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Review article

A review of manufacturing processes, mechanical properties and precipitations for aluminum lithium alloys used in aeronautic applications

El Arbi Hajjioui [a,*], Kenza Bouchaâla [a,b], Mustapha Faqir [a], Elhachmi Essadiqi [a]

[a] International University of Rabat, AERO/AUTO School of Engineering, LERMA Lab. Sala El Jadida, Morocco
[b] Mohammed V University, Mohammadia School of Engineers, ITACS Lab. Rabat, Morocco

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ABSTRACT

Military applications and the aeronautic industry are increasingly interested in aluminum lithium alloys (Al–Li) because of the properties required due to the presence of Lithium, which provides a very considerable gain concerning the mechanical properties compared to conventional aluminum alloys. The research and development departments are interested in improving these alloys especially in additive manufacturing process, which leads today to focus on the 3rd generation of Al–Li in terms of part quality - low density compared to the 1st and the 2nd generation. The objectives of this paper is to present a review of Al–Li alloys applications, its carachetrization, the precipitations and their impact on mechanical properties and grain refinement. The various manufacturing processes, methods and tests used are then deeply investigated and presented. The last investigations that have been gotten by scientists over the previous few years on Al–Li for different processes are also reviewed in this research.

1. Introduction

As early as the mid-1920s, many studies on Lithium addition to aluminum were reported. More attention was garnered particularly to the aeronautics and aerospace field [1]. The first generation of aluminum lithium alloys was used in military aircraft in 1957 in the form of 2020 Al–Li plate used by Alcoa in 1958 in the wings of the navy's Vigilante aircraft [2,3] and it comes down to the advantages that Lithium offers on the reduction of the density of aluminum alloys [4], compared to the commercial 7xxx and 2xxx aluminum alloys series [5,6]. Lithium is the lightest metal, just hydrogen and helium are before it in the periodic table [7]. It shows that with the addition of 1 wt% of lithium to aluminum, elastic modulus will increase by 6% and the alloy density will decrease by 3% [7,8]. Researchers often find problems with understanding the laws of compression of lithium aluminum alloys that always changes with the production process, work parameters, heat treatment so on. These parameters influence the mechanical properties such as anisotropy, hardness, and elastic limit. The objective of this paper is to make a review on the several approaches that have been employed to improve the strength, precipitations, and toughness of lightweight Al–Li alloys and anisotropic control for the different manufacturing processes exist. In particular, the relevant mechanical problems due to the formation of different types of precipitation and the influence of aging are examined with the aim of clarifying the main mechanisms of the alloys mentioned. Recent study results are highlighted, although some significant researches from earlier years are also integrated to provide continuity, Al–Li for manufacturing

* Corresponding author.
E-mail address: elarbi.hajjioui@uir.ac.ma (E.A. Hajjioui).

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processes is also investigated.

2. Aluminum lithium alloys developments

2.1. The 1st and 2nd generation of Al–Li alloys

After the first utilization of the first generation of Al–Li alloys (2020 in 1958s developed by alcoa) with so many advantages like: high creep resistance between 150 °C and 200 °C [9], and high strength, however, this alloy had a poor ductility [10,11], which aimed to develop the 1420 with low density, good weldability and stiffness. The 1421 alloy was also made with higher values of yield stress and ultimate strength, but the main defect of this alloys is the poor toughness caused by shearing of Al_3Li which considered as the most strengthening phase [9,12]. The 2nd generation Al–Li alloys is created for aerospace and aircraft applications with the objective of reducing density (for 8%–10%) compared to traditional al alloys [13–15], and stiffness improvement [3,16]. Therefore, a main challenge was to develop materials with enhancements in both mechanical properties and life cycle that can be used in the construction of wings and fuselage. Accordingly, in the 1970s and 1980s. The majority of prior research has focused on the optimization of Silicon and Iron contents that have the primary effect on ductility and toughness, the same for Manganese that was replaced zirconium to produce Al_3Zr precipitates for ductility, toughness, and grain refinement [17,18]. The increase in the percentage of lithium can generate an increase in size and volume fraction of δ′ which is responsible on strengthening [19] and was the reason for increasing lithium percentage in the second generation of Al–Li-X alloys as shown in Table 1 [9], but this higher % addition of lithium cased several advantages that limited their usage like fracture toughness, corrosion, anisotropic and fatigue [20,21].

2.2. The 3rd generation of Al–Li alloys

The defects faced in the 1st of 2nd generations have been reduced in the 3rd generation of Al–Li alloys [22]. Reducing inspection

Table 1
Densities, alloying elements and the developers on the three generations of aluminum lithium alloys [9].

Alloy	Li wt %	Cu wt %	Mg wt%	Ag wt %	Zr wt %	Sc wt %	Mn wt%	Zn wt%	Al wt %	Density g/cm^3	Place. Data
First generation											
2020	1,2	4,5					0,5			2,71	Alcoa 1958
1420	2,1		5,2		0,11					2,47	Soviet, 1965
1421	2,1		5,2		0,11	0,17				2,47	Soviet, 1965
Second generation (Li > 2 wt%)											
2090	2,1	2,7			0,11					2,59	Alcoa 1984
2091	2,0	2,0	1,3		0,11					2,58	Pechiney 1985
8090	2,4	1,2	0,8		0,11					2,54	EAA 1984
1430	1,7	1,6	2,7		0,11	0,17				2,57	Soviet 1980s
1440	2,4	1,5	0,8		0,11					2,55	Soviet 1980s
1441	1,95	1,65	0,9		0,11					2,59	Soviet 1980s
1450	2,1	2,9			0,11					2,60	Soviet 1980s
1460	2,25	2,9			0,11					2,60	Soviet 1980s
Third generation (Li < 2 wt%)											
2195	1,0	4,0	0,4	0,4	0,11					2,71	LM/Reynold s, 1992
2196	1,75	2,9	0,5	0,4	0,11		0.35 max	0.35 max		2,63	LM/Reynold s, 2000
2297	1,4	2,8	0,25 max		0,11		0,3	0,5 max		2,65	LM/Reynold s, 1997
2397	1,4	2,8	0,25 max		0,11		0,3	0,10		2,65	Alcoa, 2002
2098	1,05	3,5	0,53	0,43	0,11		0,35 max	0,35		2,70	McCook-Metals, 2000
2198	1,0	3,2	0,5	0,4	0,11		0,5 max	0,35 max		2,69	Reynolds/McCook-Metals/Alca n, 2005
2099	1,8	2,7	0,3		0,09		0,3	0,7		2,63	Alcoa, 2003
2199	1,6	2,6	0,2		0,09		0,3	0,6		2,64	Alcoa, 2005
2050	1,0	3,6	0,4	0,4	0,11		0,35	0,25 max		2,70	Pechiney/Alcan 2004
2296	1,6	2,45	0,6	0,43	0,11		0,28	0,25 max		2,63	Alcan 2010
2060	0,7	3,95	0,85	0,25	0,11		0,3	0,4		2,72	Alcoa 2011
2055	1,15	3,7	0,4	0,4	0,11		0,3	0,5		2,70	Alcoa 2012
2065	1,2	4,2	0,5	0,30	0,11		0,4	0,2		2,70	Constellium 2012
2076	1,5	2,35	0,5	0,28	0,11		0,33	0,30 max		2,64	Constellium 2012

and maintenance, weight savings, and performance are the main reasons for the development of this generation were tailored to cover the requirements of aeronautic and military industry [2]. The image below shows an example of the application of Al–Li alloys in the aircraft manufacturing. as it is seen in Table 1, the 3rd contains lower amounts of Lithium (<2%) and an important Cu/Li ratio compared to the 2nd generation alloys [23]**.** It was noted that decreasing lithium amounts can positively influence the thermal stability and toughness of aluminum lithium alloys [14,24,25] (see Fig. 1).

