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PRECIPITATION ON DISLOCATIONS IN Al-Li-Cu-Mg-Zr

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MATERIALS SCIENCE BRANCH

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ABSTRACT

Transmission electron microscopy was used to study precipitation processes on dislocation lines in Al-2.5Li-1.3Cu-0.7Mg-0.12Zr wt% aged at 190°C. Upon aging, a series of dislocation dissociation and precipitation reactions occur. The T₁-Al₂CuLi phase nucleates on dislocations in the (111) glide planes inducing the lattice dislocation to dissociate. On the remaining dislocation segment, S'Al₂CuMg plates form causing the lattice dislocation to dissociate into a configuration with a Shockley partial on one side and a climbing partial on the other, such that S' plates are on the (210) plane. T₁ phases nucleate from the surface of S plates on conjugate {111} with an interfacial dislocation glide motion.

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INTRODUCTION

Research on the structure and properties of aluminum lithium alloys is important for development in aerospace applications.^{1,2} The desirable features are the low density, high strength to weight ratio. The phase equilibria of various Al-Li alloys,³ binary, ternary, and quaternary systems, was examined by Mondolfo.⁴ The lattice parameter of aluminum was found to decrease with increasing lithium concentration. In the binary system, there is fcc-AlLi of lattice parameter $a = 0.638\text{nm}$, AlLi_2 , and cubic δ' - Al_3Li of lattice parameter $a = 0.401\text{nm}$. Al_3Li is thought to form as part of a precipitation sequence from supersaturated solid solution $\text{SSSS} \rightarrow \text{Al}_3\text{Li} \rightarrow \text{AlLi}$.⁵ In the Al-Li-Cu ternary, the compounds which form are tetragonal θ - CuAl_2 of lattice parameters $a = 0.6063\text{nm}$, $c = 0.4872\text{nm}$, hexagonal T_1 - Al_2Cu Li of lattice parameters $a = 0.497\text{nm}$, $c = 0.934\text{nm}$, T_2 - $\text{Al}_5\text{Li}_3\text{Cu}$ bcc of lattice parameter $a = 1.3914\text{nm}$, and T_B $\text{Al}_{7.5}\text{Li Cu}_4$ fcc of lattice parameter $a = 0.583\text{nm}$, as well as transition phases. The quaternary Al-Cu-Li-Mg was reported to have the orthorhombic $\text{S}'\text{Al}_2\text{CuMg}$ with lattice parameters $a = 0.400\text{nm}$, $b = 0.925\text{nm}$, and T_1 - Al_2CuLi .

The mechanical properties of Al Li alloys depend on the structure. The strength of Al-Li increases with lithium concentration.⁵⁻⁸ The effect is thought to be order hardening and modulus hardening associated with Al_3Li precipitation.⁶ The increase in modulus can be attributed to both Li in solution and Al_3Li . The addition of Mg causes the modulus to drop slightly. The fracture toughness was found to improve with $\text{S-Al}_2\text{CuMg}$ precipitation.⁸ T_1 - Al_2CuLi contributes to the increase in strength.⁹ The addition of Mg improves the strength by replacing some T with S.¹⁰ The grain size is refined by the addition of Zr.⁸

The nucleation and growth of second phases in AlLi alloys has been investigated. Al_3Li forms homogeneously in the matrix as a dense array of spherical particles. The growth is diffusion controlled Ostwald ripening following $t^{1/3}$ kinetics. Attempts have been made to measure the interfacial energy from coarsening relations.¹¹ δ' - Al_3Li has been found to nucleate at Al_3Zr precipitates forming an outer core shell around the spherical Al_3Zr particle.¹¹ Al_3Li precipitate free zones form at grain boundaries.³ This report is on precipitation processes on dislocations in Al-Li-Cu-Mg-Zr.

EXPERIMENTAL PROCEDURE

A bar of Al-2.5Li-1.3Cu-0.7Mg-0.12Zr wt% 8090 alloy was spark cut into thin slices. The foils were polished, encapsulated in vacuum tubes, and solution annealed for 15 minutes at a temperature of 530°C . Samples were wrapped in Al foil and aged at 190°C for various lengths of time in an atmospheric tube furnace. The flowing gas was either nitrogen or

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argon. Three millimeter discs were electropolished in a 1/3 nitric acid, 2/3 methanol solution. The transmission electron microscopy was performed on the JEM 200 CX electron microscope.

