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Effect of Si and Mn on Microstructure and Mechanical Properties of Vacuum Suction Casting Al–4.5Cu Alloy

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Влияние Si и Mn на микроструктуру и механические свойства сплава Al–4,5Cu, полученного литьем методом вакуумного всасывания

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Высокая эффективность сплавов зависит от микроструктуры, при этом легирующие элементы оказывают значительное влияние на микроструктуру. В матрицу сплава Al–4,5Cu добавляли различное количество легирующих элементов Si и Mn для изучения их влияния на микроструктуру и механические свойства. Комбинированные сплавы отливали методом вакуумного всасывания. Микроструктуру комбинированных сплавов исследовали с помощью растрового электронного микроскопа. Механические свойства определяли при испытании на универсальной машине и посредством тестера микротвердости. Проанализированы экспериментальные результаты для сплавов с различным содержанием Si и Mn. Установлено, что с увеличением содержания Si и Mn появляется нерегулярная чешуйчатая структура. Твердый раствор с нерегулярной чешуйчатой слоистой структурой получен при содержании Si и Mn 3 вес.%. Максимальный предел прочности (205,87 МПа) таких сплавов получен при содержании Si и Mn 1 вес.%, относительное удлинение достигает 34,97%, микротвердость – 74,6 HV. При содержании Si и Mn 2 вес.% предел прочности является наименьшим (146,65 МПа), относительное удлинение составляет 24,15%, микротвердость – 60,2 HV. Относительное удлинение комбинированных сплавов уменьшается с увеличением содержания Si и Mn.

Ключевые слова: сплав Al–4,5Cu, микроструктура, Si–Mn, механические свойства, литье методом вакуумного всасывания.

Introduction. Al–4.5Cu alloy are widely used in many industry fields, such as the aerospace, automotive, aircraft, shipbuilding, construction, chemical industry and national defense, because of its low density, good plasticity, high specific strength, good corrosion resistance, good formability, good electrical conductivity and thermal conductivity, etc. The main strengthening phase of Al–Cu alloy is $CuAl_2$, which has strong time-hardening ability and thermal stability, so Al–Cu alloy has high temperature performance and high room temperature strength [1].

The casting performance of Al–4.5Cu is poor, because Al–Cu casting alloy is a solid solution type alloy. It has many characteristics, such as: a small amount of co-crystal, a wide range of crystallization temperature, dendrite developed resulting in poor fluidity of liquid alloy and the shrinkage than Al–Si alloy to large from liquid to solid. So, it makes thermal cracking, shrinkage, segregation and other defects [2, 3]. However, these drawbacks can be improved by adding some alloying elements [4].

Many studies have shown that silicon is the most important single alloying element, which is always used in the aluminum cast alloys to improve the casting properties of Al–Si alloys by increasing the fluidity and reducing solidification shrinkage [5, 6]. Meanwhile, the performance of casting alloy is sensitive to the content of Mn, which always is under the control of 1.0~1.6 wt.% [7]. In commercial Al–Cu–Si–Mn–X (X represents other elements) alloys, Mg2Si, Al5FeSi, α-AlFeMnSi, AlCuMgSi, and CuAl2 are the second phase, which have influence on the microstructure and mechanical properties [8]. Furthermore, the content of Mn has the largest effect on the transformation rate of Al5FeSi to α-AlFeMnSi [9, 10].

The traditional casting process of Al-based alloys containing Si and Mn is simple and practicable. However, thermodynamic optimizations have been performed for the Si–Mn binary system. As for the Si–Mn system, all the available descriptions had certain disadvantages [11, 12]. Aluminum-copper alloy with the addition of Cu element has a good mechanical properties and room and high temperature performance. When the Cu content is 4.0~6.0 wt.%, the tensile strength of the alloy reaches its maximum, so Al–Cu alloy mechanical properties higher [13].

The vacuum suction casting (VSC) is a popular technology process. It is beneficial to improve mechanical properties, because of its fast melting and smooth filling, less casting porosity and slag, and cooling in the copper mold, resulting in the small and uniform grain structure [14]. Therefore, the VSC method in this article is used to prepare Al–Cu–Si–Mn quaternary alloy.

