Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Engineering applications and research progress on mechanical properties of cast aluminium alloy for spatial structures

Huan Lu*, Yuanqing Wang, Xinhang Zhi, Beibei Li[a], Shuai Mo[b]

*School of Civil Engineering, Tsinghua University
Tsinghua University, Beijing, 100084, China
lu-h23@tsinghua.edu.cn

[a] School of Civil Engineering, Hefei university of Technology, Anhui Province, 230009, China
[b] School of Mechanical Engineering, Guangxi university, Guangxi Province, 530004, China

Abstract
Design of joints were asked to meet higher demands with the development of long-span spatial structures. Cast aluminium alloy joints are found to have broad application prospects in the field of civil engineering as it owns the advantages of flexible design, wide application range, and excellent mechanical properties, which also raises new demands for cast aluminium alloys. This paper introduces the cast aluminium alloy materials, and its applications in engineering, and summarizes the research status of mechanical properties of cast aluminium alloys and cast aluminium alloy joints. At present, there are few applications of cast aluminium alloys in civil engineering, and researches mostly focused on the microstructure level of materials, lacking experimental research and analysis related to the engineering structures. Besides, the researches regarding to cast aluminium joints remain in lack. This paper also presents test results of the mechanical properties of one type of the cast aluminium alloy. The results of this paper can help promote the application of cast aluminum alloys in the field of civil engineering.

Keywords: cast aluminium alloy, engineering application, mechanical properties, research progress.

1. Introduction
Aluminium alloys have been widely used in structural engineering field due to their excellent material properties [1,2,3]. With the development of long-span spatial structures, joint connection was supposed to achieve higher requirements. The strength of aluminum alloy is greatly affected by the welding, a reduction up to 70% of strength will be reached in the heat affected zone [4,5]. Mechanical connecting was commonly used and investigated for joint connection, including connections with rivets, screws or bolts [6]. However, larger span and more diversified structural forms may have adverse effect on the flexible structural design, construction and simulation of mechanical behaviour, while using mechanical connections.

Recently, cast aluminium alloys were developed and used in practical engineering. One obvious application for such new material is in thin-walled or complex components. By adopting integral casting in factories and getting impurity content well controlled, cast aluminium components own excellent ductility and tenacity [7]. This may also result in superior behaviour and broad application prospect in structural engineering, especially for structural connections. However, limited applications of such material were put into structural engineering due to insufficient studies [7,8,9] on the related mechanical properties and the lack of summarized research.

This study presents the current engineering applications of cast aluminium alloy with an introduction of such material. The mechanical property of cast aluminium joint and such materia is reviewed to provide reference for the follow-up theoretical research and engineering application. In addition, test results of mechanical properties of a type of cast aluminium alloy were reported.

2. Introduction of cast aluminium alloy

According to the different alloying elements added, cast aluminium alloys can be divided into six major categories: Al-Si series, A1-Si-Cu series, Al-Mg series, A1-Si-Mgseries, A1-Si-Cu-Mg series and Al-Zn series [10]. The Al-Si series cast aluminium alloys were widely used in the manufacturing industry due to its excellent flowability, castability, corrosion resistance and small shrinkage after cooling [11]. The major constituents and mechanical properties of several types of the commonly used cast aluminum alloys were summarized in Table 1. The advantages and disadvantages of different series of cast aluminium alloys were summarized in Table 2. It should be noted that additions of different elements resulted in varied mechanical properties: the addition of Si element and Fe element benefits fluidity and demolding of the castings, respectively. The addition of Mg element helps to enhance corrosion resistance, while adding Cu element improves mechanical strength but may negatively affect corrosion resistance.