RESULTS

The precipitation in Al-Li-Cu-Mg-Zr was examined by transmission electron microscopy. Annealed samples were found to contain coherent CuAl_2 precipitates. Helical dislocations form on quenching as a result of dislocation climb. On aging at a temperature of 190°C three phases nucleate: δ' - Al_3Li , S' - Al_2CuMg , and T_1 - Al_2CuLi .

All four phases are visible in the bright field image from a sample aged for 16 hours at 190°C (see Figure 1). Double lobe strain contrast is present from round θ - CuAl_2 precipitates in the matrix. A layer of δ' - Al_3Li forms around the particles, as well as in the matrix, as small round coherent phases. The S' - Al_2CuMg nucleates on dislocations as parallel plates and in the matrix as large rods at three orientations. Composite sheets of S' plates were also observed.¹²



Figure 1. Four phases in Al-Li-Cu-Mg-Zr aged for 16 hours at 190°C . θ - CuAl_2 , δ' - Al_3Li , T_1 - Al_2CuLi , and S' - Al_2CuMg .

The T_1 - Al_2CuLi phase nucleates on dislocations and at heterogeneous sites in the matrix. There are displacement fringes on the surface of large T_1 plates at one orientation in Figure 1 and dark lines of the projected thickness at the other. The S' and T_1 phases can be distinguished by orientation since the S' is in the $\{210\}$ plane and the T_1 in the $\{111\}$. Both S' - Al_2CuMg and T_1 - Al_2CuLi nucleate on dislocations after aging for eight hours at 190°C (see

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Figure 2). The T_1 phases are both in the glide plane of the dislocation line and on conjugate $\{111\}$ planes. The lattice dislocations are induced to dissociate in the glide plane by the T_1 plate. The partials are the interfacial dislocations of T_1 . There is an interruption in the dislocation line when the T_1 phases are located. The nucleation of the S' - Al_2CuMg phase on the dislocation causes the dissociation of the remainder of the dislocation line $\xi = [101]$ into a Shockley partial on one side and an indeterminate dislocation obscured by the S' precipitate plates on the other side (see Figure 3). Shockley partial dislocation loops nucleate on the surface of the plates and interfacial dislocations form a square net on the surface (see Figure 3) where plates coincide. The T_1 phase on the conjugate planes grows from segments on the (210) plane of the S' plates. θ - $CuAl_2$ is visible in the matrix.

