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Duan Mnatang[1], Zhong ziqiao[2]

Master of E.O. Paton Institute of Materials Science and Welding
National Technical University of Ukraine"Igor Sikorsky Kyiv Polytechnic Institute"[1]
Master of E.O. Paton Institute of Materials Science and Welding
National Technical University of Ukraine"Igor Sikorsky Kyiv Polytechnic Institute"[2]

STRENGTHENING AND TOUGHENING OF ALUMINUM ALLOYS

The paper focuses on the problem of traditional strengthening of aluminum alloys, such as the solid solution strengthening, second phase strengthening, grain refinement strengthening, and mechanical hardening. Composite reinforcement is the use of high-strength powder, wire, and sheet materials to undergo pressure, welding, spraying and solution dipping methods with the aluminum matrix composite, so that the matrix could obtain high strength. This article reveals the four traditional strengthening mechanisms of aluminum alloys, briefly introduces the mechanism of composite strengthening, and compares several strengthening modes. According to the shape of the composite material, composite reinforcement can be divided into fiber, particle and material wrapping one. Most of the traditional strengthening methods are to improve the strength of aluminum alloys by sacrificing plasticity and adding defects (mainly dislocations) in the crystal to impede the dislocation movement. This paper also briefly introduces the process of composite strengthening, which is different from the traditional strengthening methods which enhance the material characteristics by obstructing the movement of dislocations. The composite strengthening relies on good infiltration between the fiber and the matrix for a tight joint, so that the fiber and the matrix can obtain a good bond strength. Most of the traditional strengthening mechanisms increase the strength of the alloy at the expense of plasticity, which restricts the development of the comprehensive aspects of aluminum alloys. At present, the main methods of aluminum alloy strengthening are grain refinement and second phase strengthening. In particular, the second phase strengthening has a significant effect on the performance improvement of aluminum alloys. In the future development of aluminum alloys, it is not only necessary to improve the strength, but also to make comprehensive performance in all aspects better. Composite strengthening involves the advantages of each component, making up for their own drawbacks, and has a good development prospect.

Key words: *strengthening of aluminum alloys, traditional strengthening, composite strengthening, toughening.*

Дуань Маньтан, Чжун цзыцяо

УПРОЧНЕНИЕ И ЗАКАЛКА АЛЮМИНИЕВЫХ СПЛАВОВ

В статье описаны традиционные способы упрочнения алюминиевых сплавов: упрочнение твердым раствором, вторичной фазы, измельчением зерна и механическое упрочнение. Композитное упрочнение – это использование высокопрочных порошковых, проволочных и листовых материалов для обработки давлением, сваркой, распылением и методами погружения в раствор композита алюминиевой матрицы, благодаря чему матрица приобретает высокую прочность. В данной статье рассматриваются четыре традиционных механизма упрочнения алюминиевых сплавов в сравнительном аспекте, кратко представлен механизм композитного упрочнения. Зависимо от формы композитного материала, композитное упрочнение можно разделить на упрочнение волокнами, частицами и обертывание материалом. Большинство традиционных методов упрочнения направлены на повышение прочности алюминиевых сплавов путем потери пластичности и добавления дефектов (в основном дислокаций) в кристалл, чтобы затруднить движение дислокаций. В данной статье также кратко представлен механизм композитного упрочнения, которое отличается от традиционных методов, повышающих характеристики материала путем препятствования движению дислокаций. Композитное упрочнение основывается на хорошей инфильтрации между волокном и матрицей для тесного сцепления, так что волокно и матрица могут получить хорошую прочность связи. Большинство традиционных механизмов упрочнения повышают прочность сплава за счет пластичности, что ограничивает развитие комплексных аспектов алюминиевых сплавов. В настоящее время основными методами упрочнения алюминиевых сплавов являются измельчение зерна и упрочнение вторичной фазы. В частности, упрочнение вторичной фазы оказывает значительное влияние на улучшение эксплуатационных характеристик алюминиевых сплавов. В дальнейшем развитии алюминиевых сплавов необходимо не только улучшать прочность, но и решать вопрос по улучшению комплексных характеристик во всех аспектах. Композитное упрочнение сочетает в себе преимущества каждого компонента, компенсируя их собственные недостатки, и поэтому его дальнейшее изучение является перспективным.

