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Superplasticity Behavior of Aluminium Alloys Through FSP: A Review

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Abstract

Friction Stir Processing (FSP), an advanced modification of Friction Stir Welding (FSW), has emerged as a highly effective technique for fabricating surface composites with superior mechanical and metallurgical properties. FSP enhances the microstructure and superplastic behavior of materials, particularly aluminium alloys, by subjecting them to high strain rates at relatively low temperatures. This review paper critically examines the development and optimization of FSP for aluminium alloys, emphasizing key factors such as tool geometry, rotational speed, traverse speed, and the number of passes. These parameters play a crucial role in improving the grain structure, strength, and ductility of the processed material. Additionally, the study highlights the significant influence of FSP on achieving enhanced superplasticity in aluminium alloys, which is highly desirable for industrial applications requiring formability and lightweight materials. The review further explores the extensive use of FSP-modified aluminium alloys in sectors such as aerospace, automotive, and defense industries, where performance enhancements, weight reduction, and cost-efficiency are critical.

Keywords: Aluminium alloys, deformation mechanism, friction stir processing, superplasticity

INTRODUCTION

Superplasticity is a remarkable property of materials characterized by the ability to undergo extensive plastic deformation without necking or failure, typically under specific temperature and strain rate conditions. In the context of aluminium and its alloys, superplasticity allows for exceptional ductility, enabling the material to be stretched to several times its original length. This behavior is beneficial when producing intricate, precise parts for the aerospace and automotive industries, where material performance and weight reduction are crucial. Generally, around 100% to less than 1000% of elongations describe this phenomenon [1]. Superplasticity is divided into micrograin superplasticity and internal stress superplasticity [2]. The primary requirement of the micrograin superplasticity is to achieve fine and equiaxed grain [3].

A fine grain structure is necessary to get the superplasticity. This microstructure must consist of the following features: 1) fine grain size, 2) equiaxed grain arrangement, 3) high angular grain boundaries, and 4) the existence of fine secondary phase particles to hinder grain growth [4]. This behavior occurs at a particular temperature range above \$0.5 T_m\$. It gives a critical grain size of 10 µm in alloys and 1 µm in ceramics [5]. During processing, superplasticity experiences lower and higher temperatures [6]. A fine grain structure is necessary to achieve superplasticity. Grain boundary sliding (GBS) is the main mechanism for achieving superplasticity. A fine grain structure must be unchanging at high temperatures to reach superplasticity. The following equation expresses GBS at high-temperature deformation [7]:

$$\varepsilon^0 = \frac{ADGb}{kT}\left(\frac{\sigma}{G}\right)^n\left(\frac{b}{a}\right)^p \quad (1)$$

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Where $\dot{\epsilon}_0$ is the strain rate, p is the inverse grain size exponent, b is the Burgers vector, σ is the stress, d is the grain size in diameter, D is the diffusivity, n is the stress exponent, and A is the microstructural and mechanism dimensionless constant of n. The above equation states that grain size reduces with the increase in elongation. In the superplasticity condition, the material's plasticity increases and reduces deformation resistance. Superplasticity in a material can be achieved by changing the microstructure with numerous severe plastic deformation (SPD) methods. The primary SPD methods are equal channel angular pressing (ECAP), high-pressure torsion (HPT), accumulative roll bending (ARB), and friction stir processing (FSP). Conventional thermo-mechanical processes include various processing stages, so the process becomes very intricate and laborious. Furthermore, it increases material cost and only fabricates thin gauge sheets [8]. In ECAP, achieving a fine-grain microstructure requires a minimum of six passes. Compared with other SPD processes, FSP is one of the most promising methods for producing superplasticity in metal alloys. FSP has some advantages, such as low tooling cost, minimum processing time, fine microstructure in one pass, and effective strain generation. The first experiment was performed on Al 7075 to achieve high strain rate superplasticity using FSP; they achieved a high elongation of less than 1000% at 490 °C [9]. Similar work is reported where high elongation of 1250% was achieved at 480 °C [10]. Then, FSP was performed on commercial alloy Al 2024. They achieved maximum ductility of 525% and a strain rate of 10^{-2} s^{-1} at 430 °C. According to them, FSP is a modest and effective method for manufacturing superplasticity at a high strain rate and lower temperature [11]. FSP was applied on cast alloy A356, and they achieved a maximum elongation of 650% at 470–570 °C and achieved a maximum strain rate of $3 \times 10^{-3} \text{ s}^{-1}$ [12]. This review paper explains the FSP process with this previous research based on the superplasticity behavior of aluminium alloys. Influencing factors on superplasticity are reported with suitable diagrams, and deformation mechanisms are explained. In the end, the application of superplasticity in various sectors is reported.

FRICTION STIR PROCESSING

Friction stir processing is a novel technique modified from friction stir welding (FSW), which was invented by The Welding Institute in 1991 in the UK.

A rotating tool has a pin and shoulder plunge into the selected area of the workpiece. The tool's stirring action produces friction, creating plastic deformation that results in the weld [13]. The base metal is fixed above the support plate. The tool then gets the required rotating speed, then plunges into the workpiece until the shoulder surface comes in contact with the base metal surface. Due to this, heat is generated, which is the main reason for material softening. This soft material then moves from the advancing side (AS) to the retreating side (RS) of the base metal. After this plunging, the tool moves in a traverse direction. This intense plastic deformation helps mix reinforcement into the workpiece and yields grain refinement and a recrystallized grain structure [8]. Figure 1 shows the FSP process and selective superplastic forming of the material.

Process Variables in FSP

Generally, FSP parameters are responsible for the final properties of the fabricated composites. The combination of these parameters affects the microstructure and properties of the processed material. These parameters are mainly divided into three groups: machine parameters, tool geometry, and material properties. Properties of the base metal are crucial while choosing the parameters [14]. Figure 2 shows various parameters used in FSP.

Machine Variables

Basically, two types of tool speeds are used for processing: tool rotational speed and tool transverse speed. They are accountable for heat generation, material movement, and microstructure change in the stir zone [15]. Tilt angle and plunge depth are considered constant in many cases, but both are responsible for achieving a defect-free composite [14]. Tilt angle helps the tool in its easy movement. Tilt angle and plunge depth are associated with defects occurring in the stir zone. Generally, the tool speed range taken for experimentation is 500–1000 rpm and 50–120 mm/min. Plunge depth is also called targeted depth, which is responsible for material flow and the dispersion and homogeneity of the secondary phase particles [13].