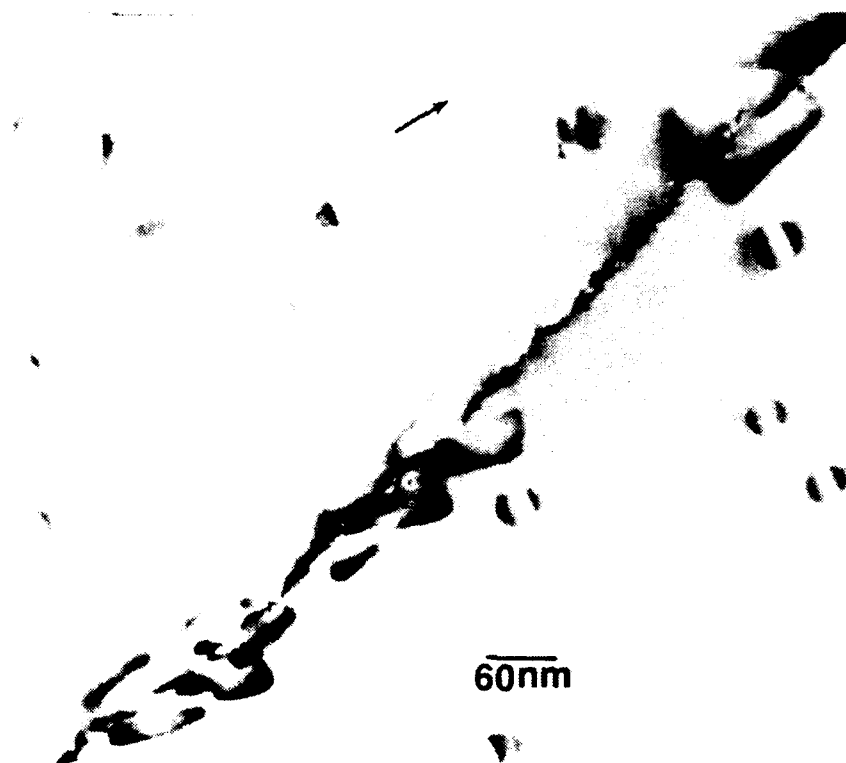


Figure 2. T_1 - Al_2 and S' - Al_2CuMg nucleate on dislocations in a sample aged for eight hours at $190^\circ C$. There are interruptions in S' precipitation where large T_1 plates are located.

The large sheets of S' plates begin growth by the nucleation of rods on dislocations. Figure 4 is a dark-field image of S' nucleation on a helical dislocation at periodic positions where the dislocation segment is parallel to the $\langle 100 \rangle$ growth axis. Closely spaced rods nucleate on the dislocation segments in between each long rod, as at the helix on the left of Figure 5. There is a well developed S' sheet on the right side of Figure 5 with plates oriented along $[010]$ direction. Nucleation on a helical dislocation results in a wavy sheet of S' plates. $\delta'Al_3Li$ precipitates on $CuAl_2$ and coarsens to form a spherical layer. Distorted spheres of Al_3Li are also observed on dislocation lines.

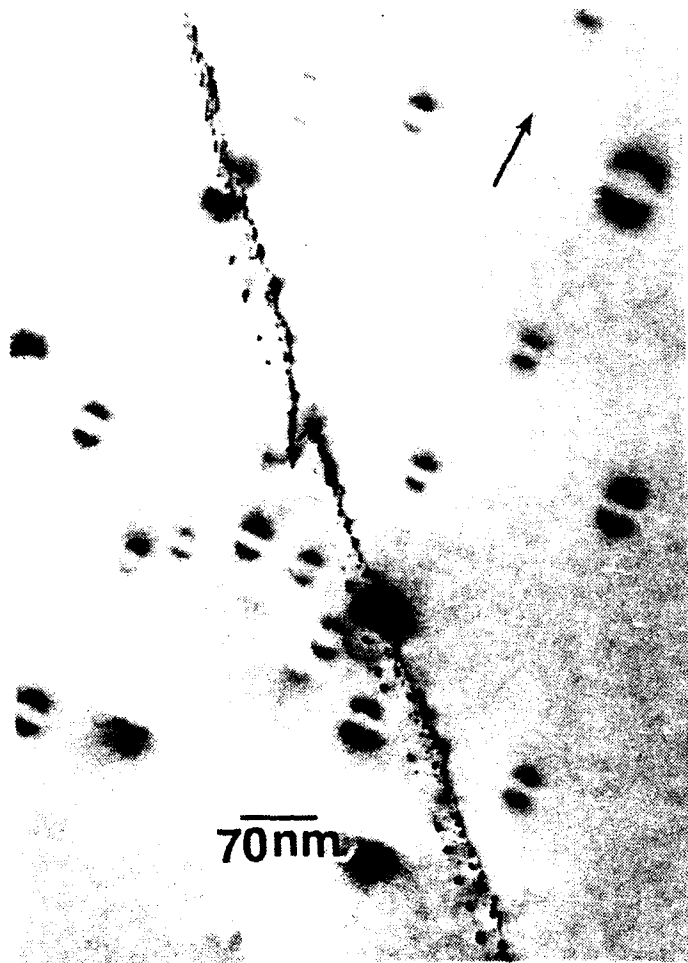


Figure 3. The precipitation of S' - Al_2CuMg and the dissociation of the lattice dislocation into a configuration with a Shockley partial on one side. Interfacial dislocation nets and Shockley partial loops are visible on the surface. The sample was aged for nine hours at $190^\circ C$.