3. Manufacturing processes for aluminum lithium alloys

3.1. Sheet metal forming process

The sheet metal forming is widely used in the aeronautic industry for manufacturing aircraft parts such as leading, trailing edges, access covers, and wing skin etc. Deep drawing process consists of manufacturing, from a thin flat blank, a part of complex shape that is generally non-developable. The blank being pressed, with a certain force against the die, by the punch force using a press, and the flange is clamped the blank holder (Fig. 2). In this part, the different studies on the lithium aluminum alloy for the stamping process will be investigated, as well as the various parameters (geometrical and process) which influence the formability from a numerical and experimental perspective.

3.1.1. Characteristics of forming limit diagram (FLD) and forming limit curve (FLC)

The FLD is widely used for the assessment of part formability using the FLC, which characterizes the boundary between the safe and failure forming region as it is shown in the (Fig. 3 a). It was first developed by M. Goodwin [29] and Keeler [30]; the limit strains at the onset of necking can be also observed [31]. Two-axis graph representing major and minor strains that can be measured by formability testing using grid sheets, the (Fig. 3 b)) shows the different specimen blanks required to establish the forming limit curve.

The most used technique in the measurement of deformation is the grid marking. In stamping, the measurement of deformations on the stamped parts was previously done using grids pre-deposited by electrochemical marking or by micro-engraving on the blank before stamping (Fig. 3b). The analysis of the evolution of these grids after drawing could then give an indication of the final state of deformation in each point of the grid. The measurement of the deformations of the network can also be carried out by the correlation of the two images: the initial image of the pattern and the phantom image. To achieve this correlation it is necessary to acquire images using a video device connected to a computer, an image acquisition program and an image correlation program [32,33]. Lou et al. [34] evaluated the ductile fracture criteria using FLDs for 30 kinds of aluminum alloys with linear strain increment, they concluded that the Oyane-Sato, Brozzo, and Ko-Huh criteria can be used for the left hand side for the FLD prediction, but they have not a good agreement with experimental data for the right hand side. Other models and criteria can be used to predict FLD diagram, such as Marciniak–Kuczynski (M−K) modified model is widely used for the FLC considering through-thickness normal stress and anisotropic yield functions [35], FLD calibration [36], at elevated temperature [37]. There are several methods for determining limit deformations [38]**,**

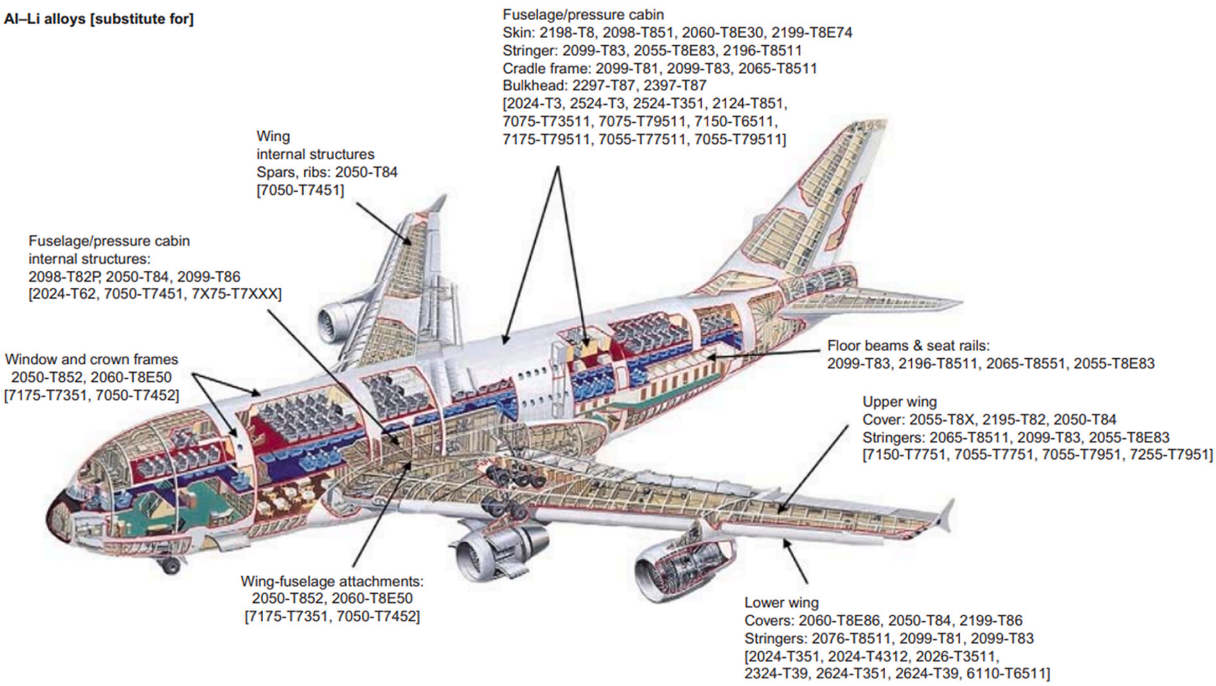

Fig. 1. Various uses of the 3rd generation of Al-Lialloys in the aircraft structure (Thomas Dorin and Justin Lamb, 2018).

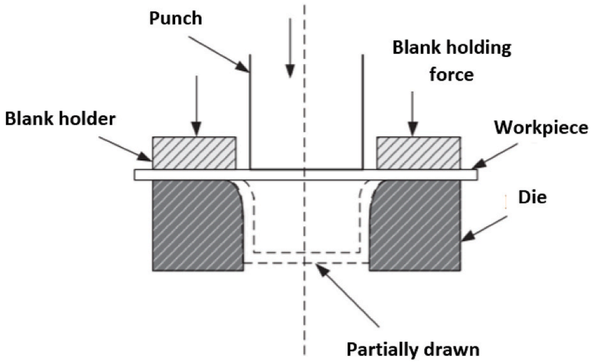

Fig. 2. Deep drawing process [26].

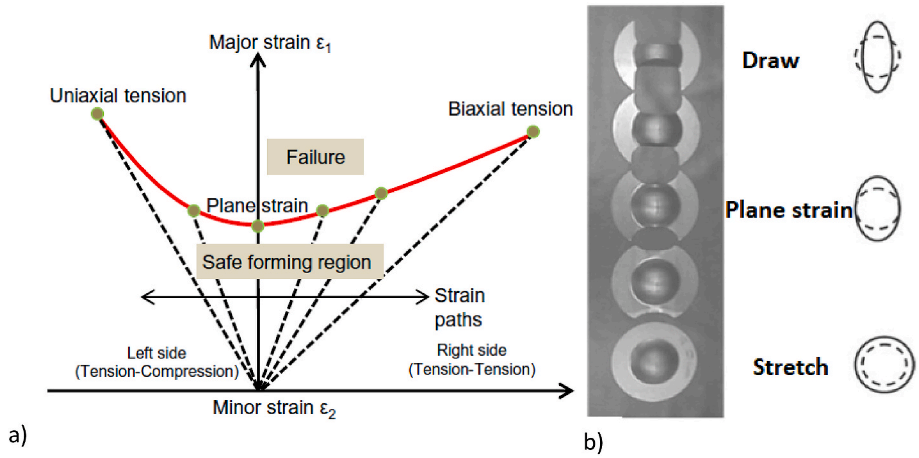

Fig. 3. a) Forming limit diagram [27] and b) specimens using to determine forming limit diagrams [28].

Veerman proposed in 1968 a method for determining the strain gradient in the vicinity of failure. a variant of the Veerman method was proposed by Bragard in 1972 where the main deformation on the ellipses along a line perpendicular to the crack are measured, then defined by a parabolic interpolation of the limiting strain. The Hecker method (1972) is based on the measurement of deformations on three kinds of circles after stamping: affected by the fracture, by and without necking. There are different types of laboratory tests used to characterize elastic behavior and formability such as: Swift test, Nakazima test, and Marciniak test [39,40]. Many numerically methods are used for the necking limit detection; (i) Iso method [41] which it is characterized by a specific specimen's geometry, limit strain determination method and lubrification condition [42]. (ii) Time dependent method [43], which consist to analyzing the strain rate in the necking region [44], (iii) Slope method and Flat-valley method, they are widely used for the FLD by necking and fracture [45,46].