Table 1: Major constituents and mechanical properties of commonly used cast aluminium alloys

Series of cast aluminium alloys	Types specified in current specifications			Major constituents	Mechanical properties	
	Chinese standard	American standard	Japanese standard		Tensile strength σ/MPa≥	Elongation δ(%)≥
Al-Si series	ZL114A	A357	ACDC	AlSi7Mg	290	2.0
	YL101	A360	ADC3	AlSi10Mg (Fe)	220	2.0
	YL102	A413	ADC2	AlSi12 (Fe)	279	2.7
Al-Si-Cu series	YL112	A380	ADC10	AlSi9Cu3 (Fe)	320	3.5
	YL113	A383	ADC12	AlSi11Cu3	230	1.0
	YL117	B390	ADC14	AlSi17Cu5Mg	220	1.0
Al-Mg series	YL302	518	ADC5	AlMg5Si1	220	2.0

Table 2: Advantages and disadvantages of different series of cast aluminium alloys

Series of cast aluminium	Advantages	Disadvantages
Al-Si series	High corrosion resistance and thermal conductivity, smaller tendency of producing thermal cracking and shrinkage defects [12][13]	Poor machinability and relatively low ductility [12][13]
Al-Si-Cu series	High creep resistance, mechanical strength and hardness, excellent castability and machinability. [14][15]	Strong tendency of producing thermal cracking [16]
Al-Mg series	High corrosion resistance and surface quality, good ductility [17]	Poor castability, obvious fluctuations of mechanically properties, easy for thermal cracking or stress corrosion [18]

3 Applications of cast aluminium alloy in engineering field

3.1. Applications in aerospace engineering

In aerospace engineering, cast aluminium alloys were widely used in aircraft due to their high strength and light weight, being beneficial for design and manufacture [19]. Compared with steels, high corrosion resistance of cast aluminium alloy helps to decrease the maintenance costs. For those structural components, shells or corresponding accessories, which have complex structural design or high requirements of gas tightness, complicated splicing design has become the common solution for traditional aluminium alloys. However, integrated design and more convenient manufacturing can be achieved by applying cast aluminium alloys, thus promoting the long-term efficiency of structures. The major applications of cast aluminium alloy in aircraft were summarized in Table 3 [20,21,22].

Table 3: Applications of cast aluminum alloy in the main components of aircraft [20,21,22]

Types of the cast aluminium alloy	Applications in detail
A356 - T6	Aeroengine
ZL101 ZL102	Cylinder frames and hubs
ZL105	Cylinder frames
356 A356	Structural components, accessories of instruments and meters, engine parts, shells of fuel pumps
A357	Leading-edge wings, vertical stabilizers, pylons, main gear boxes and supports of canopy

3.2. Applications in vehicle engineering and transportation engineering

Recently, energy consumption and pollution caused by automotive industry increased greatly with rapid growth of global economy. Light weight design of automobile, a direct method to decrease the fuel consumption, promotes the achievement of energy conservation and environmental protection [23]. Benefited from the characteristics of light weight, high strength and excellent thermal diffusivity, aluminium alloys were taken into applications as an integral means of achieving light weight design of automobile. Also, the demand for complex components of automobile has served the development of components molded by cast aluminium alloys. Currently, thin-walled aluminum alloy die casting technology has become the preferred manufacturing technology and has been highly applied in the engine systems, transmission and walking systems of automobile [24,25,26]. The applications of cast aluminium alloy in automobile were summarized in Table 4 [27,28].

Table 4: Applications of cast aluminium alloy in automobile [27,28]

Systems of automobile	Applications in detail
Engine system	Components including pistons, cylinder blocks, cylinder heads, intake tubes, oil sumps, etc.
Transmission and walking systems	Shells of gear boxes and clutches, shifting-yokes, swing-arms of chassis, knuckles, shells of brake pump, brakes, etc. Few was applied in clutch pedals and steering wheel skeletons.

Moreover, the development of casting aluminium alloy not only provided solutions for light weight design of automobile, but also became inevitable for further development of high-speed electrified railways. In recent years, cast aluminium alloys were gradually taken into applications in transportation engineering [29,30], such as suspension systems of cantilever, gear boxes for transmitting power, bearing transoms of motor system, etc. Figure 1 [31] demonstrated the aluminium suspension system of cantilever.