The aim of this work is to study the effect of alloying elements Si and Mn on microstructure and properties of Al–4.5Cu alloy. Firstly, compounded alloy (CA) is prepared using VSC method by changing the contents of alloying elements Si and Mn. Secondly, microstructure is investigated by SEM. And, mechanical properties of CA are compared using experimental results. Finally, analysis and discussion are carried out to make some conclusions.

1. **Experimental Procedure**.

1.1. ***Vacuum Suction Casting***. CA castings were conducted by high-vacuum arc melting and suction-casting based on Al–4.5Cu alloy. The high-vacuum melting and suction-casting equipment is used in this experiment, shown in Fig. 1. The arc gun is cerium-tungsten rod, which is attached to water-cooled copper electrode. The furnace is filled with high-purity inert gas to avoid oxidation reaction.

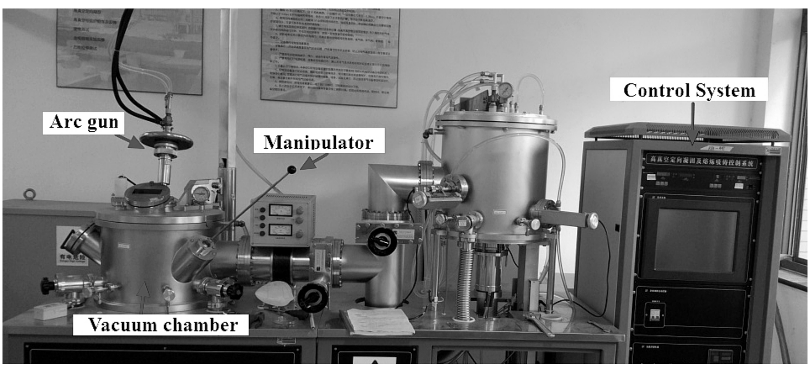

Fig. 1. Experimental equipment of vacuum suction casting.

The procedure of CA castings was divided into four steps. The first step is to weigh 0.9 g high-purity Cu and 0.9 g high-purity Al, and melt in furnace. Secondly, different content of Si and Mn were weighed and added into Al–Cu alloy. Detailed percentages of different alloying elements within CA are listed in Table 1. Thirdly, CA with different mass fraction of Al–Cu–Si–Mn was melted and fully mixed in a high-vacuum arc melting furnace. Finally, CA was sucked into the graphite nozzle with the hole diameter about 2.5 mm under the protection of argon gas, and casted into copper mold. It was cooled in vacuum to obtain a homogeneous CA bar. The alloy rod is divided into a small cylinder, whose height is about 15 mm, to study the effect of Si and Mn on the properties of Al–4.5Cu alloy.

T a b l e 1

Chemical Compositions of Alloys Studied (mass fraction %)

Samples	Cu	Si	Mn	Al
Al–4.5Cu	4.5	–	–	Bal.
Al–4.5Cu–1Si	4.5	1.0	–	Bal.
Al–4.5Cu–1(Si–Mn)	4.5	1.0	1.0	Bal.
Al–4.5Cu–2(Si–Mn)	4.5	2.0	2.0	Bal.
Al–4.5Cu–3(Si–Mn)	4.5	3.0	3.0	Bal.

1.2. ***Microstructure Investigation***. The observed specimens were prepared as small square pads by cutting from CA bar of VSC for the sake of microstructure investigation. The thickness of small square pads is 5 mm, and the length of side is 8 mm. The observed specimens were polished to reveal the CA microstructure. The microstructure of CA was observed by Hitachi SU8070 SEM.

1.3. ***Mechanical Properties Tests***. Two tests, microhardness test and tensile test, need to be conducted to evaluate the mechanical properties of CA. Microhardness test is used to measure microhardness of CA. The test specimens are consistent with the observed specimens. And, tensile test is used to measure the stress-strain relationship, i.e., tensile strength.

1.3.1. *Microhardness Test*. Microhardness of CA is measured by the following test. The test specimens were prepared as cylinders with the length of 12 mm and diameter of 10 mm using wire-cut electrical discharge machine. Then the test samples were polished, and put into an ultrasonic cleaner to clean with alcohol, then dried by a blower. The MHVD-1000IS image analysis multifunctional digital microhardness tester was used to measure the microhardness of specimen. Figure 2 shows the distribution of the force on the specimen. Four angular symmetrical heads were used to measure the HV. The maximum load of 200 N was applied with 3 s. And, seven consecutive points within specimens were selected to measure the microhardness, their average value was recorded as final value of microhardness.