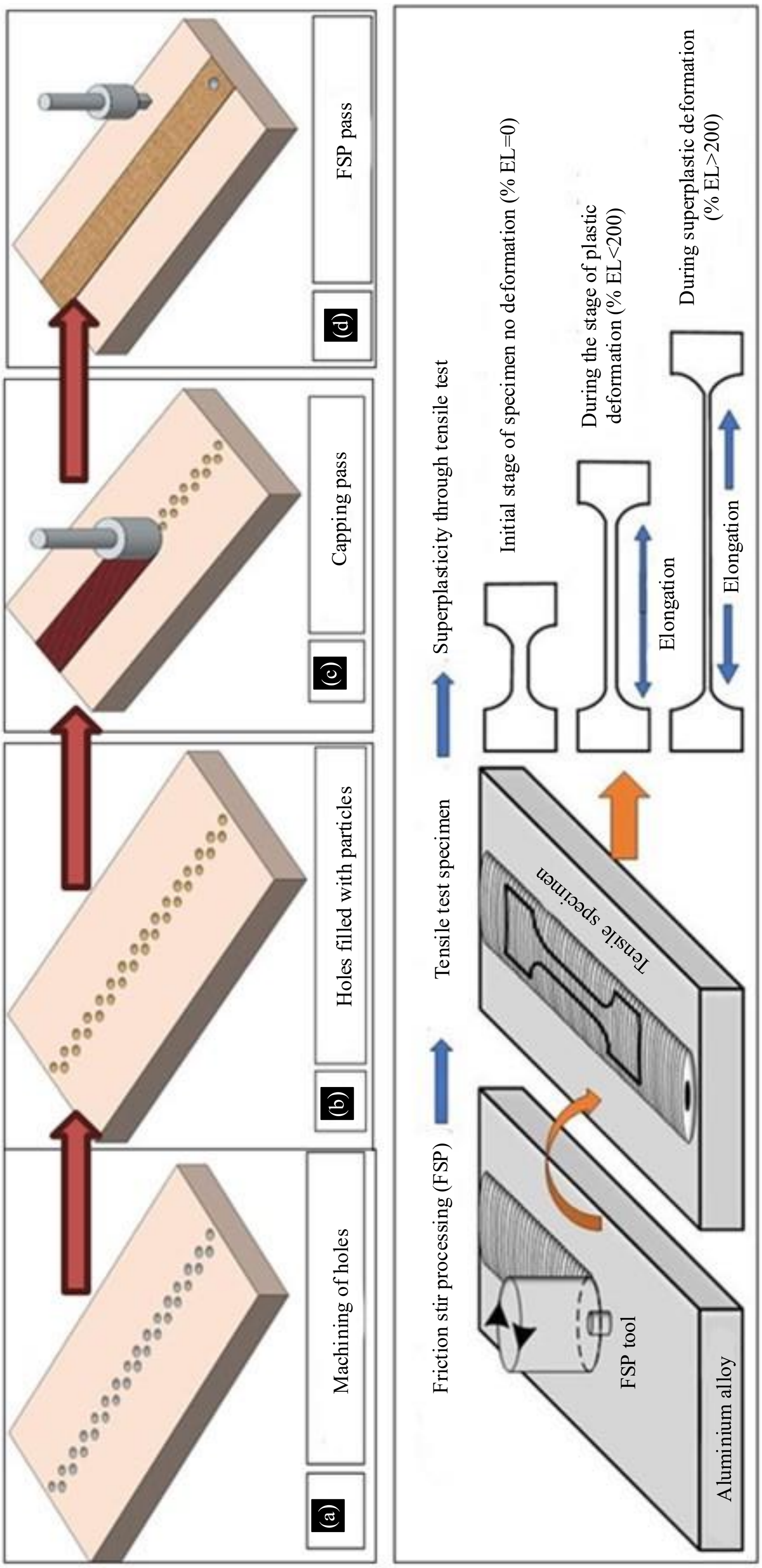

Figure 1. a to d) Steps of FSP process, e) Concept of superplastic through test.

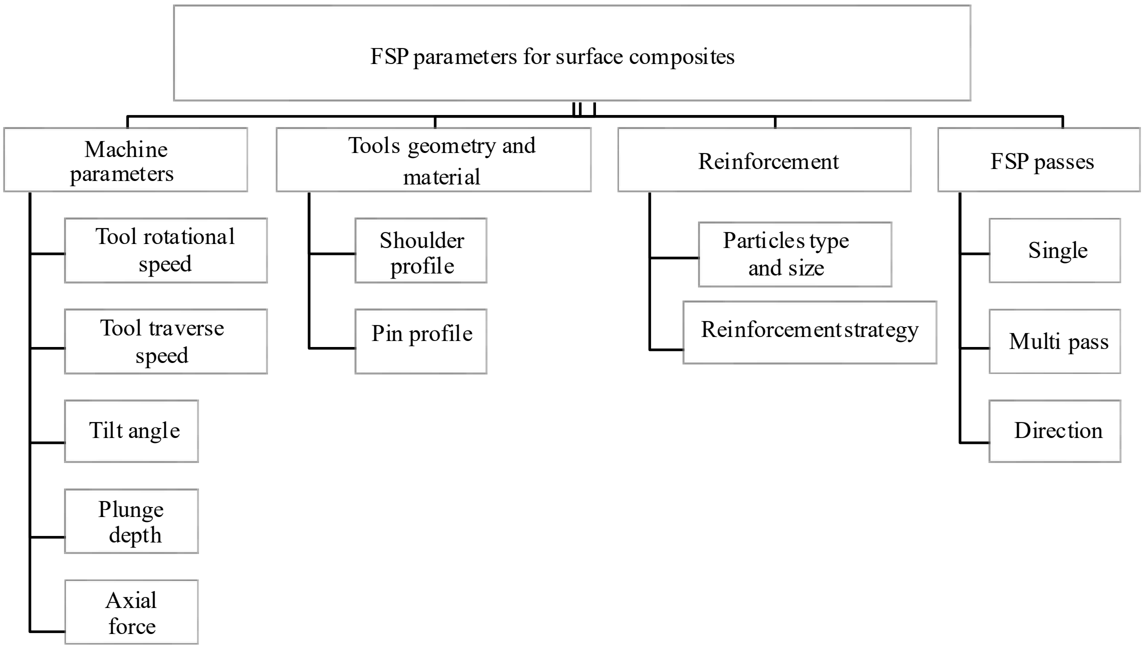

Figure 2. FSP process parameters for surface composites.