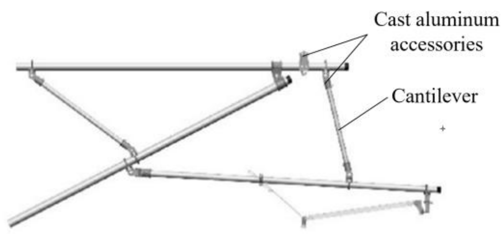

Figure 1: Suspension system of cantilever [31]

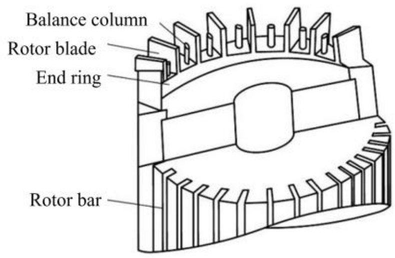

Figure 2: Diagram of cast aluminium rotor [33]

3.3. Applications in mechanical manufacturing engineering

In mechanical manufacturing industry, the adverse working conditions have brought challenges for workers. With the burgeoning trend towards industrial automation, increased criteria have been placed on the bearing capacity and corrosion resistance of equipment, especially for the precise components of machines [32]. Given the intricate structural design or non-uniform wall thickness, manufacture of production equipment components, such as rotors, hinges, and shells, necessitate higher requirements for precision. Thus, it is rational to promote the applications of cast aluminum alloys in mechanical manufacturing engineering. Recently, cast aluminum rotors have been prevalent in 300kW (or lower) induction motors, promoting operational stability and reliability while reducing the maintenance and inspection burdens. An illustrative structural diagram of a cast aluminum rotor [33] was shown in Fig. 2.

3.4. Applications in structural engineering

In response to the call for green and low-carbon construction, along with the rise of spatial structures, aluminium alloys were widely taken into applications in structural engineering. However, there were few applications of cast aluminium alloys in structures. A proposal for a cast aluminium joint was suggested during the design phase of the Chenshan Botanical Gardens in Shanghai [7], which was intended for use on the single-layer latticed dome structures constructed by aluminium alloys, as depicted in Fig. 3. However, the proposal was not adopted due to the lack of researches regarding to the mechanical properties of cast aluminium alloys. Additionally, cast aluminium joints were once used in a bus shelter in Hefei province. Owing to insufficient researches before construction, connection fractures have occurred due to snow load, resulting to serious accidents. Therefore, further study on the behaviour of cast aluminum alloy is needed to advance the applications in engineering field.

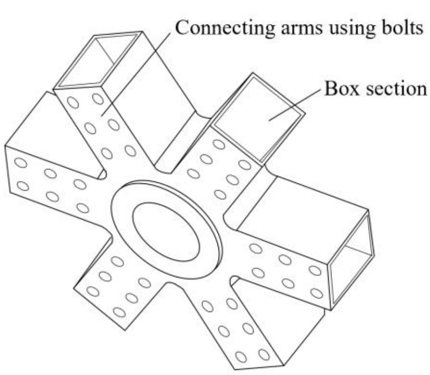

Figure 3: Diagram of cast aluminium joint proposed by Zhuhai Jingyi Company [7]

4 Research progress on cast aluminium alloy for spatial structures

4.1. Research progress on mechanical properties of cast aluminium alloy

In terms of mechanical properties of cast aluminium alloy, most research focused on the fatigue behaviour.

Mohseni [34] proposed a unified plastic flow stress model and a yield strength evolution model for artificial ageing based on the mechanical property tests of cast aluminium alloy B206, better simulating the evolution of microstructure and micro-scale defects during the manufacturing process. Yang [35] investigated the intrinsic deformation behavior and corresponding microstructure and texture evolution of A356-T6 aluminum alloy through uniaxial tensile and compressive tests. Wang [36] evaluated the applicability of Johnson-Cook (J-C) constitutive model based on the evolution of material microstructure and experimental phenomena of tensile coupon tests of die cast JDA1b aluminium alloy, thus proposing a new constitutive model to describe the relationship between flow stress and plastic strain. Osmond [37] investigated the effect of over-ageing condition on strengthening precipitate microstructures and cyclic behaviour of two cast aluminium alloys AlSi7Cu0.5Mg0.3 and AlSi7Cu3.5Mg0.1, and proposed a microstructure sensitive constitutive model for better simulations.