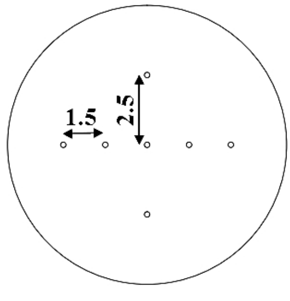

Fig. 2. Distribution of the force on the specimen.

1.3.2. *Tensile Test*. Tensile test was conducted on a JVJ-50s microcomputer controlled electronic universal testing machine. Stress-strain curves were measured at a tensile speed of 3 mm/min and room temperature during tensile test. Tensile tests were controlled by computer. Strains were measured by extensometer. The tensile test is automatically stretched by the universal drawing instrument. The global strains have been corrected taking into account the machine stiffness. Tensile specimens were stretched with three times to failure under the same tensile condition. And, the average value of the tensile test results was selected as the final experimental data.

Tensile test specimens were prepared as "dog bone" sheet by cutting from CA bars along the longitudinal direction using wire-electrode cutting. The shape and dimension of tensile test specimens is shown in Figs. 3 and 4. As shown in Fig. 3, the original gauge length of the tensile specimen is 13 mm, the width is 3.5 mm, and the thickness is 1.4 mm. And then, the tensile test specimens were polished on the abrasive paper to remove the cutting marks completely to prevent stress concentration and cracks formation during the tensile test.

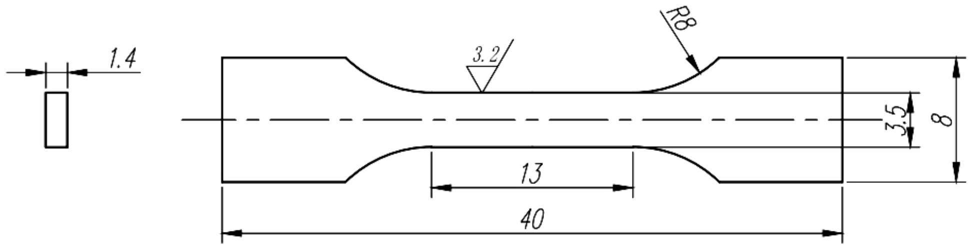

Fig. 3. The shape and dimensions of tensile specimens.

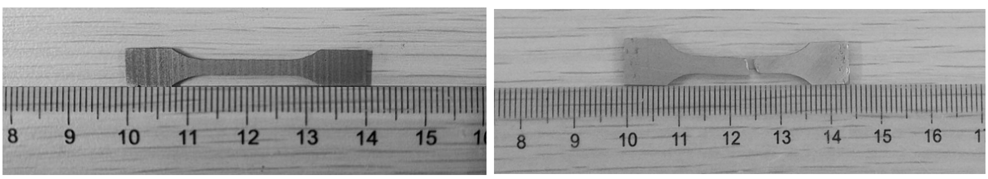

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Fig. 4. Tensile specimens: (a) before the tensile test, (b) after the tensile test.

2. **Results and Discussion**.

2.1. ***Effect of Both Si and Mn on Microstructure of CA***. Figure 5 shows the microstructures of CA with different content of Si and Mn alloy elements. It can be seen from Fig. 5. that α-Al phase matrix and solid solution change with the increases of Si and Mn alloy element. As shown in Fig. 5a, a small amount of Si and Mn elements make the grain structure of CA refinement. The structures of CA are arranged closely and cross-fused to each other. A small amount of small-size solid solution is found in the Fig. 5. Solid solution as the second phase has a certain impact on the performance of CA. That is because that although Si and Mn alloy elements can optimize the properties for the castings; Si and Mn are also known as an impurity for aluminum-copper alloys.

As shown in Fig. 5b, the structure of CA exhibits irregular sheet lamination and distributs unevenly. The grain boundary voids is too large. The grain size in Fig. 5b is obviously larger than Fig. 5a. There are inclusions and lamellar structures in Fig. 5b. The sheet-like lamellar structure is an impurity ternary phase formed by Si and Mn, and produces some large-sized inclusions. They are not conducive to improve the performance of CA, and reduce the tensile stress and microhardness.