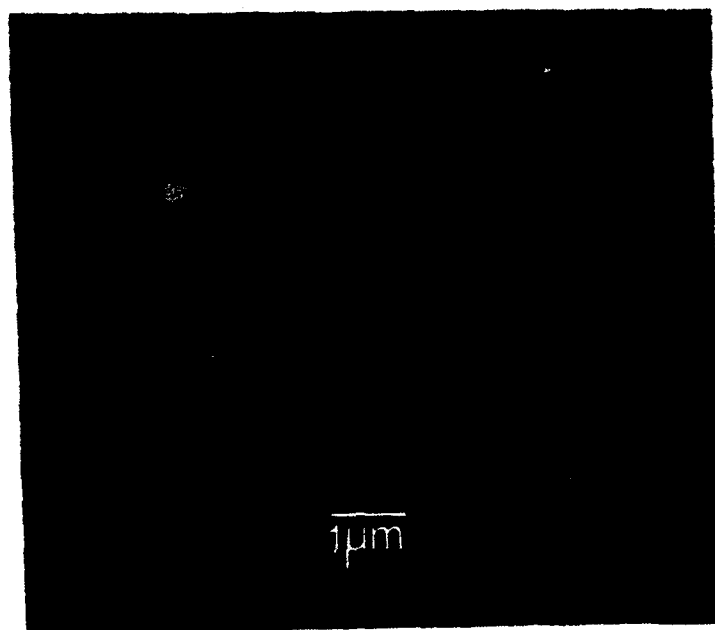


Figure 4. Dark field image of S' - Al_2CuMg rods on a dislocation helix. The specimen was aged for eight hours at $190^\circ C$.

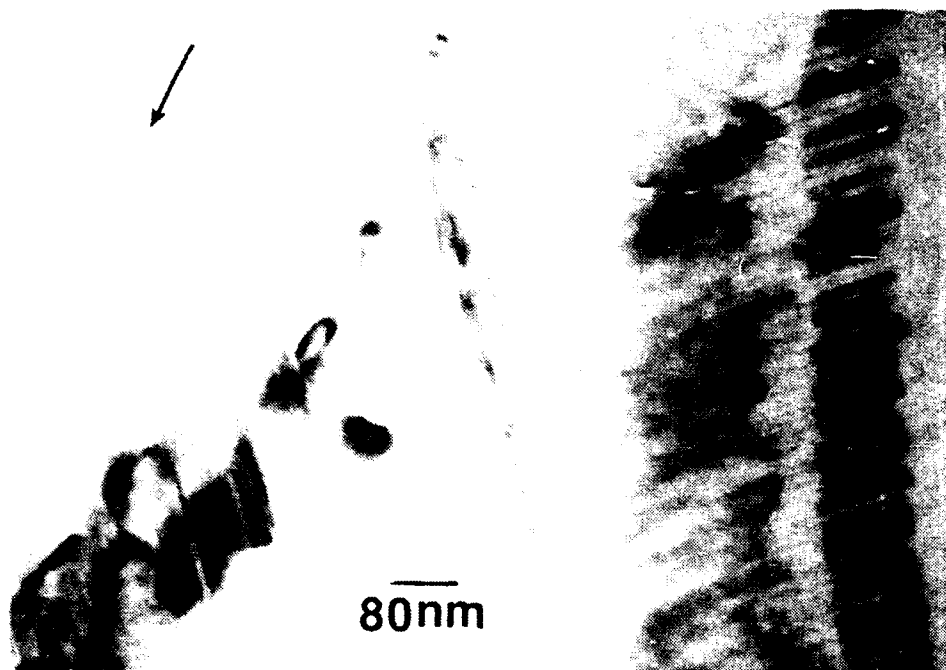


Figure 5. A wavy S'-Al₂CuMg sheet formed by precipitation on dislocation helix. The sample was aged for nine hours at 190°C.

DISCUSSION

A set of dislocation dissociation and precipitation reactions occur on dislocation lines in the Al-Li-Cu-Mg-Zr system. At shorter aging at a temperature of 190°C, the precipitation is heterogeneous. Upon annealing and quenching, dislocation climb by the absorption of vacancies produces dislocation helix configurations.¹³ This climb process involves the incorporation of vacancy loops which nucleate next to the line. The shape of the dislocation line¹⁴ depends on character, vacancy supersaturation, and solute concentration. In aluminum, the dislocations are undissociated of Burgers vector $a/2$ [110]. The Burgers vector is parallel to the axis of the helix in the case where the initial dislocation is of screw character.¹⁵ The vacancy absorption by dislocations has been found to take place in Al alloys and not in pure Al.