Tool Variables

Tool geometry consists of a shoulder and a pin. During processing, the interface of the tool and workpiece generates sufficient heat, and the stirring action of the pin is responsible for material flow [16]. For FSP, the pin-to-shoulder ratio is generally taken as 1:3 to 1:2 [17]. According to the literature, compared to other tool materials, tool steels are widely used; with square and threaded cylindrical pins, they achieved high elongation at lower temperatures and a homogenous microstructure. Ma and Mishra [13] pointed out that the tool's size is crucial for the achievement of the recrystallized grain and suggested that a decrease in tool diameter reduces the nugget zone. Figure 3 shows various pin geometries.

Number of Passes

This plays an essential role in distributing the reinforcing particle, improving the microstructure, and enhancing the composite's strength. According to the literature, in most cases, a single pass is used for processing. Compared to multipass, a single pass often gives better results. Johannes and Mishra [18] found that a single-pass showed higher elongation compared to multipass on Al 7075. Similarly, Ma et al[19]. suggest that two passes with 50% overlap do not significantly affect grain size compared to a single pass. Figure 4 shows the single and multipass used in FSP. Table 1 represents the previous studies.

INFLUENCING FACTORS

Significance of Temperature

Generally, the superplastic condition is associated with the strain rate forming temperature. Two ideal conditions are considered: high strain rate superplasticity (HSRS) and low-temperature superplasticity (LTSP), both responsible for achieving superplasticity in the material [4]. Temperature for superplastic deformation is responsible for getting improved properties in superplastic alloys. GBS is affected by increases in temperature, so viscous flow is reduced, and grain boundaries become unstable [6]. Increased temperature reduces elongation due to the soft grain boundaries and binding force [30]. Figure 5 displays the relation between elongation and temperature during testing. Many authors reported that LTSP improves the superplasticity behavior of aluminium alloys [22]. Elongation of the material increases and flow stresses decrease with increasing temperature [6]. Figure 6 displays superplastic deformation at different temperatures.

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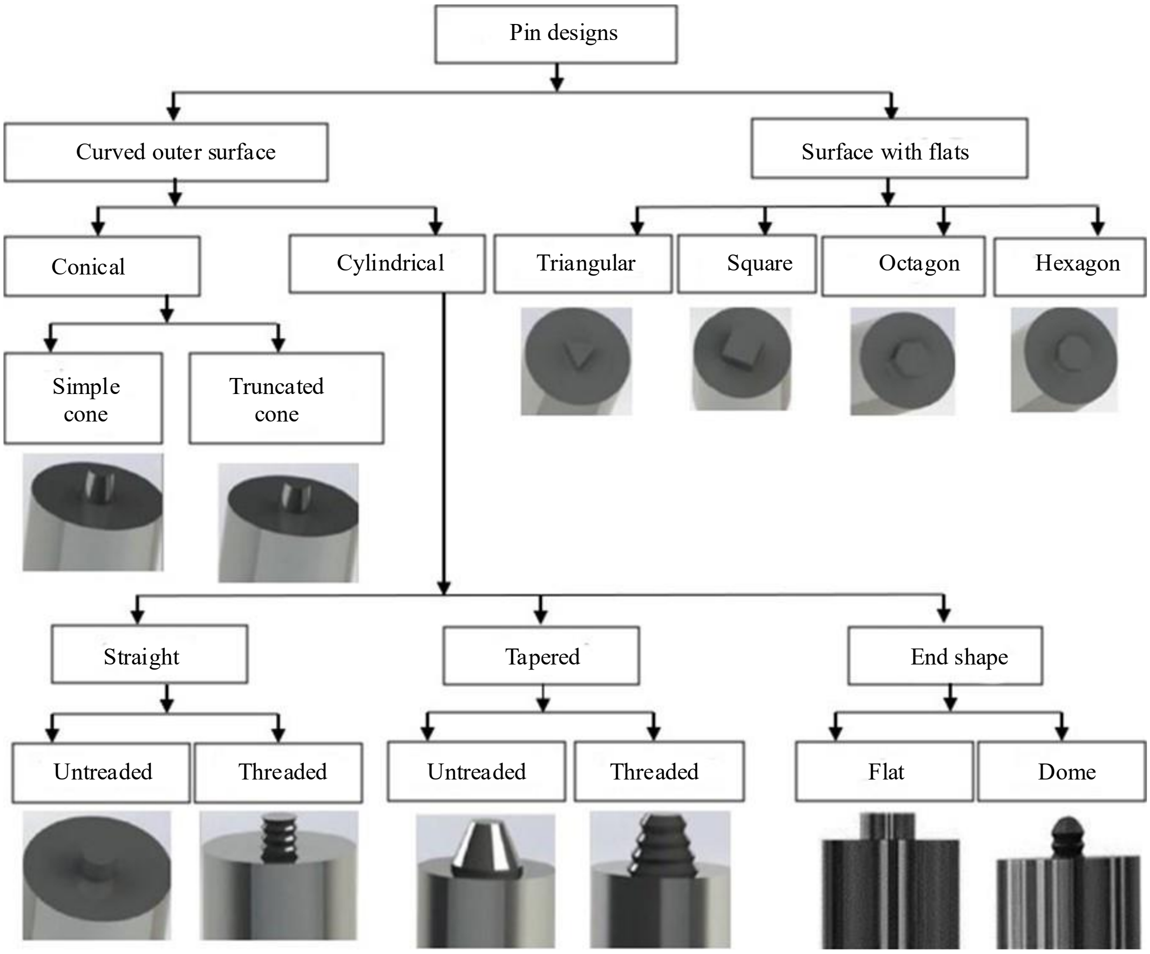

Figure 3. Various pin profiles.

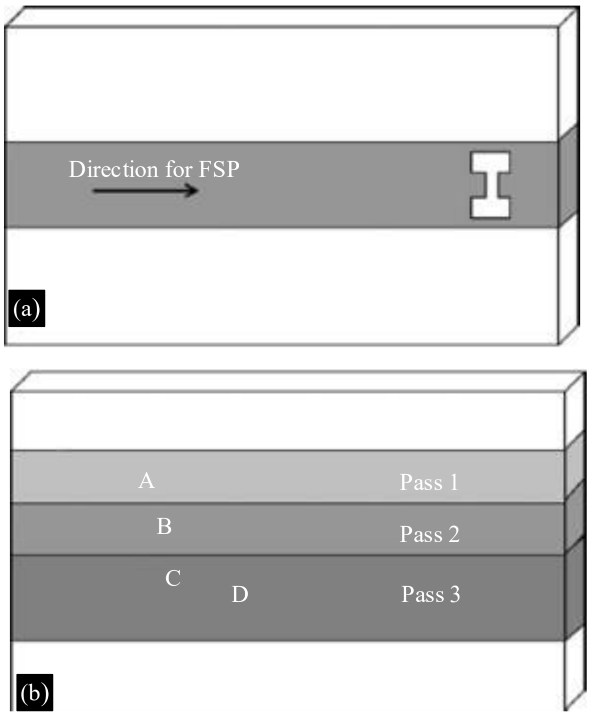

Figure 4. (a,b): Representation of single and multipass during the processing [18].