Ключевые слова: *упрочнение алюминиевых сплавов, традиционное упрочнение, композитное упрочнение, закалка.*

Дуань Маньтан, Чжун цзицяо

ЗМІЦНЕННЯ І ЗАГАРТУВАННЯ АЛЮМІНІЄВИХ СПЛАВІВ

Анотація.У статті описані традиційні способи зміцнення алюмінієвих сплавів, такі як зміцнення твердим розчином, зміцнення вторинної фази, зміцнення подрібненням зерна та механічне зміцнення. Композитне зміцнення - це використання високоміцних порошкових, дротяних та листових матеріалів для обробки тиском, зварюванням, розпиленням і методами занурення в розчин композиту алюмінієвої матриці, завдяки чому матриця набуває високу міцність. У даній статті розглядаються чотири традиційних механізми зміцнення алюмінієвих сплавів у порівняльному аспекті, коротко представлений механізм композитного зміцнення. Відповідно до форми композитного матеріалу, композитне зміцнення можна розділити на зміцнення волокнами, частинками та

обгортання матеріалом. Більшість традиційних методів зміцнення спрямовані на підвищення міцності алюмінієвих сплавів шляхом зменшення пластичності та додавання дефектів (в основному дислокацій) в кристал, щоб утруднити рух дислокацій. У даній статті також коротко представлено механізм композитного зміцнення, яке відрізняється від традиційних методів, що підвищують характеристики матеріалу шляхом перешкоджання руху дислокацій. Композитне зміцнення ґрунтується на хорошій інфільтрації між волокном і матрицею для тісного зчеплення, так що волокно й матриця можуть отримати хорошу міцність зв'язку. Більшість традиційних механізмів зміцнення підвищують міцність сплаву за рахунок пластичності, що обмежує розвиток комплексних аспектів алюмінієвих сплавів. В даний час основними методами зміцнення алюмінієвих сплавів є подрібнення зерна та зміцнення вторинної фази. Зокрема, зміцнення вторинної фази значно впливає на поліпшення експлуатаційних характеристик алюмінієвих сплавів. В подальшому розвитку алюмінієвих сплавів необхідно не тільки покращувати міцність, але й вирішувати питання щодо поліпшення комплексних характеристик у всіх аспектах. Композитне зміцнення поєднує в собі переваги кожного компонента, компенсуючи їх власні недоліки, і тому його подальше вивчення видається перспективним.
Ключові слова: *зміцнення алюмінієвих сплавів, традиційне зміцнення, композитне зміцнення, загартування.*

Problem statement. It is well know that materials are the cornerstone of development for Human Civilization; from the Stone Age to the Bronze Age, the Iron Age, and now the New Material Age; every progress of human civilization is inseparable from the invention and use of new materials [1]. In recent years, with people's attention to environmental pollution and fuel economy issues, the designing of new metallic materials with light weight and good overall performance for gradually replacing steel parts, is the mainstream of energy conservation and fuel efficiency improvement in today's transportation field [2-4]. Among them, the light metal materials, which are represented by aluminum alloys, magnesium alloys and titanium alloys, are more and more widely used. Aluminum alloy is the most common light alloy material in our life and production activities. Compared with steel, the density of aluminum alloy is one third of that of steel, and the alloys not only have high specific strength, strong plasticity, good physical properties, and rich varieties, but they also have excellent electrical conductivity and corrosion resistance. Aluminum alloy has become an important material in the field of aerospace and transportation [4].

Analysis of research and publications. However, pure aluminum is soft and cannot be used in structural components, so aluminum alloys need to be strengthened in order to accomplish the requirements of structural components [5]. Theoretically, there are two ways to improve the strength of metals by technological means, the first being to completely eliminate dislocations and other defects within the metal so that its strength approaches its theoretical strength (it has been shown that the theoretical value of the yield strength of an intact crystal is more than a thousand times higher than the measured value). However, it is still quite difficult to do so. Another way is to introduce a large number of defects in the crystal to impede the movement of dislocations (it has been shown that the plastic deformation of metals is caused by the movement of dislocations) and to increase the strength of the metal. Examples include the solid solution strengthening, grain size reduction, second phase strengthening (precipitation strengthening, dispersion strengthening) and strain hardening [6-8]. It is worth noting that an effective combination of these strengthening methods can also approach the theoretical strength of the metal from another side [9]. The purpose of this work is to test and complement the results of the received theoretical provisions, discusses the four traditional strengthening mechanisms of aluminum alloys, and briefly introduces the mechanism of composite strengthening, and compares several strengthening mechanisms.