The vacancy supersaturation is higher in alloys due to the effective reduction in vacancy formation energy associated with solute-vacancy binding.³ In this Al-Li system, both the vacancy-Mg¹⁶ and vacancy-Li¹⁷ binding energies are significant. There is likely to be solute segregation on annealing and aging with the migration of vacancies and solute to dislocation lines. The enhanced vacancy concentration increases the atomic diffusivity and reaction rate.

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In the formation of a helix, the line tension forces of the dislocation balance the osmotic forces for an equilibrium configuration.¹³ The precipitation of S'-Al₂MgCu introduces pinning points along the line equal to the pitch of the helix which increase the line tension (see Figure 4). The disturbance of the equilibrium situation by the change in line tension may cause the dislocation to climb in the reverse direction emitting vacancies. The excess vacancies near the dislocation can stimulate precipitate growth near segregated regions.

The dislocation lines are severely altered by precipitation processes involving glide and climb. The first precipitation reaction on the lattice dislocation is the nucleation of T₁ - Al₂CuLi on the (111) plane inducing the glide reaction. T₁ has been thought to nucleate by a stacking fault mechanism.^{9,15} The Suzuki effect may contribute to the dissociation reaction in Al-Li-Cu-Mg-Zr by which the stacking fault energy decreases with segregation. The decrease in stacking fault energy in Al 16% Ag with respect to pure Al was attributed to the Suzuki effect.¹⁸ Next, along undissociated segments S'-Al₂MgCu nucleates and grows on the (210) plane at a 39° inclination to the glide plane. Contrast experiments show that there is a Shockley partial remaining on one side. Since the other dislocation moves out of the glide plane by a climb motion, it must be a Frank partial by the reactions $AB \rightarrow B\alpha + \alpha A$.¹³

Unusual reactions involving simultaneous dissociation and precipitation have been observed in other systems, such as CuAg,¹⁹ austenitic stainless steel,²⁰ and AlAg.¹⁸ In these cases, large stacking faults grow by vacancy emission from the precipitation reaction. The precipitate nucleates on one side of the stacking fault. The strain from the volume difference is the suggested driving force for vacancy emission. An intrinsic fault can be converted to an extrinsic by absorption of a vacancy row.¹³ There are two differences between S' precipitation and that in these systems. The CuAg and steel alloys are low stacking fault energy materials in which the dislocations are dissociated at the onset. There is also a large volume misfit in which the transformation strain is relieved by fault, whereas there is zero volume strain in S' precipitation.

The T₁ glide reaction on conjugate planes follows S'-Al₂MgCu precipitation (see Figure 2). The T₁ phase grows from the array of S' plates in {210} on a {111} plane. Since the inclined T₁ phases are spaced along the line, irregularities in the dislocation, such as kinks or jogs, may be the nucleation sites. A jog in a dissociated dislocation contains partial dislocations which may react or glide to form interfacial dislocations on these inclined T₁ phases. Another possibility is that an interfacial dislocation of S' expands in the formation T₁.

SUMMARY

T₁-Al₂CuLi, S'-Al₂CuMg, and δ'-Al₃Li phases nucleate on dislocations in Al-Li-Cu-Mg-Zr aged at 190°C. Dislocation orientation, character, and type of helical configuration influence the final precipitate structure.

The T₁-Al₂CuLi and S'-Al₂CuMg precipitation reactions induce the dissociation of the lattice dislocations. In the case of T₁, there is a glide reaction on (111), and in S', a climb reaction where segments dissociate into a configuration with a Shockley partial on one side.

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Transmission electron
microscopy (TEM)

Transmission electron microscopy was used to study precipitation processes on dislocation lines in Al-2.5Li-1.3Cu-0.7Mg-0.12Zr wt% aged at 190°C. Upon aging, a series of dislocation dissociation and precipitation reactions occur. The T_1 -Al₂CuLi phase nucleates on dislocations in the {111} glide planes inducing the lattice dislocation to dissociate. On the remaining dislocation segment, S'Al₂CuMg plates form causing the lattice dislocation to dissociate into a configuration with a Shockley partial on one side and a climbing partial on the other, such that S' plates are on the {210} plane. T₁ phases nucleate from the surface of S plates on conjugate {111} with an interfacial dislocation glide motion.