Table 1. Previous studies of superplasticity behavior on various aluminium alloys.

Matrix	Process parameters	Tool design	No of pass	Superplastic behavior			References
				Temp.(^{0}C)	*SR (S^{-1})*	*Max. EL%*	
AA7075-T651 (Rolled)	RS: 765TS:31.5 TA: 2	M2 grade tool steelShD: 20, PiD:6, PiL:6Pin: Square, pentagon, hexagon	1	400	3*10^{-4}	227	[20]
Al6063/K_2ZrF_6 (Cast)	RS: 1000TS: 60TA: 2.5	Tool steelShD: 12, PiD: 4, PiL: 3.7	1	500	1*10^{-2}	330	[21]
Al5083 (Cast)	RS: 400TS:25T A: 2.5	MP159 alloyPin: Tapered cylindrical, short tapered cylindricalShD:12.5, 16, PDm=5, PDmi=4, PiL:3.5,5,3	1	530	3*10^{-2}	810	[22]
Al7075-T6	RS: 1000TS: 500	H-13 tool steelPin: Threaded ShD: 9.5, PiD:3, PiL:2	1	350	1*10^{-2}	510	[23]
Al7075Cast	RS:1200TS: 100	H-13 tool steelPin: Conical threadedShD:16, PDm:5, PDmi:3.5, PL: 4.5	1	450	1*10^{-2}	890	[24]
Al7075-T651(Rolled)	RS:400TS: 100	M42 tool steelPin: Conical threadedShD:14, PDm:5, PDmi:3.5, PiL: 4.5	1	350	1*10^{-2}	540	[25]
Al7075	RS: 400TS: 50	MP159 Cobalt alloyPin: Threaded ShD: 25, PiD: 6.4, PiL: 6.4	4	469	1*10^{-2}	1225	[18]
Al2024/ZrB_2	RS: 1000TS:70T A:2.5	Pin: Hexagonal, SquareShD: 12, PiD:5 PiL:3.7	1	476	5*10^{-3}	292	[26]
AA5083	RS: 95 to 750TS:73	Pin: Threaded ShD: 16, PiD: 2.37, PiL:3.9	1	500	1*10^{-3}	1900	[27]
Al7075	RS:600TS:1 02	H-13 tool steelPin: Threaded ShD: 24, PiD: 8, PiL: 6	2	480	1*10^{-2}	1250	[10]
AA6063-T6	RS: 800 to 1600TS: 22.2,	High carbon steelThreaded pinSD: 18, PD: 6	5	343	1*10^{-2}	225	[28]

RS: Rotational speed, TS: Traverse speed, ShD: Shoulder diameter (in mm), PiD: Pin diameter (in mm), PDm: Pin diameter major (mm), PDmi: Pin diameter minor (mm), PiL: Pin length (mm), Temp: Temperature, SR: Strain rate, Max: Maximum, EL: Elongation.

Effect on Grain Refinement

Small grain size can be achieved by increasing strain rate and reducing temperature. Reduction in grain size is related to low tool rotational speed and high transverse speed responsible for heat generation and defining temperature conditions. According to Pradeep and Pancholi [29], low heat input improves high-angle grain boundaries due to reduced grain size and gives a higher superplasticity rate compared to high heat input. Figure 7 showed the occurrence of randomly distributed particles as well as the generation of a large fraction of high-angle grain boundaries. Yang et al[21]. achieved reduced grain size from 30 to 2 μm in an in-situ composite. Similarly, Liu, and Ma [24] achieved a reduced average grain size of 3.2 μm in cast Al 7075. Dieguez et al[31]. found a reduced grain size of 4.65 μm at 450 °C in Al 7075-T651. Liu and Ma [25] found equiaxed grains of 2.6 μm at a high elongation of

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2150% at 450 °C in Al-Mg-Sc alloy. The cooling effect showed a significant impact on the decrease of grain size. Charit & Mishra [11] used air cooling and found a reduced grain size of 3.9 μm in Al 2024-T4, also suggesting that grain growth increases with a reduction in grain size.

Effect of Strain Rate Sensitivity and Strain Rate

Strain rate sensitivity (SRS) plays a crucial role in material deformation. It is basically used to measure changes in strain rate while temperature and microstructure are kept fixed [32]. SRS causes a reduction in shockwave amplitude and increased dynamic strength of the material [33]. Generally, superplastic materials mostly lie in an SRS range of 0.4–0.8. Strain rate sensitivity demonstrates the materials' measurements to resist necking, stability, and total deformation [34]. In superplastic materials, an increment in strain rate directly affects flow stresses. Figure 8 showed the effect of strain rate on flow stress and strain sensitivity rate.