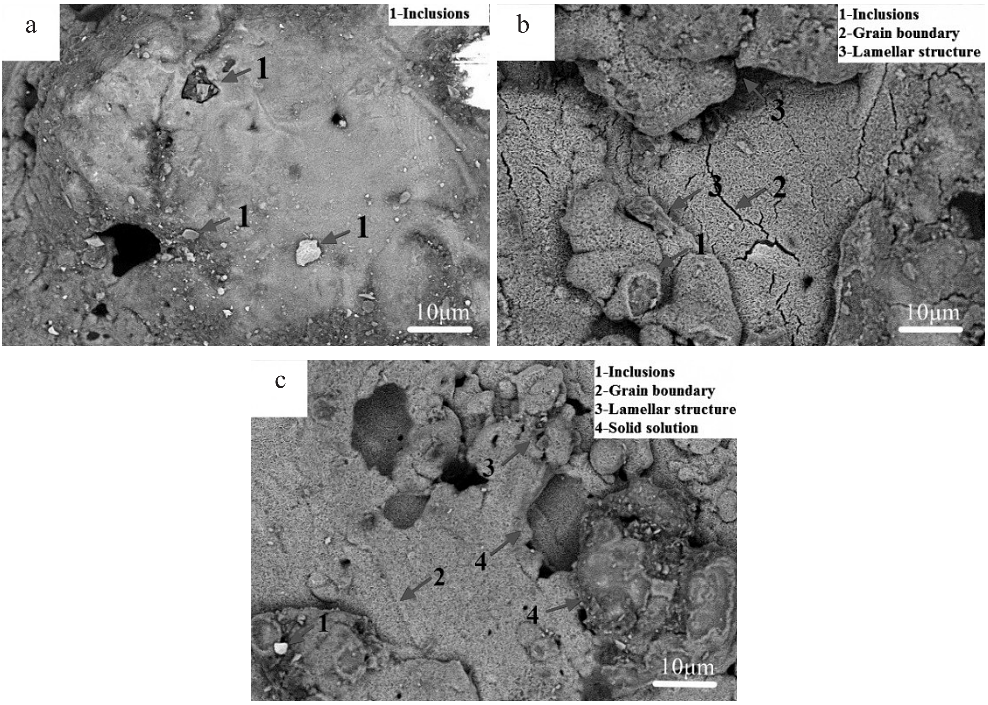

Fig. 5. Microstructures of Al–4.5Cu–1(Si–Mn) (a), Al–4.5Cu–2(Si–Mn) (b), and Al–4.5Cu–3(Si–Mn) (c) alloys.

As shown in Fig. 5c, with the increase of Si and Mn content, Si and Mn in the aluminum-copper alloy are supersaturated and partially solid solution, resulting in solid solution strengthening. Part of the emergence of a wide range of compound structure, resulting in a better refinement effect, increased tensile stress. But the large size inclusions in the tissue and the elongated grain boundaries make the tensile stress of high Si and Mn content reduced.

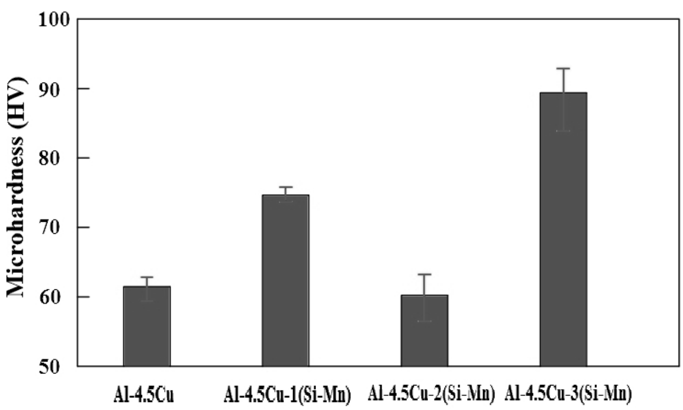

Fig. 6. Effect of both Si and Mn on microhardness of CA.

2.2. ***Effect of Both Si and Mn on the Microhardness of CA***. Figure 6 shows effect of both Si and Mn on microhardness of CA. As shown in Fig. 6, the microhardness variation trend with content of Si and Mn is the same as the tensile stress for CA. The microhardness reaches 74.6 HV when the Si and Mn are both 1 wt.%. As shown in Fig. 6, with the increase of Si and Mn content from 1 to 2 wt.%, the microhardness of CA decreases from 74.6 to 60.2 HV, i.e., decreases about 28.8%. As shown in Fig. 6, when the content of Si and Mn was 2 wt.%, the microhardness reached the lowest point 60.2 HV. Compared with A1–4.5Cu–1(Si–Mn), Al–4.5Cu–2(Si–Mn) decreases about 18.8%. When content of Si and Mn are 3 wt.%, the microhardness reaches 89.4 HV, which increases by 48.4% compared with Al–4.5Cu–2(Si–Mn).