3.1.2. Common defects in deep drawing

During deep drawing process, several defects may appear on the parts, mainly the fracture or tearing, wrinkling, and earing [47]. These defects can be the result of the process, material and geometric parameters [48]. Many researchers are carried out on study the impact of process and materials parameters on the parts.

- Defects related to process parameters

Several parameters can influence the formability in deep drawing processes, such as the Blank Holder Force (BHF), punch force and punch speed, Padmanabhan et al. [49] concluded in their studies that the die radius is the most influencing parameter on deep drawing process, while the blank holder force and friction coefficient have a minimum sensitivity for the process, but it impacts the production rate, surface quality and thickness distribution [50]. A large number of studies existing in the wider literature have investigated the impact of BHF on formability [51–53]. The blank holder force mainly affect the thinning [51,54]. Increasing the sheet thickness for AA2024-T4 produced with rolling process has a positive effect on the FLC, and the anisotropy has a minimum effect on the FLC [42]. The rupture defect can appear with a large BFH, as long as a small BHF can lead to wrinkling defect [55]. A combination of the blank holder force and punch speed fuzzy control system has been developed by Manable et al. [56], this methodology has improved product quality, and also productivity. Bouchaâla et al. [57] found that both the punch corner radius and the die shoulder radius is one of the parameters that effect earing height, they found that for minimizing this defect; the sheet thickness must be about 1/8 times die shoulder radius, and the cup failures can be accurse when the punch nose radius is less than 3 times sheet thickness. The lubrification has also a good effect on the formability by reducing the stress strain generation [58]. Dou et al. [59] demonstrated that after grinding with the die; the sliding velocity is inversely proportional with the surface roughness of the sheet metal.

- Defects related to material parameters

Generally, each material has specific properties and characteristics (mechanical properties, heat treatment, production process, etc.), these characteristics can modify the formability of these materials. Krishan et al. [60] have studied the formability of 1441 Al–Li alloy, they concluded that increasing temperature results in the increase of the FLD level due to the positive strain rate sensitivity. The planar anisotropy parameter which is mainly due to the rolling direction and mechanical properties of materials has a big effect on increasing the size of earing [57]. The wrinkling is one of the primary defects in deep drawing process which occurs at the cup ages of the parts or at the flange region, and it is due to a local buckling caused by compressive stresses. authors in Refs. [61–63] agreed that wrinkling resistance increases proportionally with strain percentage. Li et al. [64] have studied the FLC for Al–Li alloys 2198-T3 sheet, the hardening exponent (n-value) has more sensitivity for the FLC compared to the thick anisotropy coefficient (r-value). Increasing the punch travel can cause the propagation of fracture bands along the workpiece wall [65]. Annealed cups can enhance the formability (increases drawing depth and decreases earing) [52]. Thus, annealing between forming steps; the thinning amount decreases with the reduction of the blank holder [66]. Spring-back is one of the major defects in deep drawing process, this defect characterizes the difference in the final dimensions of the part produced and the dimensions of the manufacturing tools. Among the set of existing experimental tests to demonstrate this elastic return, the simplest and most widespread are bending tests; V and U bending test [67,68], Demeri test [69] and draw-bending test [70]. Most early studies as well as current works focus on spring-back phenomenon for Al-Lialloys. Liu et al. [71] in a recent paper studied the limit of bending radius for extrusions Al–Li alloys using finite element model validated by stretch bending tests, the high yield strength ratio and Young's modulus. Applying an additional tension with high value compared to the initial tension can reduce the spring-back [72].

3.2. *Hydro-mechanical and warm deep drawing process*

Many researchers conducted a lot of efforts to study hydromechanical and warm deep drawing process because of its impact on formability improvement. The hydromechanical shaping processes are based on an idea already tested at the beginning of the century [58] [75] [76], but their development and industrial use is however only very recent. There are three types of hydroforming: tube hydroforming, blank hydroforming, and double blank hydroforming. The common feature of hydroforming processes is the use of a fluid (back pressure) instead of a die. Many methods are used by researchers to study this process. Intarakumthornchai et al. [73] studied the optimal process parameters of parabolic cup using FEA based fuzzy logic and 2-D interval halving fuzzy approach. Yaghoubi et al. [74] stated that for the hydromechanical deep drawing process of 2024 al alloy; the punch radius, die entrance, and the punch-die clearance are mainly influenced parameters on the final product uniformity. The die radius is the main parameter for the hydro-mechanical process on wrinkling and erosion defects [58]. Hot forming process is a method in which the parts are formed at high temperatures when in a more ductile state, which results in an improvement in formability compared to the cold stamping process, but it is limited by the severe spring back at ambient temperature [75]. The main parameters that can influence formability of this process are: blank holder force, hydraulic pressure, temperature which is the most critical parameter [76]. The aluminum alloys under warm deep drawing can be more anisotropic by increasing the holding time and anisotropic parameters values until reaching a value equal to 1 [77,78]. The thickness after forming can be more uniform for the warm forming compared to the hydromechanics forming process [79]. Yang et al. [80] investigated the 2060 Al–Li alloy under hot deep drawing process, they concluded that increasing sheet temperature can enhance the formability and mechanical properties. It is proved that the non-uniform distribution of temperature can enhance drawability [81]. Gao et al. [82] studied the feasibility of forming the AA2060 Al–Li alloy by using heat treatment forming and in-die quench (HFQ) process, this method that can retrain mechanical behavior of al alloys [83]. Other methods can be used for the formability enhancement, Rong et al. [84] evaluated the ductile deformation behavior by using a combination of hot Nakazima and uniaxial isothermal tensile tests at different level of temperatures and strain rate. Recently, many researchers are interested on the combination of hydroforming and warm forming processes, it is proved that the combination of this two processes enabled a higher limit drawing ration [85], Elliptical warm bulging test is used by Cai et al. [86] for FLD prediction, and for a good formability; the optimal parameters must be determined. The optimal hydraulic pressure and blank holder force profiles was determined by Choi et al. [53] using finite element model, with developed Fuzzy control algorithm and anOVa (analysis of variance), the temperature of the punch and the flange is more sensitive than the die corner temperature. Other parameters such as heating time, working temperature and oil pressure setting are investigated by Palumbo et al. [87], they concluded that the increase of aging temperature till the averaging can negatively affect the FLD and mechanical properties.

