



# Consequences of rapid heating of Al–Cu alloy and martensitic stainless steel

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## ABSTRACT

In its first part, the paper describes the mechanism of constitutional liquation and specifies the conditions favourable to this phenomenon. Then, two case studies of service failure caused by non-equilibrium liquation in AlCu4MgSi alloy and in stainless steel X46Cr13 are analysed. Components made of these alloys were subject to solution annealing during their manufacturing process. Too fast heating resulted in non-equilibrium liquation between precipitates and matrix of these alloys in subsolidus temperatures. In consequence, irreversible changes occurred in microstructure, which directly contributed to service failures of the components, i.e. intergranular corrosion of the aluminium alloy and seizure of the steel shaft in its slide bearing.

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## 1. Introduction

When commercial multi-phase alloys (based e.g. on nickel, aluminium and iron) are too rapidly heated to the temperature range of homogeneous solid solution, particles of intermetallic phases have not enough time to be dissolved before reaching the eutectic temperature of the matrix–intermetallic phase system. Then, a non-equilibrium eutectic-type reaction will occur between these particles and the surrounding matrix, creating metastable solute-rich liquid film at the particle/matrix interface. This phenomenon is named constitutional liquation (CL) or non-equilibrium melting [1–5].

Constitutional liquation can be most simply explained in terms of a binary alloy using the simple phase diagram shown in Fig. 1a [5]. An alloy of composition  $C_0$  has at room temperature a certain volume fraction of second-phase particles AB. When the alloy is rapidly heated to any peak temperature  $T_s$  (above eutectic temperature  $T_E$ ), it liquates as the  $\alpha$ -matrix composition at the AB particle–matrix interface exceeds  $C_s$ . The liquid is formed in accordance with the phase diagram and its composition ranges from  $C_{L1}$  to  $C_{L2}$  (Fig. 1b). Given sufficient time and temperature, the AB particles can completely liquate.

When the particles are located on grain boundaries, coalescence of liquid drops coming from individual particles results in creating a grain-boundary liquid film with a lateral concentration gradient that ranges from  $C_{L1}$  to  $C_{L2}$  [3,4]. A schematic diagram showing sequences of how the liquid film is formed along grain boundaries is presented in Fig. 2.

Since the liquid produced during constitutional liquation is metastable, it can disappear due to back diffusion of solute into matrix. The back diffusion of solute atoms from the liquid to the matrix can cause coherency strain to develop if the solute and matrix atoms are sufficiently different in size [3]. This promotes migration of the liquid film known as constitutional liquid film migration (CLFM) [4]. It is characteristic for CLFM that the driving force can originate from either or both a lateral (in-plane) or transverse (coherent strain) solute flux. The liquid films move away from their curvature centres and new solid solution is formed behind the migrated liquid film [4,6]. Therefore, the features characteristic of CLFM (movement

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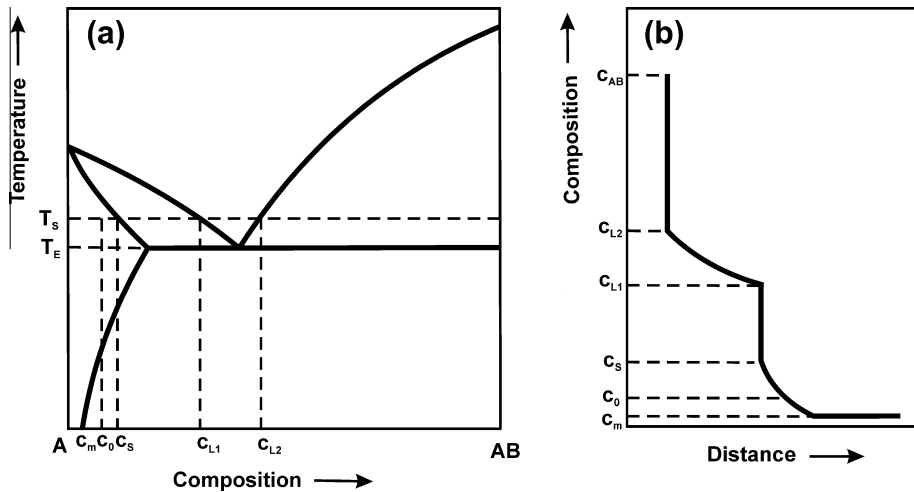


Fig. 1. (a) Constitutional liquation of AB particles, assuming diffusion controlled dissolution of AB in  $\alpha$  and (b) concentration gradient in front of the liquating AB particle (after [5]).