2.3. ***Effect of Both Si and Mn on the Tensile Properties of CA***. Figure 7 shows effect of both Si and Mn on tensile stress and elongation of CA. The maximum force-strain relationship of different content Si and Mn alloys are plotted in Fig. 7a. The ultimate tensile stress and elongation of different content Si and Mn alloys are plotted in Fig. 7b. Table 2 shows mechanical properties of CA. Al–4.5Cu–1(Si–Mn) alloy with the addition of 1 wt.% Si and 1 wt.% Mn has obviously higher ultimate tensile stress than Al–4.5Cu alloy. Its ultimate tensile stress reaches 205.87 MPa. It was found that the elongation has been declining with content of Si and Mn increased. Al–4.5Cu alloy has obviously higher elongation than others. Its elongation reaches 41.66%.

T a b l e 2

Mechanical Properties of CA

Samples	Stress (MPa)	Elongation (%)	Hardness (HV)
Al–4.5Cu	173.182	41.657	61.5 ± 1.4
Al–4.5Cu–1(Si–Mn)	205.867	34.966	74.6 ± 4.6
Al–4.5Cu–2(Si–Mn)	146.654	24.146	60.2 ± 0.2
Al–4.5Cu–3(Si–Mn)	169.970	18.963	89.4 ± 9.3

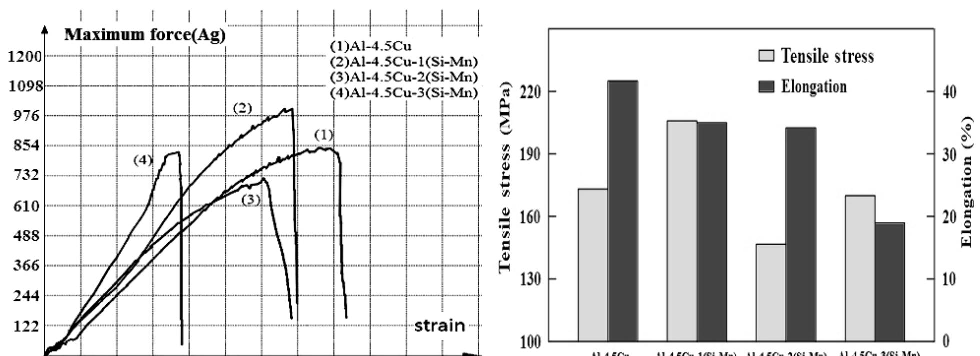

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Fig. 7. Effect of both Si and Mn on maximum force-strain curves (a) and ultimate tensile stress and elongation of CA (b).

Comparison of michenical properties is conducted between A1–4.5Cu–1(Si–Mn) and Al–4.5Cu in Figs. 6 and 7. It shows that a small amount of Si and Mn elements can enhance the tensile strength and microhardness of Al–4.5Cu alloys. Because a small amount of Si and Mn elements have the role of grain refinement. The finer grain structure, the more number of grains are in a certain volume. The effect of grain refinement strengthening is obvious. The tensile stress of A1–4.5Cu–1(Si–Mn) increases about 18.5% and the micro-hardness increases about 21.5%. Meanwhile, alloy elongation decreases. The elongation decreases about 14.6%. Therefore, adding a small amount of Si and Mn elements will help to improve the mechanical properties of Al–4.5Cu alloys.

The Si and Mn elements are apt to form the Al10Mn2Si and Al6Mn in the aluminum-copper alloy. Wherein, Al6Mn is formed in the form of fine flaky needle-like by the peritectic reaction at 983 K [15]. At room temperature, the main second phase of alloy Al6Mn also can improve the performance.