3.3. *Aluminum lithium alloys for additive manufacturing*

Additive manufacturing processes have regularly been at the heart of the news in recent years, It is opposed to subtractive manufacturing processes (machining for example) or by deformation (forging for example) by making it possible to manufacture layer parts by layer from a 3D file [88] (Reiner [89,90]. With regard to manufacturers in the aeronautics and space sector, additive manufacturing plays a very important role, with a view to significantly reducing part manufacturing time while maintaining great flexibility in design with well-defined mechanical and metallurgical properties [91] (L [92]. This technology has the advantage of not using any tools during the manufacturing process and makes it possible to produce in a very short time (a few days) small series of functional parts with complex morphologies (Reiner anderl et al., 978) [93]. According to NF ISO/ASTM 52900, additive manufacturing is the process of assembling materials to manufacture parts from 3D model data, generally layer by layer [94]. There are seven main additive manufacturing processes which have the same principle, which is the manufacture of parts by adding material layer by layer namely: Binder Jetting, Directed Energy Deposition, Powder Bed Fusion, Sheet Lamination, Material Extrusion, Material Jetting, and Vat Photo Polymerization [94]. Only few researchs are the subject of the 3rd generation of aluminum lithium alloy for additive manufacturing. Zhong et al. [95] investigated microstructure and mechanical properties of Wire arc additive Manufacturing (WAAM) for Al–Li2050 Alloy, they concluded that the micro-hardness can be improved by post-deposited solution treatment and artificial aging (T6), after post deposited heat treatment; a dispersedly distribution of the θ (Al_2Cu) and δ' (Al_3Li) secondary phases at the grain boundary are observed. Most often, the cooling rate is characterized by the dendritic fineness which can be estimated by DAS (Dendrite Arm Spacing), Also an increase in grain size is explained by the increase in heat flow per unit length which justifies the fines of the grain size of additive manufacturing processes compared to conventional processes (Fig. 4) [96,97]. Liu et al. have studied the Al-14at%Li (Atomic %) high lithium alloy as cast and Laser Powder Bed Fusion (L- PBF), the cooling rate is higher for the laser power bed fusion process which leads to a uniform Li distribution in the primary α phase through solute trapping rather than to the formation of the brittle δ–Al-Liphase which is prevented, which can improve the hardness (G. Liu et al., 2021). Urekli et al. demonstrated that the for the additive manufacturing (L PBF) process using binary Aluminum lithium alloys, the elastic modulus radically increases with increasing of lithium content, and the high cooling rate is the most important parameters to reduce the negative effect of δ–Al-Li phase on yielding an inhomogeneous microstructure and degraded mechanical properties [98]. Raffeis et al. investigated the microstructures of an AA2099 Al–Cu–Li Alloy for the Laser Powder Bed Fusion process (LPBF), the T_1 phase cannot nucleate on dislocations without appropriate heat treatment, the preheating gave birth to two main precipitation, T_1 (Al_2CuLi) and T_B ($Al_{7.5}Cu_4Li$) [99]. Xin et al. studied the effect of heat treatment process on mechanical properties and microstructures of laser additive manufactured 5.02w% Cu-1.04%wLi aluminum Lithium alloys, they concluded that α(Al) matrix and T_B(Al_7Cu4Li) are the main phases on as deposited microstructure with small amount of copper rich phase in the grain boundary (Xin [100]. The T_B phase and copper-rich disappear after anneAling, with Al–Cu–Fe impurity phase presented in the grain boundary. The solid solution quenching and heat treatment enhance microhardness and tensile strength of Al–Li alloys compared to as-deposited alloys (Xin [100]. Jiao et al. investigated the heat treatment microstructures, T_B phase and its influence on the micro-hardness of laser additive manufactured Al–Cu–Li alloys [101], they have confirmed results in the (Xin [100] ref, they observed Also that during aging at 400 °C; the micro-hardness decreases before it reaches the maximum vAlue [101].

3.4. Forging/extrusion process for aluminum lithium alloys

The processes for obtaining parts vary depending on the nature of the materials, their function and their geometry. Most products are obtained by forming processes such as extrusion (hot or cold), stamping, rolling (hot or cold) and forging (hot or cold) ("advancement in Forging Process," 2017). Rolling and stamping processes are used for sheet metal processing (Vallabh Bhoyar and Swapnil Umredkar, 2020) [102]. Forging is a shaping process by hammering or pressing after hot softening. Forging techniques are useful because they Allow it to be shaped into the desired shape. This process enhances the structure performance of the metal since it reduces the grain size. Forged metal in general has a good stiffness and more ductility compared to cast metal and exhibits high fatigue resistance. The forging process is rarely used for Lithium aluminum alloys [3], but it is used for some parts in the aeronautical field such as aircraft bulkheads, wing attachment and crown frames using 2050-T852 and 2060-T8E50 alloys [48]. As for the extrusion process, it makes it possible to obtain a long product with a constant cross section over its entire length [103]. Extrusion is a process by which metal, originally in billet form, is pushed under high pressure by the action of a punch through a die, and out as a channel. It can be

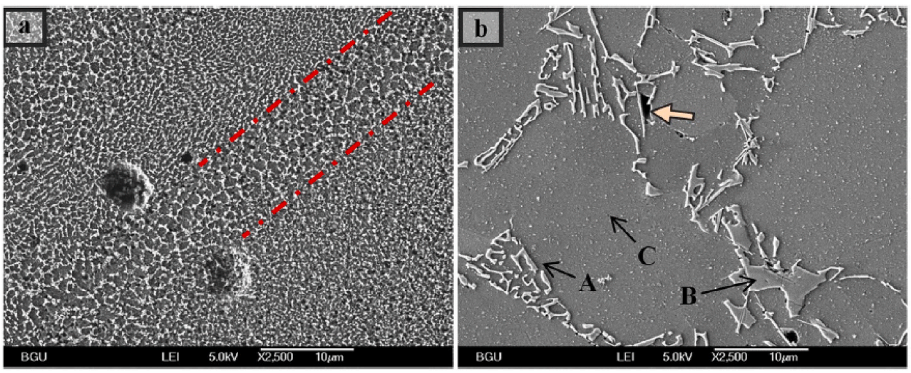

Fig. 4. Microstructure of AlSi10Mg manufactured by a) SLM, b) foundry. With (a) the Al–Si eutectic, (B) Si dispersed in the Al matrix and (C) the intermetAllic phases containing Fe [96].

done in cold extrusion process in the case of low mechanical strength and high ductility alloys (1000 and 3000 series), and hot extrusion process mainly in the case of higher mechanical strength Alloys such as series 2000 and 7000, but also 5000 and 6000 series [104]. Aluminum alloys are considered as the most suitable materials for extrusion and are distinguished by a variety of profiles unmatched compared to other materials. The extrusion alloy can include 2.6 to 3.0 wt% Cu, and 1.4 to 1.75 wt% Li [9]. Denzer et al. [105] noted that the plate and extruded 2055-T8E83 alloy can have similar mechanical properties compared to 7055-T7751 such as strength and toughness with lower density, but it has been found that the oxidation rate can presents a high value for the Al–Li alloys compared to some conventional Al alloys such as the Al–Mg alloys [106]. The NASA use extruded Al–Li 2195 structures produced by spin or stretch forming, heat treatment process dramatically enhances the formability [107]. Extensive research work has been conducted on the effect of double stage for solution heat treatments [6,108], it increases dramatically mechanical properties by increasing solutes supersaturations.

3.5. Friction/stir welding FSW for aluminum lithium alloys

According to ISO 25239–1:2011 [109]; friction stir welding is a hot working process of permanent assembly of parts based on the principle of resistance between the surfaces of two bodies in contact which move in relation to each other, the first utilization was in 1991 by Thomas Wayne au TWI, and it is widely used for welding aluminum alloys that cannot be welded by conventional welding processes. FSW Allows to obtain welded joints with high mechanical characteristics, generally superior to those obtained with traditional fusion techniques [110]. The temperatures reached in FSW are relatively low, thus limiting the deformations generated by the welding cycles [111]. One of the main challenges in this process is to have final parts without the following main defects: hot crack/weld solidification cracking and weld holes [112]. This requires a control of both the applied load, the rotation speed and the translation speed [113], other parameters have to be considered in this process are mentioned in Refs. [114,115] references. All input parameters are summarized in Fig. 5 a large number of existing studies in the broader literature have examined the weldability of Al-X-Li Alloys [116–118]. Hatamleh et al. [119] studied the peening effect in SFW for 2195 aluminum alloys, they mentioned that the strain hardening positively affect mechanical properties due to the dislocation that can increase flow resistance generated by high energy peening. For the 2090 Al–Li alloy, heavy precipitation of T_1 (Al_2CuLi) in the heat affected zone can ameliorate hardness, and δ′ (Al_3Li) can be observed in the nugget zone [120]. [121] have studied the effect of heat treatments on the microstructure of 2198/2024 aluminum alloys for dissimilar FSW with T3 and T8 heat treatment, they concluded that during welding process; the mechanical characteristics can be enhanced due to the re-precipitation of dissolved T_1 (Al_2CuLi) and θ (Al_2Cu), while the heterogeneous nature of the nugget area of the nugget region with Mg element on the border inside joint S1 and S2 (Fig. 6, Fig. 7). The initial temper of the material is the main parameter that effect the microstructure for the different weld zones [122,123]. Mechanical properties of 2219-T6 FSW aluminum alloy are investigated by Xu et al. [124]; they concluded that the rotary speed has a big influence compared to transverse speed. Redissolution of precipitation in the heat-affected zone can generate an amount of softening that can degrade the mechanical properties after FSW [82,125,126], but the impact of softening can be reduced by heat treatment [127–129].