Results

1. Strengthening mechanism of aluminum alloy

1.1. Solid solution strengthening

At present, solid solution strengthening is one of the most widely used and most matured strengthening methods in the field of metallic materials. Normally, a small amount of other metals are added to the pure metal to form an alloy phase in which the solute atoms fuse into the solvent lattice while still maintaining the solvent type, which is called a solid solution. Solid solution strengthening is a kind of strengthening to form point defects; solute atoms are dissolved into the metal matrix to increase the dislocation density of the base metal and produce lattice distortion. The stress field generated by the distortion interacts with the elastic stress field around the dislocation, constituting an obstacle to dislocation slip and thereby increasing the stress required for plastic deformation i.e., the impurity atoms cause lattice strain which can "anchor" dislocations. Alloying elements, such as Mg, Mn and Cu can 'pin' dislocations, thereby strengthening the Al-based alloys. The solid solution strengthening effect depends on the concentration of solute atoms, the relative size of the atoms, the type of solid solution, and electronic factors. The greater the difference in the number of valence electrons between solute atoms and aluminum atoms, the greater the solid solution strengthening effect [6-8, 10].

1.2. Grain refinement strengthening

The microstructure of metallic materials is composed of a large number of grains stacked. The empirical relationship between yield stress and grain size for polycrystals was derived by Hall and Petch after extensive experiments in 1951[11].

$$\sigma = \sigma_0 + kd^{-\frac{1}{2}}$$

where: σ_0 is the frictional resistance to dislocation motion in the crystal, which is related to the material type; k is a constant to be obtained experimentally; and d represents the grain size.

It can be seen that when the grain size is reduced, the yield strength of the crystal increases dramatically due to the effect of the interaction of grain boundaries and dislocations. Fine grain strengthening is also one of the most common means of metal strengthening in industry, which can effectively improve the strength and plasticity of metals. Other strengthening mechanisms basically increase the strength while losing the plasticity of the alloy [6]. As shown in the Figure 1 below, there are several ways of grain refinement for aluminum alloys. Grain refinement mainly focuses on the use of grain refiners, stirring and vibration, rapid solidification, and super plastic deformation, etc. According to research, use of chemical grain refinement is an effective way to increase the strength of cast Al alloys [12].