However, all of the above-mentioned investigations were mainly focus on their characteristics of particle and micro structure, which were related to fatigue performance and corresponding interfering factors. No work is available in the literature studying the mechanical behaviour of cast aluminium alloy related to structural engineering at macro level, highlighting the importance of supplement of experimental and numerical work for structural engineering, thus promoting the future application of cast aluminium alloys in spatial structures.

4.2. Research progress on cast aluminium alloy joints

In the literature, limited research has been conducted on the mechanical performance of cast aluminum joints. Luo [38] et al. proposed basic design criteria for cast aluminum joints, including material selection, casting process and quality control based on JGJ 61-2003. Luo [39] et al. carried out nonlinear numerical simulations on a proposed cast aluminum joint designed for the aluminium single layer latticed dome structures, with results showing that such cast aluminium joint owns sufficient strength and stiffness. In addition, Shi [7,8] et al. conducted experimental and numerical study of such cast aluminium joint, and derived the stress concentration factor. Also, a simplified formula for predicting the ultimate strength of cast aluminium joint was proposed. Hu et al. found that the connection between variable cross-section members could be achieved by cast aluminum joints, and optimized strategies for single-layer shell structures constructed by aluminium alloys.

5. Experimental work

5.1 Tensile coupon tests

Four tensile coupon tests were conducted to obtain the mechanical properties of a type of cast aluminium alloy named ZL102. Tensile coupons were cut from the original castings, with four repeated coupons for each type of cast aluminium alloy. The nominal thickness of cast aluminium alloy plates was 10 mm. Tensile coupon tests were undertaken utilizing a 100kN testing machine in accordance with GB/T 228.1-2010 [40], as depicted in Fig. 4.

The full stress-strain curves of three types of cast aluminium alloys were obtained from the strain gauges and extensometer, as illustrated in Fig. 5. The key material characteristics acquired from the tested coupons are summarized in Table 2, in which E_0 is the initial Young's Modulus, $f_{0.1}$ is the 0.1% proof stress, $f_{0.2}$ is the 0.2% proof stress, f_u is the ultimate stress, ε_f is the elongation after fracture. It should be noted that the test results of ZL102-4 were excluded as the fracture occurred outside the parallel parts. Based on the test results presented in Table 5, the following conclusions can be drawn: (1) The mean value of elastic modulus of the ZL102 cast aluminium alloy is 67.3 GPa, which is closer to that of aluminium alloys; (2) The mean value of 0.2% proof stress of the ZL102 cast aluminium alloy is 68.9 MPa, which is about 60% lower than that of the commonly used aluminium alloys (ie. 6063-T5 or 6061-T6); (3) The ZL102 cast aluminium alloy has a lower percentage of elongation, suggesting appropriate safety factors should be taken for practical engineering design.