As shown in Fig. 7, with the increase of Si and Mn content from 1 to 2 wt.%, the ultimate tensile stress of CA decreases from 205.87 to 156.65 MPa, i.e., decreases about 28.8%, but the elongation keep constant. As shown in Fig. 6, when the content of Si and Mn is 2 wt.%, the microhardness reaches the lowest point 60.2 HV. Compared with A1–4.5Cu–1(Si–Mn), A1–4.5Cu–2(Si–Mn) decreases about 18.8%. Research has shown that Al and Mn form fine dispersed Al6Mn particles to promote the formation of subgrain boundaries and retard the grain growth. But Si and Mn also can form an impurity ternary phase T(Al12Mn3Si2), which weaken the tension strength and microhardness [16].

When content of Si and Mn are 3 wt.%, the ultimate tensile stress of CA reaches 169.97 MPa. And, microhardness reaches 89.4 HV, which increases by 48.4% compared with Al–4.5Cu–2(Si–Mn). With the increase of Si and Mn content from 0 to 3 wt.%, Al–4.5Cu–3(Si–Mn) alloy internal grain refinement. Si and Mn dissolve supersaturation, resulting in solid solution strengthening. At the same time, irregular sheet-like stacks are reduced. Therefore, its microhardness reaches the highest value. However, the increasing rate of ultimate tensile stress is lower than Al–4.5Cu–1(Si–Mn).

2.4. ***Effect of Si or Mn on the Mechanical Properties of CA***. The experimental results from Figs. 6 and 7 show that the comprehensive mechanical properties of Al–4.5Cu–1(Si–Mn) alloy are the best. The addition of Mn is advantageous for the ductility of the cast Al–Cu alloy. However, if Mn is added above a certain level, the primary coarse Al20Cu2Mn3 phase will form during casting. And, Al20Cu2Mn3 does not dissolve into the α-Al matrix in the solution, adversely affecting the ductility of the Al–4.5Cu alloy [17]. On the other hand, the Al20Cu2Mn3 dispersion formed in the solution will inevitably consume some of the Cu element, resulting in lower tensile properties due to reduced precipitation hardening [18]. Therefore, Al–4.5Cu–1Mn is not considered in this experiment. Figure 8 shows effect of Si on tensile stress and elongation of CA. Table 3 shows mechanical properties of CA containing 1 wt.% Si and without Si. It can be seen from Fig. 8 that a small amount of Si element is conducive to enhance the tensile properties of CA. Al–4.5Cu–1Si alloy with the addition of 1 wt.% Si has obviously higher ultimate tensile stress than Al–4.5Cu alloy. Its ultimate tensile stress reaches 194.2 MPa. The ultimate tensile stress increases about 12.1% and the elongation reaches 46.79%. And, two small amounts of Si and Mn are also more conducive to enhance the tensile properties of CA. It can be found that the tensile stress of Al–4.5Cu–1(Si–Mn) is the highest. Al–4.5Cu–1(Si–Mn) alloy with the addition of 1 wt.% Si and 1 wt.% Mn has obviously higher ultimate tensile stress than Al–4.5Cu–1Si alloy. Its ultimate tensile stress reaches 205.87 MPa and the elongation reaches 34.97%. And, tensile stress of Al–4.5Cu without any Si and Mn is the lowest.

Table 3

Mechanical Properties of CA Containing 1 wt.% Si and without Si

Samples	Stress (MPa)	Elongation (%)	Hardness (HV)
Al–4.5Cu	173.182	41.657	61.5
Al–4.5Cu–1Si	194.202	46.789	75.0 ± 4.9
Al–4.5Cu–1(Si–Mn)	205.867	34.966	74.6

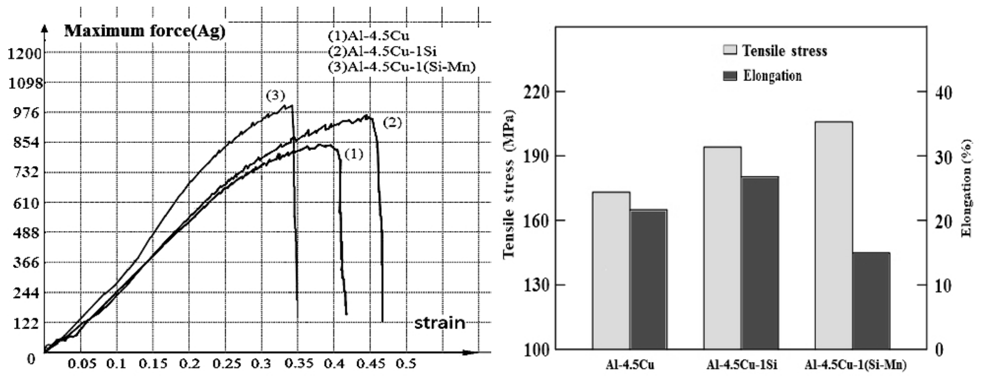

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Fig. 8. Effect of Si or Mn on maximum force–strain curves (a) and ultimate tensile stress and elongation of CA (b).