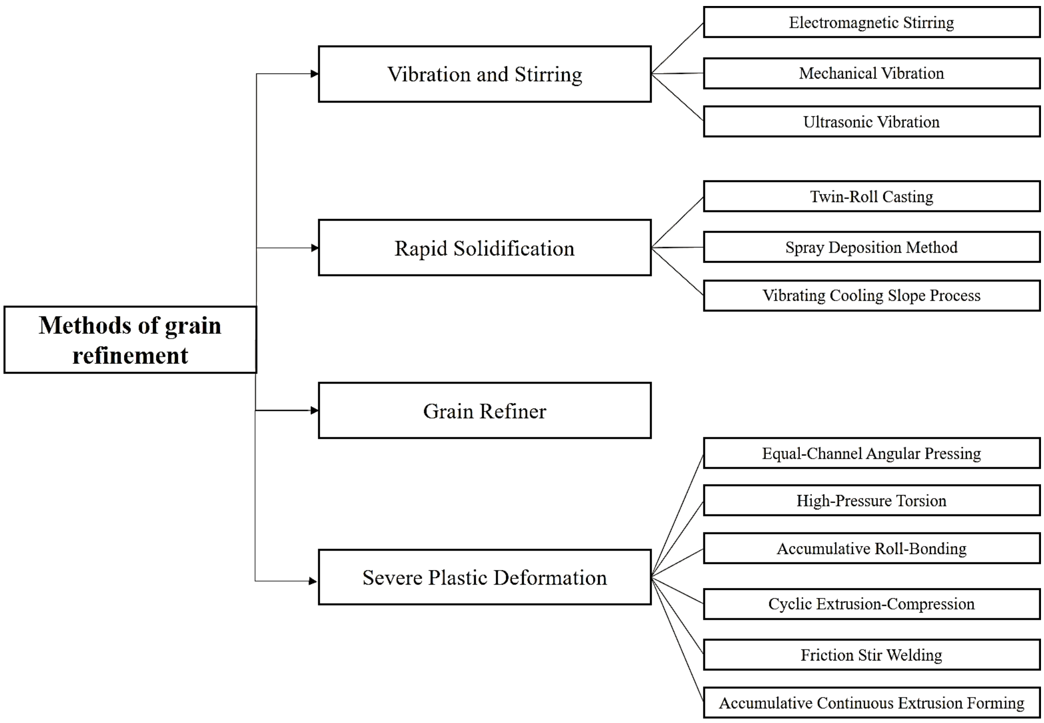


Fig. 1. **Methods of grain refinement**

1.3. Second phase strengthening

On a Friday in 1906, Alfred Wilm of Germany tried to strengthen the Al-Cu alloy by quenching, but after quenching the specimens were soft. However, after a weekend, they were measured again and found to be significantly stronger, but the exact strengthening method was not known. Later, with the development of modern experimental instruments, this mystery was first solved by Guinier and Preston in 1937 through their work on X-ray diffraction [13, 14]. The essence of age strengthening is that the dislocation movement is impeded by small, hard, diffusely distributed second-phase particles in the base metal, which are stronger than the individual solute atoms, and the dislocation movement must bypass or cut through these obstacles (particles), thus increasing the yield strength of the material [15].Table 1 below shows the second phase precipitation sequence of common aluminum alloy series. The precipitation of the second phase is a complicated process, and the precipitated substances change with time.

There are two common methods to introduce the second phase into the base metal; one is to use the precipitation of the supersaturated solid solution for precipitation strengthening by aging heat treatment, and the other is to introduce the second phase from outside the system by mechanical or chemical methods (such as sintering by adding the second phase powder, internal oxidation, etc.) called dispersion strengthening. Generally speaking, the larger the volume content of the precipitated phase and the greater the dispersion, the better the strengthening effect of the alloy[8].

Tabl.1.

Precipitation sequence of aluminum alloy

Series	Precipitation sequence	Strengthening phase
2XXX[16]	SSSS→solute clusters→GP zones→θ”→θ’→θ(Al_2Cu)	Al_2Cu
6XXX[17]	SSSS→atomic clusters→GP zones (pre β″)→β’→ β(Mg_2Si)	Mg_2Si
7XXX[18]	SSSS→VCR→GP Ⅱzones→intermediate structures→η’→η ($MgZn_2$)	$MgZn_2$
SSSS- supersaturated solid solution，VCR-vacancy-rich clusters，GP-Guinier-Preston		

1.4. Strain hardening

The essence of work hardening is the strengthening of the dislocation density of metal materials during the cold deformation process. According to statistics, after the metal is violently deformed, the dislocation density increases from 10^6 roots/cm² to more than 10^{12} roots/cm²[19]. Because of the higher density of dislocations in the alloy, there are more opportunities for dislocations to cross each other during the sliding process when the deformation continues, and the greater the mutual resistance, so the greater the deformation resistance and the alloy is strengthened. This strengthening is general When the strength of the material increases, the plasticity of the material will decrease. How to increase the strength of the material without reducing its plasticity, or increase the strength and plasticity of the material at the same time, is a research hotspot of this strengthening method. In addition, All aluminum alloys can be strengthened by work hardening[6, 20].

1.5. Composite Strengthening

In addition to the above-mentioned strengthening mechanisms, there are also composite reinforcements of aluminum alloys. Composite reinforcement is the use of high-strength powder, wire, and sheet materials to undergo pressure, welding, spraying and solution dipping methods with the aluminum matrix composite, so that the matrix to obtains high strength. According to the shape of the composite material, composite reinforcement can be divided into fiber reinforced, particle reinforced and wrapped material. The strengthening mechanism is different from the above four methods. It is not due to the obstruction of the dislocation movement, but by the good infiltration between the reinforcement material and the matrix material to obtain a good bond strength so giving full play to the advantages of each component material such that the entire composite material has a high strength and toughness. Composite reinforcement methods are mechanical composite methods (such as blasting composite, pressure processing composite), metallurgical methods (such as casting, spray deposition, self-propagation high-temperature synthesis) and chemical methods (such as gluing, surface coating). Composite reinforcement combines the advantages of each component to make up for their respective shortcomings, and has a very good development prospects[21, 22].