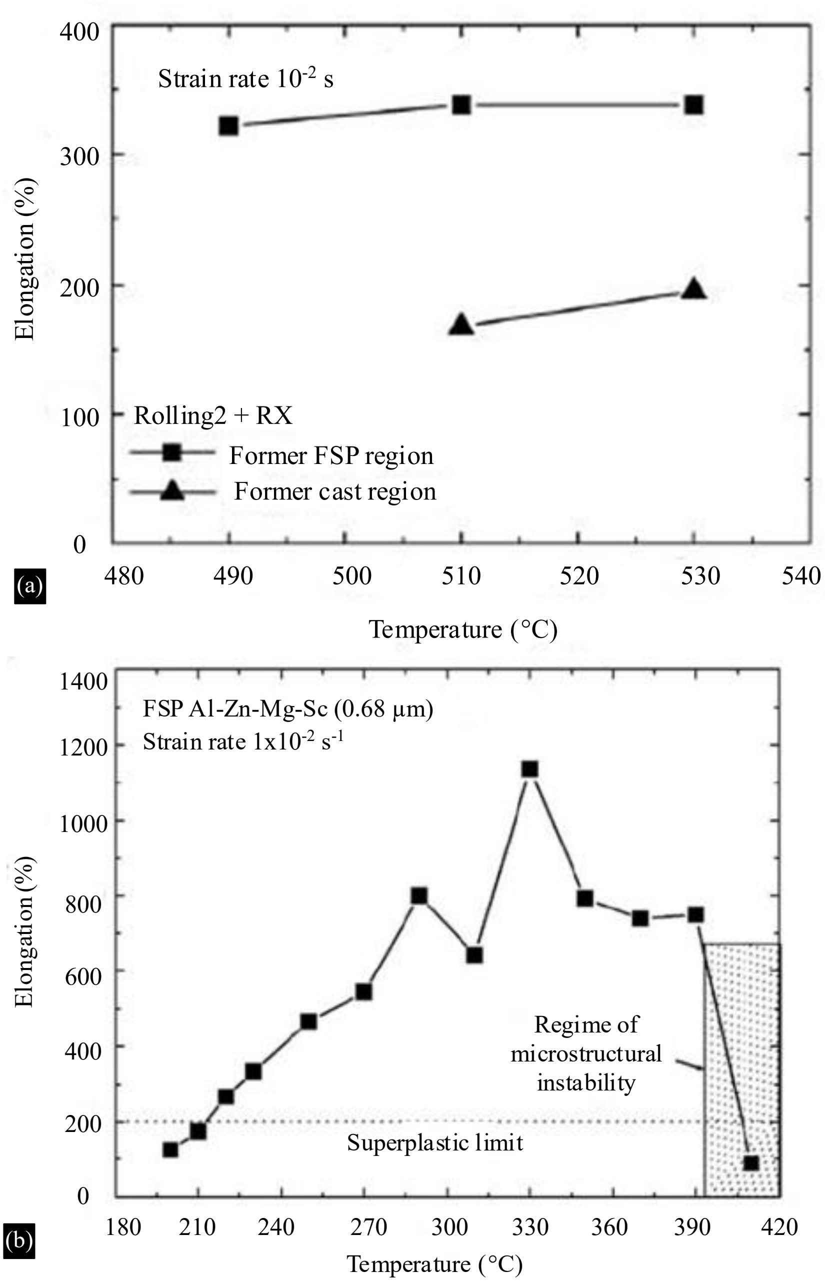

Figure 5. (a,b): Relation between elongation and temperature during the testing [18].

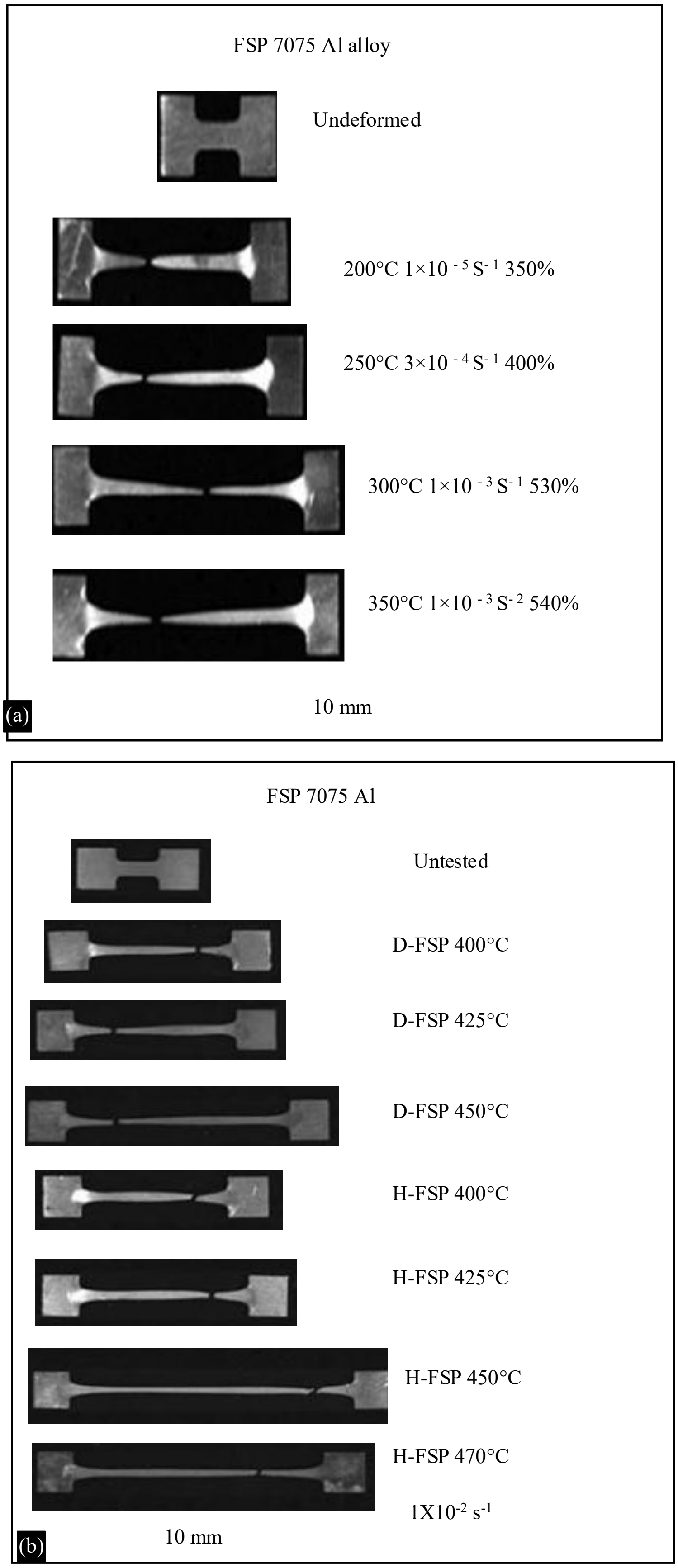

Figure 6. (a, b): Superplastic deformation at different temperature [25].