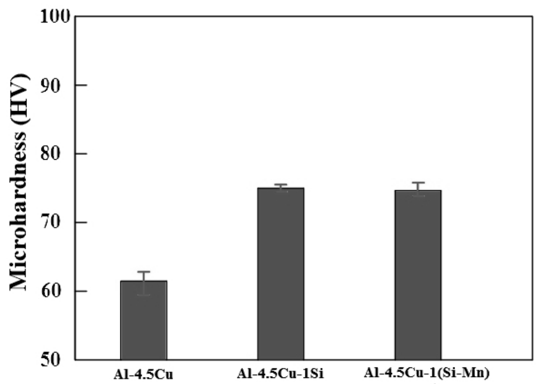

Fig. 9. Effect of Si or Mn on the microhardness of CA.

Figure 9 shows effect of Si or Mn on the microhardness of CA. It can be seen from Fig. 9 that a small amount of Si or Mn elements can enhance the microhardness of CA. A small amount of Si and Mn make the grain boundary clear, small, and the grain becomes smaller, the size tends to be uniform, which is conducive to enhance the mechanical properties of the alloy. The microhardness reaches 75 HV when the Si is 1 wt.% of CA. The microhardness increases about 22.0%. The microhardness reaches 74.6 HV when the Si and Mn are both 1 wt.%. Meanwhile, alloy elongation decreases. But the tensile stress increases about 6.0%, while the microhardness decreases about 33.8%. As shown in Fig. 9, the microhardness increasing trend of CA is the same as the tensile stress increasing trend, shown in Fig. 8.

Conclusions

1. With the increase of Si and Mn content, the irregular lamellar structure of CA appears, and finally the solid solution is coexisted with the irregular lamellar laminated structure.

2. When both Si and Mn are not added into CA during casting, the elongation of Al–4.5Cu is the highest, reaching 41.66%. When both Si and Mn are 1 wt.% in CA, the tensile stress of CA is the highest, reaching 205.87 MPa. When both Si and Mn are 2 wt.%

in CA, the tensile stress of CA is the lowest, reaching 146.65 MPa. The microhardness of CA is the lowest, reaching 60.2 HV. When both Si and Mn are 3 wt.% in CA, the elongation of CA is the lowest, reaching 18.96%. And, the microhardness of CA is the highest, reaching 89.4 HV.

3. Adding 1 wt.% Si in the Al–4.5Cu alloy, it is beneficial to enhance the mechanical properties of CA. The tensile stress of CA reaches 194.2 MPa. And, its' elongation of CA is the highest, reaching 46.79%. The microhardness of CA is the highest, reaching 75.0 HV. Meanwhile, adding 1 wt.% both Si and Mn in the Al–4.5Cu alloy, it is also beneficial to enhance the tensile stress of CA.

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Р е з ю м е

Висока ефективність сплавів залежить від мікроструктури, при цьому легуючі елементи значно впливають на мікроструктуру. У матрицю сплава Al–4,5 Cu додавали різну кількість легуючих елементів Si і Mn для вивчення їх впливу на мікроструктуру і механічні властивості. Комбіновані сплави відливали методом вакуумного всомктування. Мікроструктуру комбінованих сплавів досліджували за допомогою растрового електронного мікроскопа. Механічні властивості визначали при випробуваннях на універсальній машині та за допомогою тестера мікротвердості. Проаналізовано експериментальні результати для сплавів із різним вмістом Si і Mn. Установлено, що зі збільшенням вмісту Si і Mn має місце нерегулярна лускоподібна структура. Твердий розчин із нерегулярною лускоподібною шаруватою структурою отримано при вмісті Si і Mn 3 ваг.%. Максимальну границю міцності (205,87 МПа) таких сплавів отримано при вмісті Si і Mn 1 ваг.%, відносне подовження сягає 34,97%, мікротвердість – 74,6 HV. При вмісті Si і Mn 2 ваг.% границя міцності є найменшою (146,65 МПа), відносне подовження сягає 24,15%, мікротвердість – 60,2 HV. Відносне подовження комбінованих сплавів зменшується зі збільшенням вмісту Si і Mn.