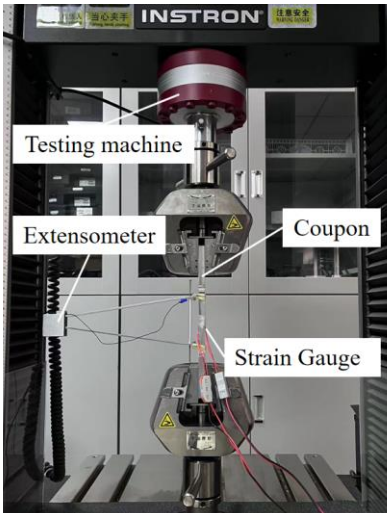

Figure 4: Photograph of tensile coupon tests

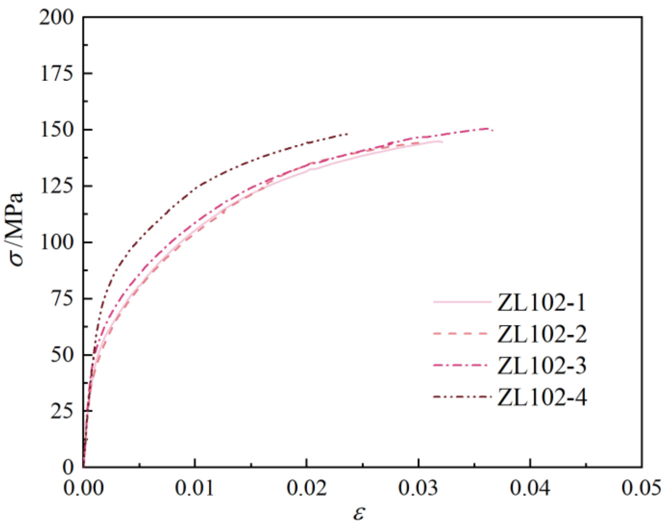

Figure 5: Stress-strain curves of ZL102

Table 5: Mechanical properties acquired from tensile coupon tests

Coupon ID	E_0/GPa	$f_{0.1}$/MPa	$f_{0.2}$/MPa	f_u/MPa	ε_f/%
ZL102-1	65.4	57.7	67.5	144.9	3.5
ZL102-2	66.7	54.1	66.0	144.2	3.6
ZL102-3	69.7	62.9	73.1	150.5	4.4
ZL102-4	68.4	79.4	90.7	148.2	3.4
Mean	67.3	58.2	68.9	146.5	3.8

5.2 Material model

In recent years, mixed hardening criterion were widely used due to its high accuracy on predicting the material properties. A strength model [41], which combines the Ludwik law and Voce law, was utilized to approach the plastic deformation of the three cast aluminium alloys using Eq. (1).

$$\sigma_{eq} = \alpha(A + B\varepsilon_{eq}^{n}) + (1-\alpha)\{A + Q(1 - e^{-\beta\varepsilon_{eq}})\} \tag{1}$$

where σ_{eq} is the von Mises stress; ε_{eq} is the equivalent plastic strain; α, A, B, n, Q, and β are six parameters that can be calibrated based on the above tensile coupon tests. Their values in this research are summarized in Table 6. A comparison between the combined Ludwik-Voce model and test results was performed, as depicted in Fig.6.

Table 6: Calibrated parameters of the combined Ludwik-Voce model

α	A	B	n	Q	β
0.24	43.91	608.32	0.4856	105.30	108.78

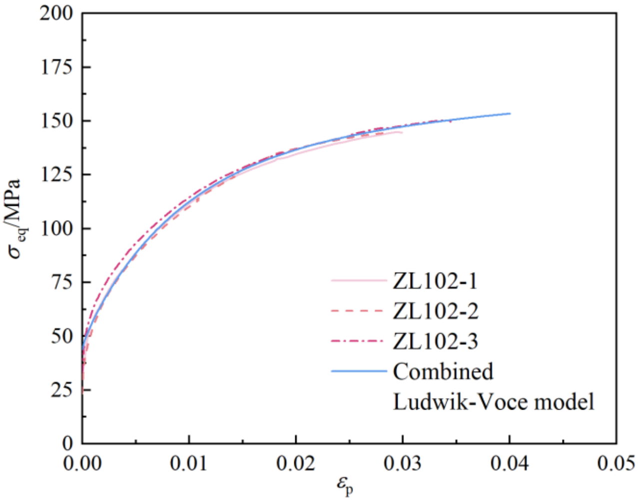

Figure 6: Ccomparison between the combined Ludwik-Voce model and test results

6. Conclusions

This study reported a detailed survey of the applications of cast aluminium alloys in engineering, with investigations of the research progress on mechanical properties of cast aluminium alloys and cast aluminium joints. In addition, Detailed test results of mechanical properties of the ZL102 cast aluminium alloy were presented. The following conclusions may be generated in this study:

(1) In recent years, cast aluminium alloys have been widely used in the engineering fields of aerospace and transportation, however, limited applications have been found in structural engineering.