4. Precipitations, mechanical properties and grain refinement of aluminum lithium alloys

4.1. The precipitate structure for age hardening

The mechanical properties of third generation Al–Li alloys are dramatically affected by the precipitates in their microstructures [130]. A large number of existing studies in the broader literature have examined of phase equilibria and precipitation reactions for these alloys. The structure of the homogeneously nucleated zones changes because of the presence of small amounts of lithium [131]. Depending on the ratio Cu/Li, the major strengthening phase Al_2CuLi (T_1) and Al_2Cu (θ') can be formed by the additions of Cu, in addition; Li additions form the coherent Al_3Li (δ_0) and the zirconium additions form the coherent Al_3Zr phase this precipitations which can eliminate recrystallization and thus generate a strong deformation at the texture [132,133]. The Al–Cu–Li alloys can present high amount of δ′ (Al_3Li) precipitate as compared to Al–Mg–Li alloys [134]. Strengthening of Al_3Li is caused by several mechanisms such as modulus hardening and order hardening, coherency and surface hardening (Minoru [135]. The Schematics of typical microstructural for Al–Li alloys are presented in Fig. 8.

The plasticity and toughness of Al–Cu–Li alloys can be improved by double aging from high to low (165 °C, 10 h) + (140 °C, 35 h)

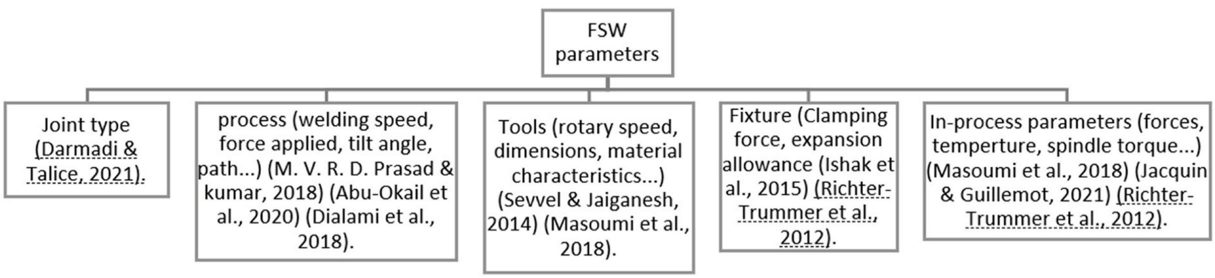

Fig. 5. The different parameters considered in the FSW process.

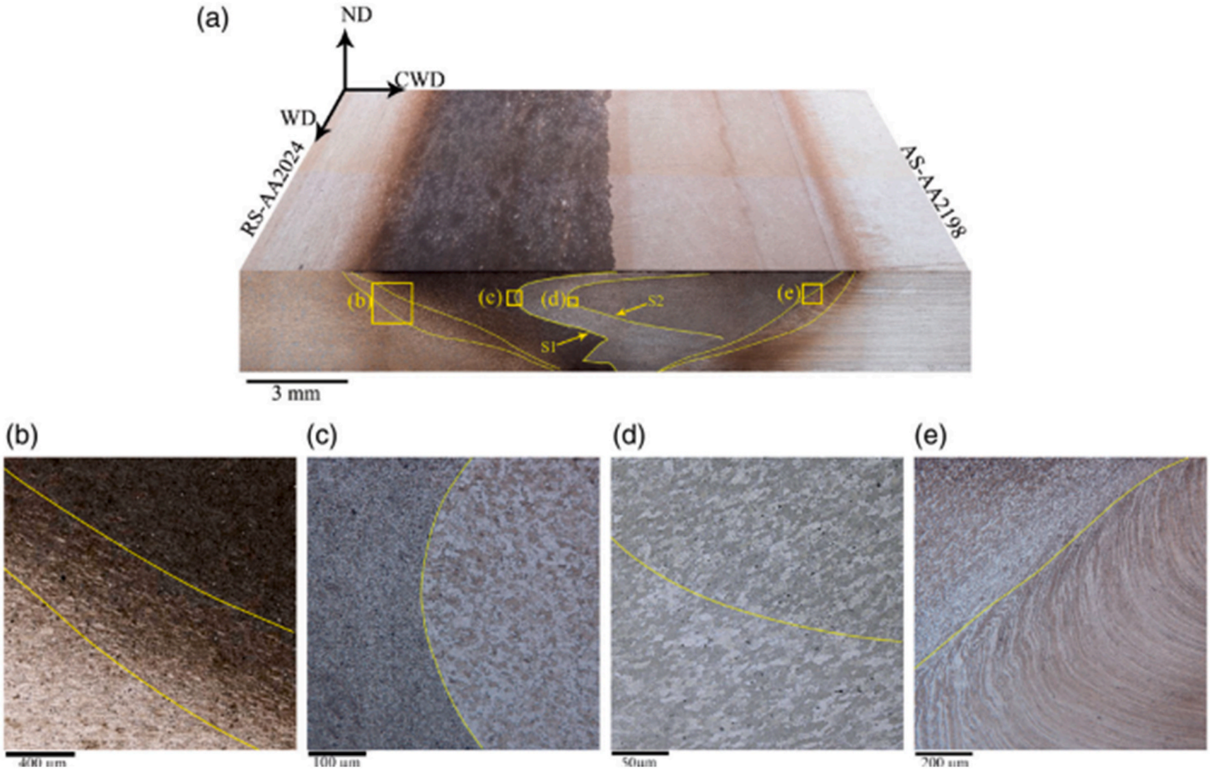

Fig. 6. Joint aW-T3 microstructure for the cross-welding direction, (a) joint macrograph, (b) retreating side transition, (c) S1 border inside joint, (d) S2 border inside joint, (e) advancing side transition [121].

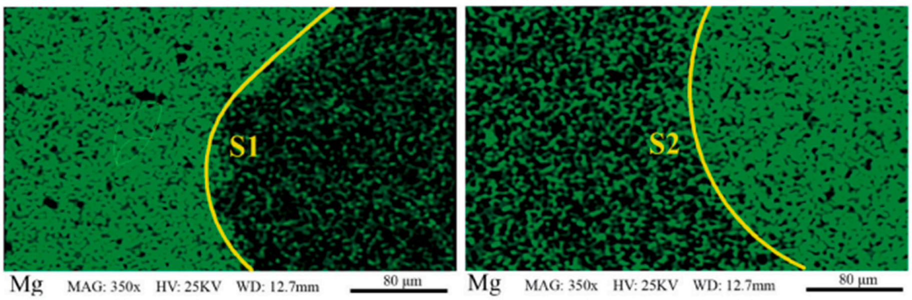

Fig. 7. EDS map of Mg element in the joint region around (a) S1 border, and (b) S2 border [121].

due to the growing of the T1 phase (the major phase with a non-uniform size distribution) after the first ageing step and promoted the formation of new precipitates [6]. The Al_2MgLi and δ_0 phases may form in Al–Mg–Li alloys but in complex Al–Li alloys containing Cu, Al_2CuMg (S_0) forms and can eliminate the formation of Al_2Cu [137]. For the 2a97 aluminum lithium alloys, Guinier- Preston zone (GP zone) can be formed after aging without pre-deformation for 12 h at 165 °C, with cubic precipitates can only be observed after aging at 40 h. The T1 precipitates in 2A97 alloy aged at 150 °C for 4 h for alloys aged with 6% pre-deformation at 150 °C which is longer than the alloy aged at 165°c without pre-deformation [138], Fig. 9, shows the DF image of the 2A97 aged for 4 h at 150 °C.