1. S. K. Xie, R. X. Yi, Q. Huang, et al., "Effects of rare earth Ce on fluidity and hot tearing trend of Al4.5Cu alloy," *Nonferr. Met.*, No. 6, 007 (2011).
2. L. A. Dobrzański, R. Maniara, M. Krupiński, and J. H. Sokowski, "Microstructure and mechanical properties of AC AiSi9CuX alloys," *J. Achiev. Mater. Manuf. Eng.*, **24**, No. 2, 51–54 (2007).
3. G. Mrówka-Nowotnik, J. Sieniawski, and M. Wierzbińska, "Analysis of intermetallic particles in AiSi1MgMn aluminium alloy," *J. Achiev. Mater. Manuf. Eng.*, **20**, Nos. 1–2, 155–158 (2007).
4. M. Wierzbińska and J. Sieniawski, "Effect of morphology of eutectic silicon crystals on mechanical properties and cleavage fracture toughness of AlSi5Cu1 alloy," *J. Achiev. Mater. Manuf. Eng.*, **14**, Nos. 1–2, 31–36 (2006).
5. S. O. Adeosun, S. A. Balogun, L. O. Osoba, et al., "Effect of Cu and Zn addition on the mechanical properties of structural aluminum alloy," *J. Modern Manuf. Technol.*, **3**, No. 1, 103–110 (2011).
6. H.-F. Huang, "The influence of pure rare earths Ce on the castability of Al-4.5%Cu," *Mech. Eng.*, No. 6, 35–36 (2004).

7. M. Zhao and B. Liu, "Friction and wear behavior of aluminum manganese alloy and its composites," *Spec. Cast. Nonferr. Alloy.*, **31**, No. 12, 1148–1150 (2011).
8. J. E. Janse, L. Zhuang, J. Mooi, and P. De Smet, "Evaluation of the effect of Cu on the paint bake response of preaged AA6xxx," *Mater. Sci. Forum*, **396–402**, No. 2, 607–612 (2002).
9. W. F. Miao and D. E. Laughlin, "Effects of Cu content and preaging on precipitation characteristics in aluminum alloy 6022," *Metall. Mater. Trans. A*, **31**, No. 2, 361–371 (2000).
10. Y. Wu, J. Xiong, R. Lai, et al., "The microstructure evolution of an Al–Mg–Si–Mn–Cu–Ce alloy during homogenization," *J. Alloy. Compd.*, **475**, Nos. 1–2, 332–338 (2009).
11. A. Allam, P. Boulet, C. A. Nunes, et al., "Phase transformations in higher manganese silicides," *J. Alloy. Compd.*, **551**, 30–36 (2013).
12. A. Berche, E. Ruiz-Théron, J. C. Tedenac, et al., "Thermodynamic description of the Mn–Si system: an experimental and theoretical work," *J. Alloy. Compd.*, **615**, 693–702 (2014).
13. S. K. Xie, X. Q. Zheng, R. X. Yi, et al., "Analysis on microstructure of AlSi7Cu5 alloy by slope near-liquidus method," *Key Eng. Mater.*, **419–420**, 517–520 (2010).
14. B. Aremo and M. O. Adeoye, "A low-cost vacuum casting equipment for aluminium alloys," *Russ. J. Non-Ferr. Met.*, **51**, No. 2, 124–130 (2010).
15. D. T. L. Alexander and A. L. Greer, "Solid-state intermetallic phase tranformations in 3XXX aluminium alloys," *Acta Mater.*, **50**, No. 10, 2571–2583 (2002).
16. L. Niu-Can, L. Jun-Qing, Y. Ming-Sheng, "Influence of Re and Mn additions on Fe-containing phase in Al-Si alloys," *Foundry Technol.*, No. 11, 014 (2011).
17. L. F. Mondolfo, "Aluminum alloys: structure and properties," *Metal Sci.*, **35**, No. 11, 408 (1976).
18. A. Chen, L. Zhang, G. Wu, et al., "Influences of Mn content on the microstructures and mechanical properties of cast Al-3Li-2Cu-0.2 Zr alloy," *J. Alloy. Compd*., **715**, 421–431 (2017).

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