(2) Research regarding to the mechanical properties mainly focused on the microstructure level of materials, lacking experimental or numerical research related to the engineering structures. This issue may be a major impediment to the development and application of cast aluminum alloys in structural engineering.

(3) Limited research work have been found on the behaviour of cast aluminum joints. According the experimental and numerical results shown in the researches [7,8,9], cast aluminium joints were reported to have sufficient strength but poor ductility, with the advantages of flexible design and wide application range. Thus, cast aluminium joints may own a broad application prospect in structural engineering field. Further works related to cast aluminium joints are needed for promoting its applications and ensuring safety in engineering field.

(4) Four tensile coupon tests were conducted, indicating that the yield strength and percentage of elongation of 7ZL102 cast aluminium alloy are 68.9 MPa and 3.8%, respectively. Thus, it is rational to take appropriate safety factors in practical engineering design.

Acknowledgements

The authors are grateful to support from the National Natural Science Foundation of China (Grant No. 52178146). The authors are also grateful to the support of the Key Laboratory of Civil Engineering Safety and Durability of China Education Ministry at Tsinghua University.

References

[1] K. Roy, B.S. Chen, Z.Y. Fang, *et al*., "Local and distortional buckling behaviour of back-to-back built-up aluminium alloy channel section columns," *Thin-Walled Structures*, vol. 163, pp. 107713, 2021.

[2] A.V. Nguyen, S. Gunalan, P. Keerthan, *et al*., "Structural behaviour and design of roll-formed aluminium lipped channel beams subjected to combined bending and shear," *Thin-Walled Structures*, vol. 174, pp. 109015, 2022.

[3] Z.Y. Fang, K. Roy, Y.C. Dai, *et al*., "Effect of web perforations on end-two-flange web crippling behaviour of roll-formed aluminium alloy unlipped channels through experimental test, numerical simulation and deep learning," *Thin-Walled Structures*, vol. 179, pp. 109489, 2022.

[4] Y.Q Wang, Z.X. Wang, F.X. Yin, *et al*., "Experimental study and finite element analysis on the local buckling behavior of aluminium alloy beams under concentrated loads," *Thin-Walled Structures*, vol. 105, pp. 44-56, 2016.

[5] *Eurocode 9: design of aluminium structures—part 1-1: general rules—general rules and rules for buildings*, BS EN 1999-1-1:2007, 2007.

[6] Y. Zhang, Y.Q. Wang, B.B Li, *et al*., "Structural performance of novel aluminium alloy gusset joints for connecting four I-section beam members, " *Journal of Building Engineering*, vol. 553, pp. 104547, 2022.

[7] G. Shi, C. Luo, Y.Q. Wang, *et al*., "Experimental study on mechanical performance of novel cast aluminum joints in aluminum reticulated shell structures, " *Journal of Building Structures*, vol. 33, no. 03, pp. 70-79, 2012. (in Chinese).

[8] G. Shi, C. Luo, Y.Q. Wang, *et al*., "Simplified design method of loading capacity of novel cast aluminum joint in aluminum reticulated shell structures, " *Spatial structures*, vol. 18, no. 01, pp. 78-84, 2012. (in Chinese).

[9] Y.Q. Wang, C. Luo, Y.J. Shi, *et al*., "Analysis of cast aluminum joints in aluminum alloy lattice shell structures," in Research on Steel Structure Engineering (vol. 7)—Proceedings of the Sub-association for Stability and Fatigue of Steel Structures Association, CSCC 2008, Shenyang, Liaoning, China, August 27-30, 2008, Y.J. Shi, Y.Q. Wang, Eds. Beijing: Industrial construction magazine, 2009, pp. 802-808.