Hekma$_t$-ardakan et al. [139] observed that the as-cast AA2195 alloys exhibit a very low ductility and strength, and it is not recommended to be used directly in the mold application. As a result of the previously mentioned issues, the different aging statuses and strain rate influence the adiabatic shear behaviors of 2195 aluminum–lithium alloy, The peak-aged (heat treated at 500 °C for 30 min, then water-quenched and subsequently aged at 180 °C for 4 h) 16 h (peak-aged), 40 h (over-aged), specimen has the highest adiabatic shearing susceptibility, while the under-aged specimen has the least adiabatic shear susceptibility [140]. During deformation, the ability of the various precipitates to resist dislocation motion is the essential factor for the strengthening response of age-hardenable Al–Li–Cu-X alloys [132]. Walker et al. [141] have worked on the effect of incomplete solution treatment on 2195 Al–Li alloy. They have demonstrated that the strength values is higher in case of full heat treatment and the incomplete heat treatment can reduce the

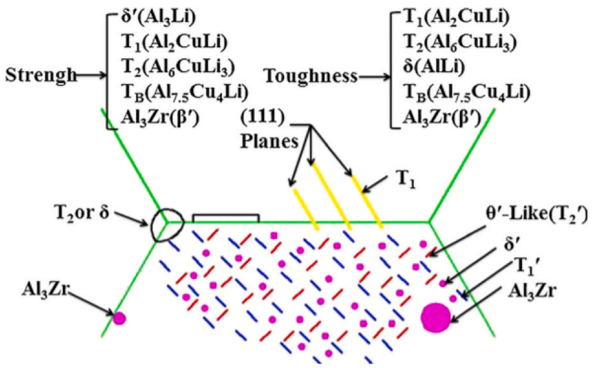

Fig. 8. Schematics of typicAl microstructural features for Al–Li Alloys [136].

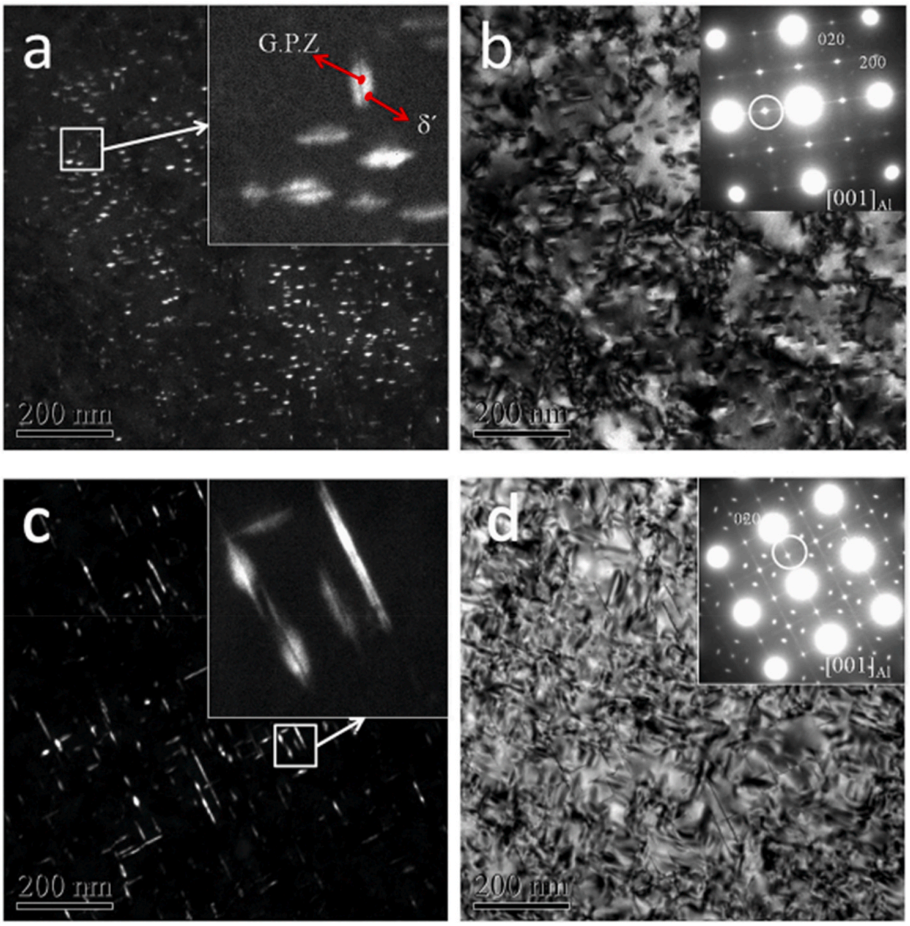

Fig. 9. DF images of the 2a97 alloy aged at 150 °C for (a) 4 h, (c) 16 h, and BF images and corresponding SaED pattern of the 2a97 alloy aged at 150 °C for (b) 4 h, (d) 16 h all images are viewed along the [001]Al direction [138].

amount of T1 precipitates that can be nucleated on the dislocation structures during cold work. T1 precipitation can be formed after ageing treatment and can decrease copper content in solid solution in Al–Cu–Li alloys [142]. For the Al–4Cu–1Li-0.25Mn–alloy; the age hardening can influence the thickness of Al_2Cu precipitate, which is the major phase, it increases continuously with time (aging at 17 h–180 °C) and the Al_2CuLi phase growth slowly with time [143]. While for the Al-1.3Li-5.8Cu-0.4Mg-0.4ag-0.14Zr-0.3Ce an achievement of excellent mechanical properties and microstructure evolution during hot treatment (520° at 30 min) was carried out due to a large amount of Al_2CuLi precipitate and a few needle phases like Al_2Cu (compared to Ref. [143] results) that can be observed [144]. Table 2 [3], presents the impact of alloying elements for the Al–Cu–Li alloys.

4.2. Effect of precipitations on mechanical properties of Al–Li alloys

Several studies which focus on mechanical properties of Al–Li alloys. The initial microstructure is the essential parameter in the determination of ductility, cracking resistance, strength, and fracture toughness [145]. The Ce + Zr addition can enhance mechanical properties of Al–Cu–Li alloys, the alloys with Ce and Zr have higher yield strength and ultimate tensile strength [146,147]. Si and Fe can influence negatively the properties like toughness fracture, affect strength and work hardening by coursing intermetallic compounds that can be seen at grain boundaries [148–150]. The addition of various amounts of Mg and Cu can give rise to precipitation of the S' (A12CuMg) that depends strongly on the amount of Li present and on the presence of reinforcing SiC particles phase [151] which can improve strength and tensile ductility [9]. It was noted that the hardness increasing with a good combination of toughness and strength can be caused by the addition of different amounts of rare earths for the Al–Li–Cu alloys [152]. A peak in the strength was observed for 1.3 wt% Li of Al–Li–Cu–Zr alloys with trace additions of Mg and Ag compared to various amounts of lithium from 0 wt% Li to 1.3 wt% Li [153]. The tensile properties of 2099 alloys is improved by homogenization treatment compared to as-cast alloy by the dissolution of interdendritic phases, uniform deformation caused by the decrease of dendritic structures that can enhance ductility, reduction of grain boundaries phases which positively influences the propagation of micro-cracks under stress at grain boundaries that increase strength [154]. For the Al–Li 2198-T8 alloys processed by (high pressure torsion) HPT, the strength and hardness increase because of dislocation strengthening and grain refinement [155], and its plasticity is inversely proportional with the tensile strength in case of processing by Friction Spot Welding (FSpW) [83]. The effect of different phases on mechanical properties for Al–Li alloys are summarized in Fig. 10.

Recent studies have directed their interest toward the Processing-Structure-Properties Performance (PSPP) Maps to study, design and optimize materials used in the industry. This structure is generally used because it describes all hierarchical scales (microscopic/atomic and macroscopic) [156]. Thus, the PSPP map is an important communication tool the properties required, the entire desired processing route, various structural features of the material and the relationships between the blocks (Fig. 11).