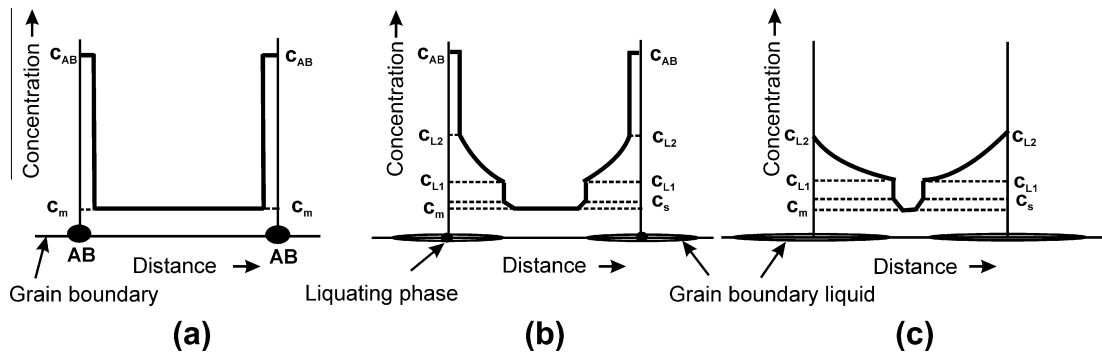


Fig. 2. Schematic presentation of a grain-boundary liquid film formation and lateral concentration gradient in the liquid due to constitutional liquation of AB particles (after [4]).

away from the curvature centre, formation of new solid solution and reversals of curvature) can present microstructural evidences of this phenomenon occurrence.

The theory of constitutional liquation is based on the assumption of local equilibrium at the interface between dissolving particle and the matrix, which means that the particle dissolution and liquation reactions are fully diffusion controlled. Radhakrishnan [2] revised this theory describing the conditions under that local equilibrium may not exist at moving interfaces, i.e. the conditions under that precipitate dissolution is interface controlled. In these circumstances, mobility of the precipitate–matrix interface is controlled by [2]: interface structure (coherent and semicoherent), relative diffusivities of solutes (coherent and incoherent precipitates containing both substitutional and interstitial atoms in the lattice) and free energy of precipitates formation (the rate of dissolution may be limited e.g. by the rate at that strong chemical bonds of precipitates can be broken). Interface controlled precipitates dissolution can occur in binaries as well as in multicomponent systems and can result in lower concentration at the precipitate–matrix interface than that predicted by the phase diagram (not sufficient to cause liquation). It follows from this that susceptibility of the alloy to subsolidus liquation during rapid thermal processing is determined by its microstructure (type/morphology of precipitates).

As mentioned above, it is characteristic for CL that, during prolonged annealing at solutionizing temperature, the metastable liquid slowly dissolves back in the surrounding matrix. It may leave no traces of melting provided that hydrogen does not condense on the phase boundary and does not create microvoids. Hydrogen dissolved in alloys occurs in the mono-atomic form (as a interstitial solute diffusible even in ambient temperature) and in the immobile molecular form (when is trapped on defects like dislocations, grain boundaries or interphase interfaces [7]). Since hydrogen solubility in a liquid is much higher than in solid [8], hydrogen in both atomic and molecular form can dissolve readily (up to the equilibrium solubility) in a liquid produced by CL of second-phase particles. When the hydrogen reach liquid is solidified, excess of hydrogen (above solubility in solid state) is rejected at the solid solution–liquid interface. The educing hydrogen atoms join to molecules cre-

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