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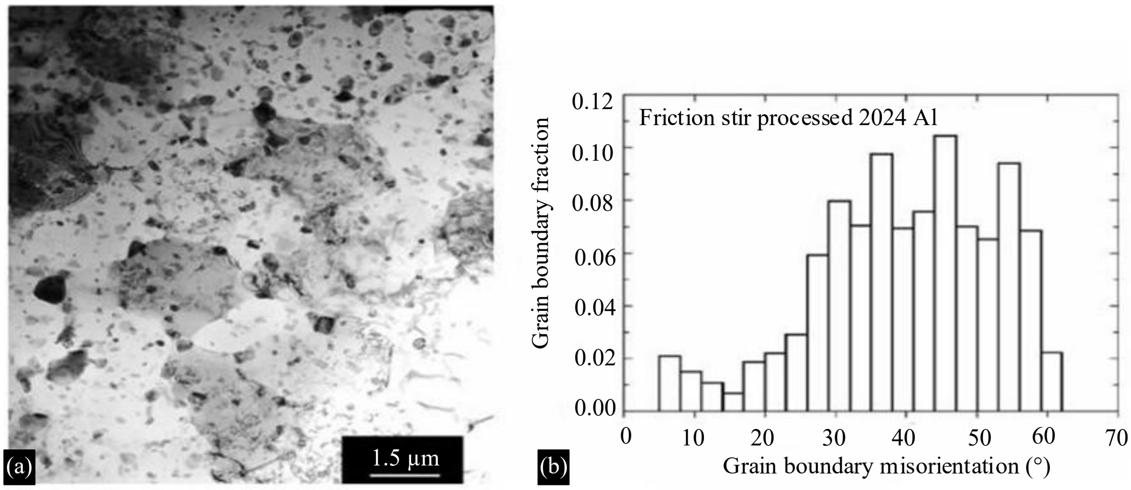


Figure 7. a) TEM of Al2024 b) Grain boundary misorientation distribution [11].

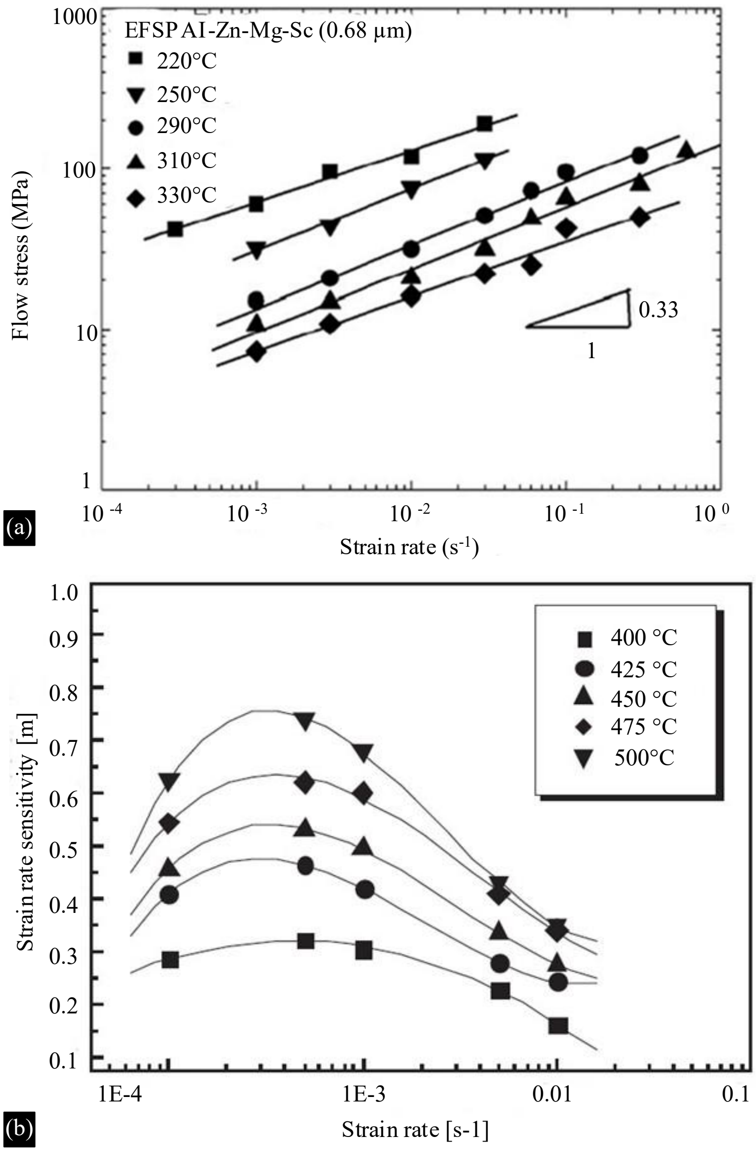


Figure 8. a) Relation among strain rate and flow stress [11], b) Relation among strain rate and flow stress [36].

The influence of strain rate on flow stress is negligible at room temperature but increases with temperature [35]. Cavaliere and Squillace [36] found higher SRS at a temperature of 500 °C with a strain rate of $5 \times 10^{-4} \text{ s}^{-1}$. They also suggest that SRS increases with strain rate. Ma et al[10]. found higher elongation of 1220% at 480 °C with a strain rate of $3 \times 10^{-4} \text{ s}^{-1}$ and SRS of 0.5. S-type behavior of stress-strain is found with high strain rate sensitivity.

DEFORMATION MECHANISMS

Superplastic deformation mechanisms are divided into three types: grain boundary sliding, diffusion creep, and slip by dislocation movement. All the mechanisms are considered high-temperature deformation mechanisms [37]. Generally, deformation is expressed by two shapes: S-shaped and peak-shaped curves. For aluminium alloys, GBS is the working mechanism [6]. GBS is mainly divided into two types: Rachinger sliding and Lifshitz sliding. The combination of both is responsible for GBS. In Rachinger sliding, dislocation movement occurs within the grains only, but in Lifshitz sliding, it depends on Nabarro and Coble creep [38]. The main issue is the development of a void in the microstructure that GBS must accommodate. Accommodation is divided into: diffusion, dislocation motion, and a mixture of dislocation and diffusional accommodation [39]. Johannes and Mishra [18] found that GBS is the working mechanism for Al 7075. Table 2 shows some of the deformation mechanisms that occur during superplastic behavior. Ashby-Verrall explained the theoretical model for superplasticity deformation. Figure 9 explains the three stages of deformation where GBS equiaxed grains move and take their final shape.