4.3. Grain refinement

Final grain size control is the main influencing factor to enhance mechanical properties for aluminum alloys in general. Grain refinement of the third generation Al–Li alloys has been investigated by so many researchers [18,158–160]. Xinxiang et al. [146] have worked on the effect of Cerium and Zirconium microalloying addition in Al–Cu–Li alloys, they proved that the intermetallic dispersoids can be refined by Ce addition after homogenization, grain refinement can be obtained also by four methods: Severe Plastic Deformation (SPD), the addition of Grain Refiner (GR), Rapid Solidification (RS), Vibration and Stirring (VS) during solidification [161]. The presence of Zr on Al–Li alloys can control grain structure during high temperature by promoting $Al_3Zr\_Al_3Li$ dispersoids, which minimize the planar slip and improve ductility [162]. For the 2099 alloys, the dendritic structures can disappear after two-step of homogenization treatment with a degreasing of segregation at the grain boundaries with residual AlCuFeMn/AlCuMn particles around it [154]. Liu et al. [159]. Concluded that for the 2195 Al–Li alloy, the grain size increases with annealing at a lower temperature (300–350 °C), and increase when the annealing temperature rose (350–400 °C) as well as the deformation texture. Suresh et al. [158] in the investigation on effect of Sc addition on the evolution on the texture of AA2195 alloys during thermo-mechanical processing, they concluded that the Sc addition reduce the grain size and enhanced precipitation kinetics with hardness and strength improvement as well as the presence of fine Al_3(Sc,Zr) dispersoids.

4.4. Macroscopic anisotropy and texture in Al–Li alloys

Several parameters can influence the anisotropy of Al–Li alloys such as crystallographic texture, shearing of the Al_3Li phases and the subsequent flow localization orientation relative to the current stress states, recrystallization degree, type and history of the deformation process before artificial ageing, the distribution and morphology of the main strengthening phases, which are governed by alloying additions [9]. Al–Li alloys presents high anisotropy than traditional Al alloys, and its due to the coherent ordered δ′ phase (up to 20%) [134]. For the 1445 Al–Li alloy sheet; the non-recrystallization is caused by Al_3(Sc,Zr) nano-sized that can be coarsened when being solutionized of 575 °C and pin the grain boundaries, dislocations and subgrain boundaries while the main recrystallization model is subgrain coalescence and increase [163]. Controlling sheet metal's anisotropy can improve its formability and plastic anisotropy [164]. For 2195 Al–Li alloy cold-rolling sheet, the investigation for the anisotropy during aging treatment shows that the anisotropy decrease during aging time as long as over-aging is not reached [165,166]. During the sheet metal forming of Al–Li alloys anisotropy

Table 2
The impact of alloying element on Al–Cu–Li alloys [3].

Alloying Element	Impact
Li and Mg	Increase strength, decreasing density, and solid solution
Sc, Mn, Zr, and Cr	Texture and grain size control due to dispersoid formation.
Cu	Increase strength, and solid solution.
Zn	Increasing strength, corrosion, and solid solution.
Ag	Nucleation agent, coats the T1 precipitate.
Ti and B	Grain refinement
Na, Si, Fe, and K	Impurities, adversely affect mechanical properties

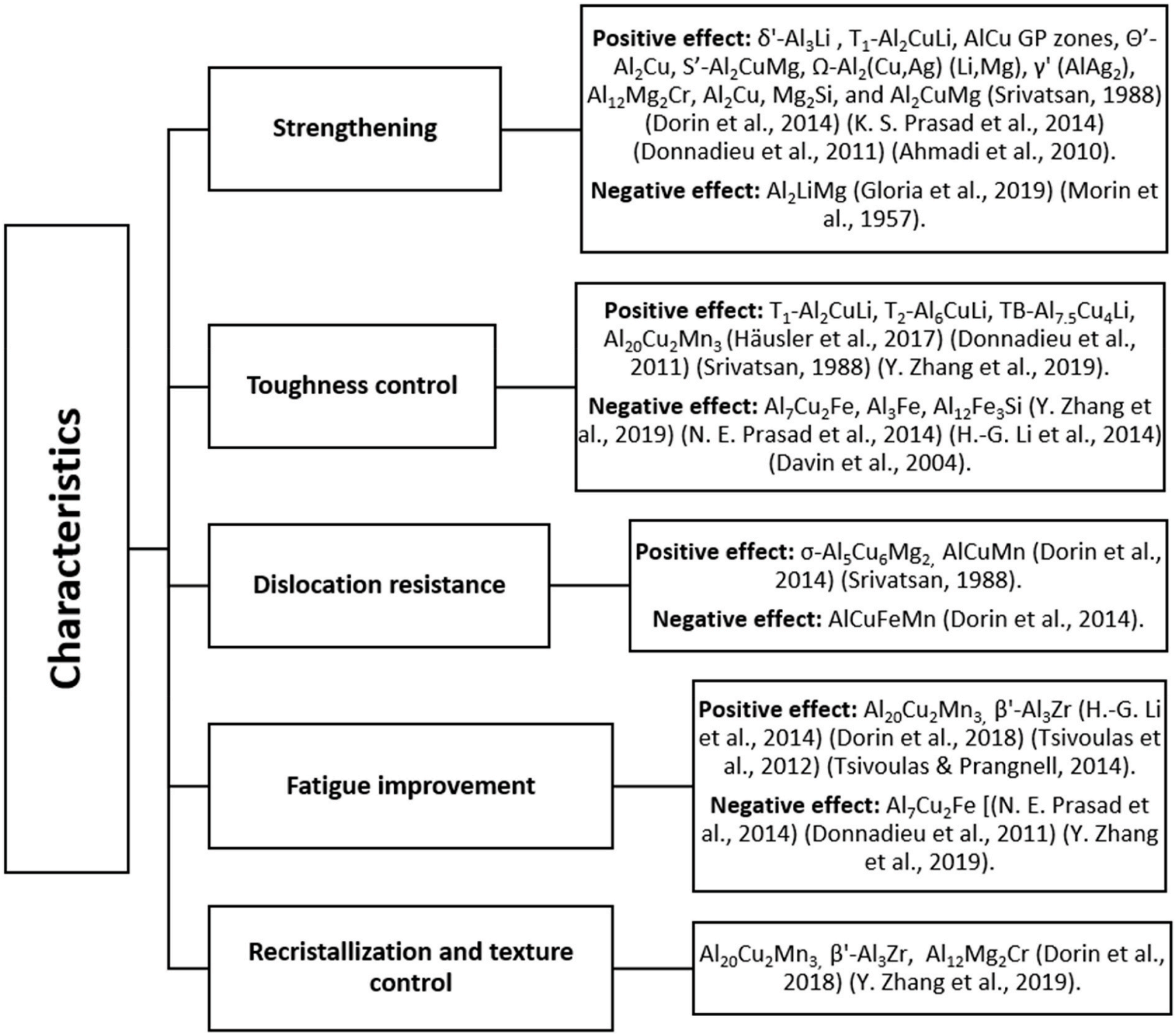

Fig. 10. Root cause - Effect of different phases on mechanical properties for Al–Li alloys.

affect the final formed shape. Bouchaâla et al. [167] investigated the effect of anisotropic and isotropic yield functions of AA2090 Al–Li alloy on the thickness distribution during sheet metal forming process. Many phenomenological yield functions have been proposed to predict the anisotropic plastic behavior of the sheet metal forming (e.g. Hill [168], Barlat et al. [169,170], Bron and Besson [171]). Bouchaâla et al. studied the influence of contact surface between the blank and the tools (Punch force, die shoulder radius, Blank holder force, Friction), two aluminum lithium alloys were used AA 2090 [172] and AA2198 [172,173], for this studies; a combination between FEM and Tagushi optimization was carried out [172].

5. Conclusion

This paper aimed to review and summarize studies for Al–Li alloys, especially on the different types of precipitations, the influence of the addition elements and their impact on the microstructure and mechanical properties. Research and development priorities have been discussed in the literature. The present study leads to conclude the following.

- The formability of parts depends on several parameters, in particular: the manufacturing process (forging, stamping, casting …), material parameters (chemical composition, anisotropy, fracture toughness …) and process parameters.
- Additive manufacturing processes present many limitations and challenges compared to conventional manufacturing processes. Manufacturing parameters, process defects (anisotropy, porosity, etc.), and manufacturing cost are the main challenges for industrial applications of additive manufacturing, particularly in the aeronautic industry.