[10] *Standard Specification for Aluminum-Alloy Die Castings*, ASTM Standard B85/B85M-10, 2010.

[11] J.E. Gruzleski and B.M. Closset. *The Treatment of Liquid Aluminum-Silicon Alloys*, USA, 1990.

[12] Y.C. Tzeng, C.T. Wu, H.Y Bor, *et al*., "Effects of scandium addition on iron-bearing phases and tensile properties of Al-7Si-0.6Mg alloys, " *Materials Science & Engineering A*, vol. 593, pp. 103-110, 2014.

[13] W.M. Jiang, Z.T. Fan, Y.C. Dai, *et al*., "Effects of rare earth elements addition on microstructures, tensile properties and fractography of A357 alloy," *Materials Science & Engineering A*, vol. 597, no. 3, pp. 237-244, 2014.

[14] S. Gowri and F.H. Samuel, "Effect of Mg on the solidification behavior of two Al-Si-Cu-Fe-Mg

(A380) die casting alloys," *Transactions of the American Foundry Mens Society*, vol. 101, pp. 611-618, 1993.

[15] M.M. Makhlouf and D. Apelian, "Casting characteristics of aluminum die casting alloys, " *Office of Scientific & Technical Information Technical Reports*, vol. 5, pp. 21, 28-29, 42, 2002.

[16] M.M. Makhlouf, D. Apelian and L. Wang, "Microstructures and properties of aluminum die casting alloys," *Material science*, 1998: 485-553.

[17] J.B. Tan, Z.M. Li and L.X. Li, "Effects of injection specific pressure on the microstructure and properties of semi-solid AlSi9Mg alloy," *Special Casting & Nonferrous Alloys*, vol. 30, no. 11, pp. 1016-1018, 2010. (in Chinese).

[18] C.D. Cai, "The microstructures and properties of high strength Al-Si-Cu die casting alloys and their heat treatment," Master. dissertation, Dept. Material sci. & Eng., Chongqing University, China, 2017.

[19] D.A. Nikolaos and S. Antonis, "Impact mechanical behaviour of Al-7Si-Mg (A357) cast aluminum alloy. The effect of artificial aging," *Materials Science & Engineering A*, vol. 528, pp. 6303-6312, 2011.

[20] Q.G. Wang, "Microstructural effects on the tensile and fracture behavior of aluminum casting alloys A356/357," *Metallurgical and Materials Transactions A*, vol. 34, pp. 2887-2899, 2003.

[21] G.J. Wang and Z.T. Wang, "Application of aluminum alloy on China's civil aircraft," *Light Alloy Fabrication Technology*, vol. 45, no. 11, pp. 1-11, 2017. (in Chinese).

[22] N. Chomsaeng, M. Haruta, T. Chairuangsri, *et al*., "HRTEM and ADF-STEM of precipitates at peak-ageing in cast A356 aluminium alloy," *Journal of Alloys and Compounds*, vol. 496, pp. 478-487, 2010.

[23] B. Wang, Z.Y. Zhang, G.C. Xu, *et al*., "Wrought and cast aluminum flows in China in the context of electric vehicle diffusion and automotive lightweighting," *Resources, Conservation and Recycling*, vol. 191, pp. 106877, 2023.

[24] Q.G. Wang and P.E. Jones, "Fatigue life prediction in aluminum shape castings," *International Journal of Metalcasting: Leading the Transfer of Research and Technology for the Global Metalcasting Industry*, vol. 8, no. 3, pp. 29-38, 2014.

[25] R. J. Rioja RJ and J. Liu, "The Evolution of Al-Li Base Products for Aerospace and Space Applications," *Metallurgical and Materials Transactions A*, vol. 43, no. 9, pp. 3325-3337, 2012.

[26] B. Kashyap and M. Chaturvedi. "Stain anisotropy in AA8090 Al-Li alloy during high temperature deformation, " *Material Science & engineering A*, vol.28, no. 1-2, pp. 88-95, 2000.