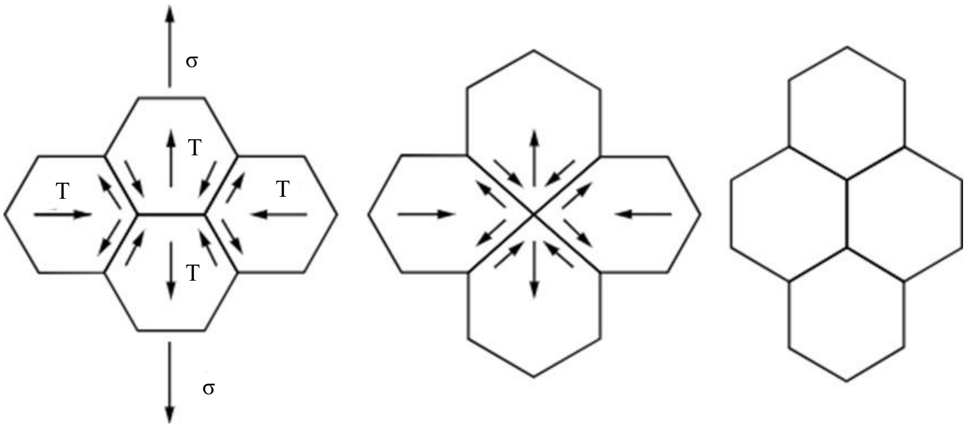
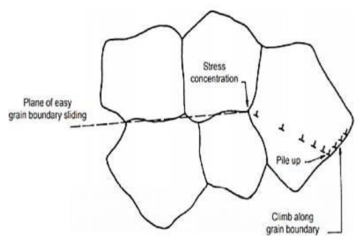
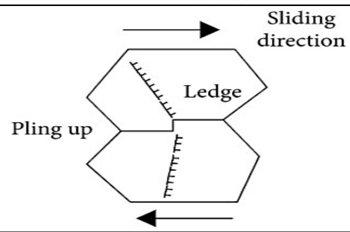


Figure 9. Ashby-verrall theoretical model [40].

Table 2. Deformation models used for superplasticity.

Modelname	Description	Images	References
Ball-Hatchison model	GBS accommodated by dislocation movement. Explained that during the superplastic behavior cluster of grains slides as a unit till the critically oriented grains hinderthe process		[41]
Mukherjee model	GBS accommodated by Slip. Modification of the Ball-Hatchison modelExplained that adjacent grains do not slide as a unit.		[42]

APPLICATIONS

Superplastic aluminium alloys are widely utilized in industries requiring lightweight, durable, and complex-shaped components. In the aerospace sector, they are used to manufacture critical structural parts like fuselage panels, wing ribs, and engine components, where weight reduction and aerodynamic efficiency are essential. The automotive industry also benefits from these alloys, particularly in forming body panels, structural reinforcements, and bumpers, improving fuel efficiency and crash performance. Additionally, superplastic aluminium alloys are applied in defense for lightweight armor and vehicle components. In the medical field, they are used to create strong yet lightweight surgical instruments and implants. Their ability to form intricate, thin-walled designs makes them valuable for heat exchangers and consumer electronics, where precise, lightweight frames are essential. These applications highlight the versatility of superplastic aluminium alloys across various high-performance industries. Applications of superplastic forming aluminium alloys are used in aerospace but not widely found in the automobile sector because of the material's high initial cost [45]. Superplasticity is used in the aerospace sector because it gives close tolerance in a single piece. Due to this, it decreases separate part fabrication and assemblage costs [46]. According to Sereni [47], the first vehicle component produced by superplasticity was made of AA5083. He also reported that subway cover plates and railway head parts could be fabricated to meet unique requirements. Dassault Aviation used AA5083 and 7475 for fabricating military and civil aircraft parts using superplastic forming. Patel et al[4]. detailed various applications of superplastic aluminium alloy in the aerospace industry. Aluminium alloys and their composites are used to manufacture various parts of aerospace engines. With advancements, aluminium alloys are used to produce automobile components, complicated, and curved parts, and small-scale industry components associated with high stiffness and low weight.

FUTURE ASPECTS

Superplasticity in aluminium is an attractive topic. It involves studying how aluminium can exhibit remarkable plastic deformation at elevated temperatures and specific strain rates. Future work in this area could focus on several key aspects:

- *Alloy composition:* Investigating how different alloying elements like magnesium, silicon, or copper influence grain growth and deformation mechanisms
- *Temperature and strain rate effects:* Determining optimal conditions for achieving maximum ductility
- *Grain boundary engineering:* Exploring techniques to manipulate grain boundary characteristics to enhance superplastic properties
- *Failure mechanisms:* Identifying and understanding the failure modes that occur during superplastic deformation to improve material performance and reliability
- *Fabrication techniques:* Developing new fabrication methods or optimizing existing ones like FSP to exploit superplasticity

CONCLUSION

FSP is becoming a well-known process for processing material in selected areas. The literature confirmed that FSP showed encouraging results in achieving superplasticity in aluminium alloys. Superplasticity eliminates the need for joint formation in the material. Researchers reported most of the work on superplasticity behavior using aluminium alloy 7075. With a single pass of FSP, researchers achieved a high elongation rate at low temperatures. FSP has not received much attention due to the limited literature available. For the commercialization of this process in other sectors, more effort is needed. Most of the work is focused on aluminium alloys, so other alloy processing is needed. Variations in process parameters and innovative tool designs are needed to further explore superplasticity.

