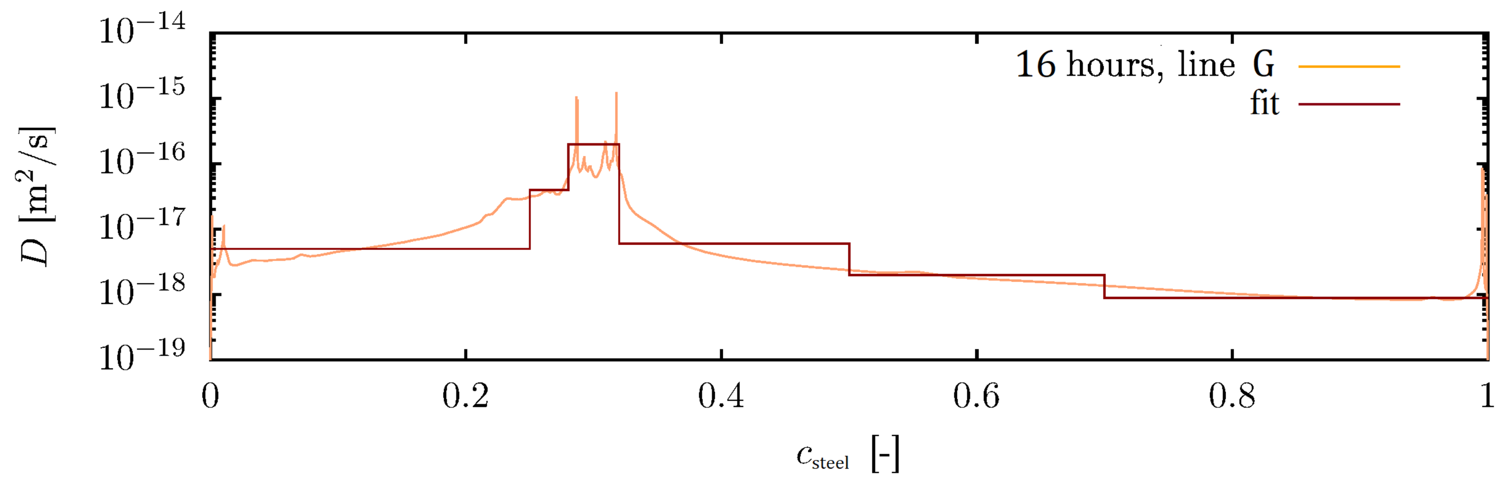


Figure 8: Diffusion coefficient $D(c)$.

FEM analysis

- plotting of initial condition – original interface position
- intermetallic layer grow rather towards Al
- Fe difuses faster than Al
- satisfactory agreement between analytical and simulated profile

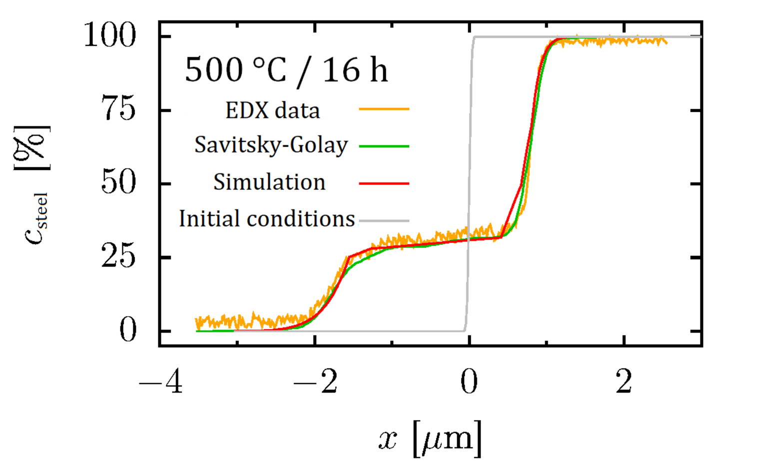


Figure 9: Simulated and measured concentration profile after 500 °C / 16 h.

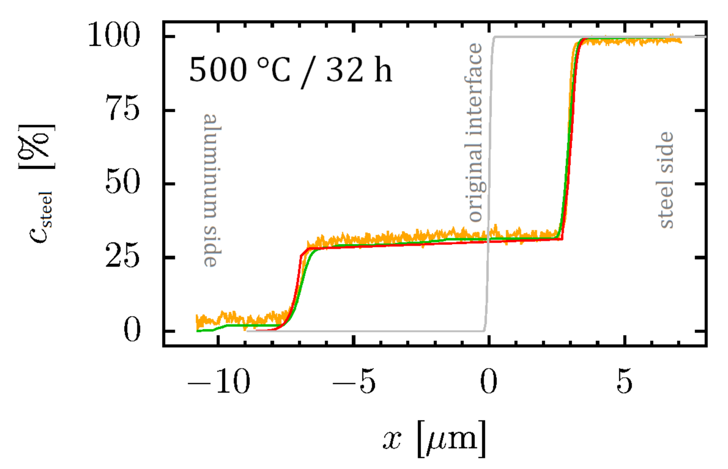


Figure 10: Simulated and measured concentration profile after 500 °C / 32 h.

In-situ annealing in TEM (SEM) IN CONTRADICTION: IMC grows towards steel layer!

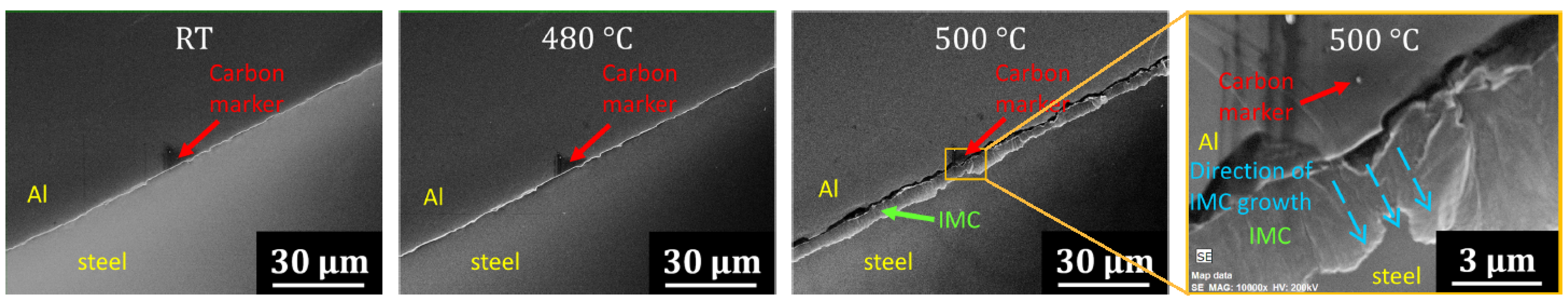


Figure 11: Evolution of IMC layer during in-situ annealing in TEM.

Summary

Results of in-situ annealing are in contradiction to the simulation of diffusion according to Fick's second law and published values of diffusion coefficients. Therefore, Fick's laws and the related diffusion coefficient are rather disputable for interpretation of experimental results in case of Al-steel diffusion couple, which is often used in present studies dealing with the Al-steel cladding. Gradient of chemical potential as a driving force of diffusion should be used instead of gradient of concentration.

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