1.6. Comparison of strengthening mechanisms

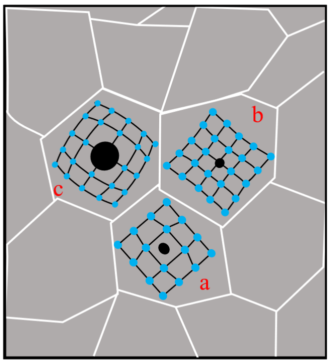
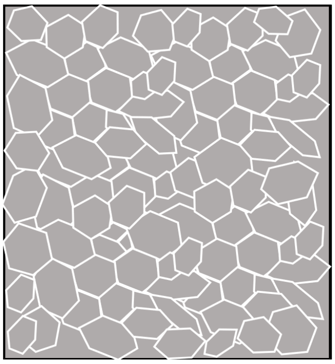
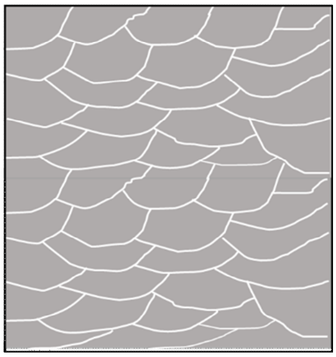
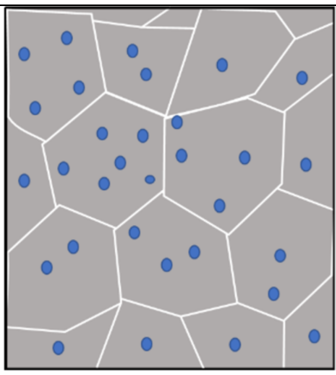
The above-mentioned strengthening and toughening mechanisms have certain applications in aluminum alloys, but the degree of strengthening is different. In the following table 2, the schematic diagrams of different strengthening methods and the comparison between strengthening methods are shown. The main dislocation barriers are solute atoms. The dislocation barriers for grain refinement are grain boundaries. The second phase strengthening dislocation barriers are precipitates. For work hardening, it mainly increases the dislocation density and strengthens the aluminum alloy. The second phase is the main method of strengthening the aluminum alloy, especially, grain refinement strengthens the aluminum alloy more obviously.

Conclusion

Most of the traditional strengthening mechanisms increase the strength of the alloy at the expense of plasticity, which restricts the development of the comprehensive aspects of aluminum alloys. At present, the main methods of aluminum alloy strengthening are grain refinement and second phase strengthening. In particular, the second phase strengthening has a significant effect on the performance improvement of aluminum alloys. The chemical grain refinement in grain refinement is compared with other fine grains. and the strengthening effect of chemical methods is more obvious. In the future development of aluminum alloys, it is not only necessary to improve the strength, but also to face the improvement of comprehensive performance in all aspects. Composite strengthening combines the advantages of each component, making up for their own shortcomings, and has a good development prospect.

Tabl.2.

Comparison of traditional reinforcement mechanisms in a tabular format

Mechanism (Dislocation barrier)	Schematic	Comparative description
Solid solution strengthening (Solute atoms) a-interstitial solid solution b,c-substitutional solid solution		Solid solution strengthening is limited by the degree of solid solution and the degree of supersaturation. When the alloy composition is certain, the solid solution degree is also certain, and the solid solution strengthening has no direct application value. The purpose of solid solution treatment (strengthening) is to prepare the structure for precipitation strengthening, and its strengthening effect is smaller than that of precipitation strengthening.
Grain refinement strengthening (Grain boundaries)		Fine grain strengthening is also a major means of strengthening high-strength aluminum alloys, and has a wide range of direct applications, and its strengthening effect can be described by the Hall-Petch relationship. Its effect on the strength and toughness of aluminum alloys is greater than that of solid solution strengthening and deformation strengthening.
Strain hardening (Other dislocations)		All aluminum alloys can be strengthened by deformation strengthening. Deformation strengthening is generally used to change the internal structure of the material through deformation. For heat-treatable aluminum alloys, strain hardening is the preparation of precipitation strengthening, and for non-heat treatment strengthened aluminum alloys, strain hardening causes stresses within the alloy, which need to be relieved by heat treatment at a later stage.
Second phase strengthening (Precipitates)		Second-phase strengthening is a major strengthening tool for high-strength aluminum alloys and has a wide range of direct applications. The strengthening effect is not only related to the characteristics, quantity, size, shape, and distribution of the second phase, but also related to the crystallographic matching between the second phase and the matrix, the interfacial energy, and interfacial bonding.

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