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REFERENCES

1. Kassner ME. *Fundamentals of creep in metals and alloys*. Oxford: Butterworth-Heinemann; 2015.
2. Sakuma T. Superplasticity in alloys. Curr Opin Solid State Mater Sci. 1997;2(3):296–299.
3. Mukherjee AK. Superplasticity in metals, ceramics and intermetallics. In: *Plastic deformation and fracture of materials*. New York: Marcel Dekker; 1993.
4. Patel VV, Badheka V, Kumar A. Friction stir processing as a novel technique to achieve superplasticity in aluminum alloys: process variables, variants, and applications. Metallogr Microstruct Anal. 2016;5:278–293.
5. Maehara Y, Langdon TG. Superplasticity of steels and ferrous alloys. Mater Sci Eng A**.** 1990;128(1):1–3.
6. Bhatta L, Pesin A, Zhilyaev AP, Tandon P, Kong C, Yu H. Recent development of superplasticity in aluminum alloys: a review. Metals**.** 2020;10(1):77.
7. Nieh TG, Wadsworth J, Sherby OD. *Superplasticity in metals and ceramics*. Cambridge: Cambridge University Press; 1997.
8. Ma ZY, Mishra RS, Mahoney MW. Superplasticity in cast A356 induced via friction stir processing. Scripta Mater. 2004;50(7):931–935.
9. Mishra RS, Mahoney MW, McFadden SX, Mara NA, Mukherjee AK. High strain rate superplasticity in a friction stir processed 7075 Al alloy. Scripta Mater. 1999;42(2):163–168.
10. Ma ZY, Mishra RS, Mahoney MW. Superplastic deformation behaviour of friction stir processed 7075 Al alloy. Acta Mater. 2002;50(17):4419–4430.
11. Charit I, Mishra RS. High strain rate superplasticity in a commercial 2024 Al alloy via friction stir processing. Mater Sci Eng A**.** 2003;359(1–2):290–296.
12. Ma ZY, Mishra RS. Development of ultrafine-grained microstructure and low-temperature (0.48 Tm) superplasticity in friction stir processed Al–Mg–Zr. Scripta Mater. 2005;53(1):75–80.
13. Mishra RS, Ma DZ. Friction stir welding and processing. Mater Sci Eng R Rep. 2005;50(1–2):1–78.
14. Sharma V, Prakash U, Kumar BM. Surface composites by friction stir processing: a review. J Mater Process Technol. 2015;224:117–134.
15. Sharma DK, Patel V, Badheka V, Mehta K, Upadhyay G. Different reinforcement strategies of hybrid surface composite AA6061/(B_4C + MoS_2) produced by friction stir processing. Materwiss Werksttech**.** 2020;51(11):1493–1506.
16. Asadi P, Givi MKB. General introduction. In: *Advances in friction stir welding and processing*. New Delhi: Woodhead Publishing; 2014.
17. Azizieh M, Kokabi AH, Abachi P. Effect of rotational speed and probe profile on microstructure and hardness of AZ31/Al_2O_3 nanocomposites fabricated by friction stir processing. Mater Des. 2011;32(4):2034–2041.
18. Johannes LB, Mishra RS. Multiple passes of friction stir processing for the creation of superplastic 7075 aluminum. Mater Sci Eng A**.** 2007;464(1–2):255–260.
19. Ma ZY, Mishra RS, Liu FC. Superplastic behavior of micro-regions in two-pass friction stir processed 7075 Al alloy**.** Mater Sci Eng A**.** 2009;505(1–2):70–78.
20. Patel VV, Badheka V, Kumar A. Effect of polygonal pin profiles on friction stir processed superplasticity of AA7075 alloy. J Mater Process Technol. 2017;240:68–76.
21. Yang Y, Zhao Y, Kai X, Tao R. Superplasticity behavior and deformation mechanism of in-situ Al_3Zr/6063 Al composites processed by friction stir processing. J Alloys Compd. 2017;710:225–233.
22. Orozco-Caballero A, Cepeda-Jiménez CM, Hidalgo-Manrique P, et al. Lowering the temperature for high strain rate superplasticity in an Al–Mg–Zn–Cu alloy via cooled friction stir processing. Mater Chem Phys. 2013;142(1):182–185.

23. García-Bernal MA, Mishra RS, Verma R, Hernández-Silva D. Influence of friction stir processing tool design on microstructure and superplastic behavior of Al–Mg alloys. Mater Sci Eng A. 2016;670:9–16.
24. Liu FC, Ma ZY. Achieving high strain rate superplasticity in cast 7075 Al alloy via friction stir processing. J Mater Sci. 2009;44(10):2647–2655.
25. Liu FC, Ma ZY. Low-temperature superplasticity of friction stir processed Al–Zn–Mg–Cu alloy. Scripta Mater. 2008;58(8):667–670.
26. Zhao Y, Kai X, Chen G, et al. Effects of friction stir processing on the microstructure and superplasticity of in-situ nano-ZrB_2/2024 Al composite. Prog Nat Sci Mater Int. 2016;26(1):69–77.
27. Smolej A, Klobčar D, Skaza B, et al. Superplasticity of the rolled and friction stir processed Al–4.5 Mg–0.35 Sc–0.15 Zr alloy. Mater Sci Eng A. 2014;590:239–245.
28. Karthikeyan L, Senthil Kumar VS, Padmanabhan KA. Investigations on superplastic forming of friction stir-processed AA6063-T6 aluminum alloy. Mater Manuf Process. 2013;28(3):294–298.
29. Pradeep S, Pancholi V. Effect of microstructural inhomogeneity on superplastic behaviour of multipass friction stir processed aluminium alloy. Mater Sci Eng A. 2013;561:78–87.
30. Zhang N, Wang YQ, Hou HL, et al. Superplastic deformation behavior of 7B04 Al alloy. J Mater Eng. 2017;45(4):27–33.
31. Dieguez T, Burgueño A, Svoboda H. Superplasticity of a friction stir processed 7075-T651 aluminum alloy. Procedia Mater Sci. 2012;1:110–117.
32. Ghosh AK. On the measurement of strain-rate sensitivity for deformation mechanism in conventional and ultra-fine grain alloys. Mater Sci Eng A. 2007;463(1–2):36–40.
33. Borodin EN, Gruzdkov AA, Mayer AE, Selyutina NS. Physical nature of strain rate sensitivity of metals and alloys at high strain rates. J Phys Conf Ser. 2018;991(1):012012.
34. Nazzal MA, Khraisheh MK, Abu-Farha FK. The effect of strain rate sensitivity evolution on deformation stability during superplastic forming. J Mater Process Technol. 2007;191(1–3):189–192.
35. Hosford WF. *Mechanical behavior of materials*. Cambridge: Cambridge University Press; 2010.
36. Cavaliere P, Squillace A. High temperature deformation of friction stir processed 7075 aluminium alloy. Mater Charact. 2005;55(2):136–142.
37. Raja A, Jayaganthan R, Tiwari A, Rakesh CS. Effect of grain size on superplastic deformation of metallic materials. In: *Aluminium alloys and composites*. London: IntechOpen; 2019.
38. Langdon TG. Grain boundary sliding revisited: developments in sliding over four decades. J Mater Sci. 2006;41:597–609.
39. Masuda H, Sato E. Diffusional and dislocation accommodation mechanisms in superplastic materials. Acta Mater. 2020;197:235–252.
40. Wang XG, Li QS, Wu RR, Zhang XY, Ma L. A review on superplastic formation behavior of Al alloys. Adv Mater Sci Eng. 2018;2018:7606140.
41. Ball A. Superplasticity in the aluminium–zinc eutectoid: an early model revisited. Mater Sci Eng A. 1997;234:365–369.
42. Mukherjee AK. The rate controlling mechanism in superplasticity. Mater Sci Eng. 1971;8(2):83–89.
43. Gifkins R. Grain-boundary sliding and its accommodation during creep and superplasticity. Metall Trans A. 1976;7:1225–1232.
44. Langdon TG. A unified approach to grain boundary sliding in creep and superplasticity. Acta Metall Mater. 1994;42(7):2437–2443.
45. Barnes AJ. Industrial applications of superplastic forming: trends and prospects. Mater Sci Forum. 2001;357–359:3–16.
46. Mouritz AP. *Introduction to aerospace materials*. Oxford: Elsevier; 2012.
47. Sereni JGR. Reference module in materials science and materials engineering. Oxford: Elsevier; 2016.
48. Gratiot E, Surdon G. Industrial applications of superplastic forming with aluminum alloys. Mater Sci Forum. 1997;242:239–242.