[27] Y. Wu, H.C. Liao and Y.Y. Tang, "Enhanced high-cycle fatigue strength of Al-12Si-4Cu-1.2Mn-T6 cast aluminum alloy at room temperature and 350 C," *Material Science & engineering A*, vol. 825, pp. 141917, 2021.

[28] M. Mirzaee-Moghadam, S. Zangeneh, H.R. Lashgari, *et al*., "The effect of Ni-doping on the microstructure, hot deformation behavior, and processing map of as-cast Al-Si piston alloy," *Journal of Materials Science*, vol. 55, pp. 16394-16418, 2020.

[29] Z.K. Wu, S.C. Wu, W.J. Qian, *et al*., "Structural integrity issues of additively manufactured railway components: Progress and challenges," *Engineering Failure Analysis*, vol. 149, pp. 107265, 2023.

[30] Ż. Krzysztof, S. Przemysław, W. Daniel, *et al*., "Insight into the fracture behaviour and mechanical response of ECAP processed cast and LPBF AlSi10Mg alloy," *Engineering Fracture Mechanics*,

vol. 295, pp. 109785, 2024.

[31] Z.H. Hu and J.F. Yan, "Manufacturing and installation of a new type of cantilevers for OCS of high speed railway, " *Electric Railway*, vol. 30, no. 04, pp. 4-7+19, 2019. (in Chinese).

[32] F. Ding, J.W. Wang, W. Wang, *et al*., "Research on application of high strength die cast aluminum alloy in industrial hinge," *Advances in Applied Sciences*, vol. 7, no. 3, pp. 73-78, 2022.

[33] H.H. Ni and X.Z. Guo, "Optimization of die-casting process of motor casting aluminum rotor based on GA-BP neural network," *Hot Working Technology*, vol. 50, no.15, pp. 61-63+66, 2021. (in Chinese).

[34] S.M. Mohseni, A.B. Phillion and D.M. Maijer, "Modelling the constitutive behaviour of aluminium alloy B206 in the as-cast and artificially aged states," *Materials Science & Engineering A*, vol. 649, pp. 382-389, 2016.

[35] B.C. Yang, H.W. Song, S.W. Wang, *et al*., "Tension-compression mechanical behavior and corresponding microstructure evolution of cast A356-T6 aluminum alloy," *Materials Science & Engineering A*, vol. 821, pp. 141613, 2021.

[36] X.Q. Wang, L.Y. Yuan, G. Xiao, *et al*., "A high-accuracy dynamic constitutive relation of die-cast Alˆa¿¿Si aluminium alloy," *International Journal of Mechanical Sciences*, vol. 251, pp. 108304, 2023.

[37] P. Osmond, L. Rémy and L. Nazé, "Cyclic stress-strain behaviour of particle-hardened cast aluminium alloys: Microstructure sensitive modelling of the effect of non-shearable precipitates," *Materials Science & Engineering A*, vol. 820, pp. 141492, 2021.

[38] C. Luo, Y.Q. Wang, Y.J Shi, *et al*., "Research on the application of cast aluminum joints in aluminium spatial structure. Sub-association for Stability and Fatigue of Steel Structures," *Industrial Construction*, 2008: 8. (in Chinese).

[39] C. Luo, Y.Q. Wang, Y.J Shi, *et al*., "Nonlinear analysis for the bearing properties of cast aluminum joint in the aluminum alloy lattice shell structures," *Building science*, vol. 26, no. 05, pp. 57-61+13, 2010. (in Chinese).

[40] Standard Administration P.R.China. GB/T 228.1: Metallic materials - tensile testing - Part 1: Method of test at room temperature. China Standards Press 2011. (in Chinese)

[41] L. Qian, G. Fan and P. Zeng, "Modeling of the ductile fracture during the sheet forming of aluminum alloy considering non-associated constitutive characteristic," *International Journal of Mechanical Sciences*, vol. 126, pp. 55-66, 2017.