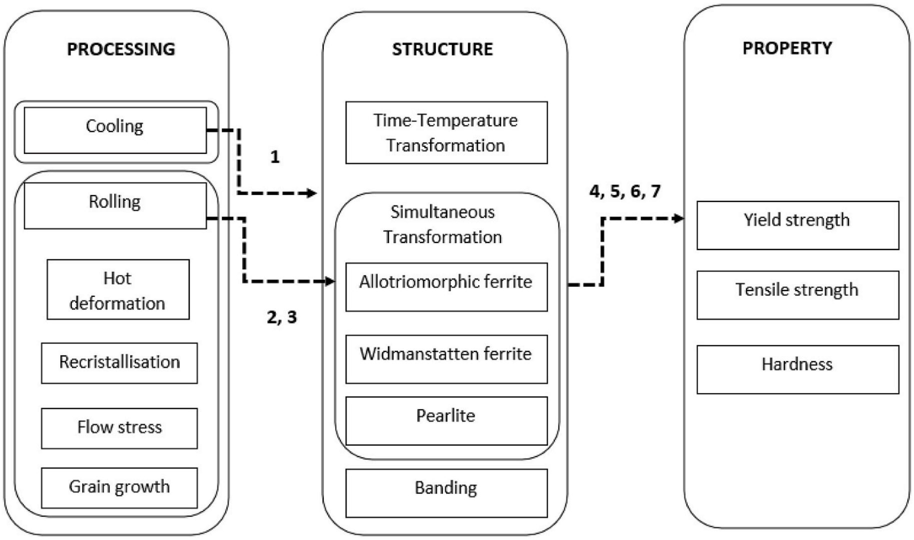

Fig. 11. Example of generalized PSPP map of hot rolling and cooling processes for steel production, 1: cooling rate, 2: austenite grain size, 3: chemical composition, 4: phase fractions, 5: ferrite grain size, 6 pearlite interlamellar spacing, 7 chemical compositions [157].

- The mechanical properties of Al–Li alloys are dramatically affected by the precipitates in their microstructures. The phase structures (T1 phase) control is the key influencing factor to enhance mechanical properties for the third generation of aluminum lithium alloys.
- Al–Li alloys exhibit different types of precipitations which can be varied depending on different parameters: addition elements, Cu/Li ratio, manufacturing process, and heat treatment. a good combination of these parameters provides an excellent characteristic of the Al–Li alloys.
- Final grain size control and the control of the different types of precipitations are the main influencing factor to enhance mechanical properties for aluminum alloys in general.

References

[1] a. Gloria, R. Montanari, M. Richetta, a. Varone, Alloys for aeronautic applications: state of the art and Perspectives, Metals 9 (6) (2019) 662.
[2] R.J. Rioja, J. Liu, The evolution of Al-LiBase products for aerospace and space applications, Metall. Mater. Trans. 43 (9) (2012) 3325–3337.
[3] T. Dorin, a. Vahid, J. Lamb, Aluminium lithium alloys, in: FundamentAls of Aluminium MetAllurgy, Elsevier, 2018, pp. 387–438.
[4] J. Li, Y. Li, M. Huang, Y. Xiang, Y. Liao, Improvement of Aluminum lithium Alloy adhesion performance based on sandblasting techniques, Int. J. Adhesion Adhes. 84 (2018) 307–316.
[5] Ph Lequeu, K.P. Smith, a. Daniélou, Aluminum-copper-lithium alloy 2050 developed for medium to thick plate, J. Mater. Eng. Perform. 19 (6) (2010) 841–847.
[6] H. Li, Y. Hu, J. Ling, C. Liu, G. Tao, Z. Sun, J. Tao, Effect of double aging on the toughness and precipitation behavior of a novel aluminum-lithium alloy, J. Mater. Eng. Perform. 24 (10) (2015) 3912–3918.
[7] C.L. Zou, G.H. Geng, W.Y. Chen, Development and application of aluminium-lithium alloy, Appl. Mech. Mater. 599 (601) (2014) 12–17.
[8] B. Noble, S.J. Harris, K. DinsdAle, The elastic modulus of Aluminium-lithium Alloys, J. Mater. Sci. 17 (2) (1982) 461–468.
[9] a. Abd El-aty, Y. Xu, X. Guo, S.-H. Zhang, Y. Ma, D. Chen, Strengthening mechanisms, deformation behavior, and anisotropic mechanical properties of Al-Li alloys: a review, J. Adv. Res. 10 (2017) 49–67.
[10] M.a. Muñoz-Morris, D.G. Morris, Microstructure control during severe plastic deformation of Al–Cu–Li and the influence on strength and ductility, Mater. Sci. Eng. 528 (9) (2011) 3445–3454.
[11] a. a. Alekseev, O.a. Setjukov, E.a. Lukina, I.n. Fridlyander, Nature of formation of the areas having an ultrafine grain structure in Al-Li-Mg system alloys, Mater. Sci. Forum 519–521 (2006) 265–270.
[12] E.a. Starke Jr., J.T. StAleyt, Application of modern aluminum alloys to aircraft, Pro 9. Aerospace Sci. 32 (1995) 131–172. University of Virginia, Charlottesville, Va 22901, U.S.A.
[13] R.G. Buchheit, D. Mathur, P.I. Gouma, Grain boundary corrosion and stress corrosion cracking studies of Al-Li-Cu alloy aF/C458, in: K. Jata, E.W. Lee, W. Frazier, n.J. Kim (Eds.), Lightweight Alloys for Aerospace Application, John Wiley & Sons, 2013, pp. 109–118.
[14] R.J. Rioja, C.J. Warren, M.D. Goodyear, M. Kulak, G.H. Bray, Al-Li alloys for lower wings and HorizontAl stabilizer applications, Mater. Sci. Forum 242 (1997) 255–262.
[15] J.-C. Huang, a.J. ardell, STREnGTHEnInG MECHANISMS aSSOCIaTED WITH T $_1$ PaRTICLES In TWO Al-Li-Cu AlLOYS, J. Phys. Colloq. 48 (C3) (1987). C3-373-C3-383.
[16] T. Dursun, C. Soutis, Recent developments in advanced aircraft Aluminium Alloys, Mater. Des. 56 (2014) 862–871, 1980-2015.
[17] B.-P. Huang, Z.-Q. Zheng, Effects of Li content on precipitation in Al-Cu-(Li)-Mg-ag-Zr alloys, Scripta Mater. 38 (3) (1998) 357–362.
[18] R.K. Gupta, n. nayan, G. nagasireesha, S.C. Sharma, Development and characterization of Al–Li alloys, Mater. Sci. Eng. 420 (1–2) (2006) 228–234.
[19] B. Noble, S.J. Harris, K. DinsdAle, Yield characteristics of aluminium–lithium alloys, Met. Sci. 16 (9) (1982) 425–430.
[20] M. Peters, J. Eschweiler, K. Welpmann, Strength Profile in Al-Liplate Material vol. 20, 1986, pp. 259–264 (Printed in the U.S.A.; Scripta METAlLURGICa).
[21] Y. Erisov, S. Surudin, a. Grechnikova, Structure and anisotropy of the mechanical properties of hot- and cold-rolled semi-finished products from aluminium-lithium alloys, Mater. Sci. Forum 945 (2019) 611–616.
[22] E.J. Lavernia, T.S. Srivatsan, F.a. Mohamed, Strength, deformation, fracture behaviour and ductility of Aluminium-lithium Alloys, J. Mater. Sci. 25 (2) (1990) 1137–1158.
[23] R. Rajan, P. Kah, B. Mvola, J. Martikainen, TREnDS in AlUMInIUM AlLOY DEVELOPMEnT anD THEIR JOInInG METHODS vol. 16, 2015.
[24] n.E. Prasad, a. a. GokhAle, P.R. Rao, Mechanical behaviour of aluminium-lithium alloys, Sadhana 28 (1–2) (2003) 209–246.

[25] V.V. Zakharov, Thermal stability of Al−Li alloys, Met. Sci. Heat Treat. 41 (1999) 1–2.
[26] U.S. Dixit, Modeling of metAl forming: a review, in: Mechanics of Materials in Modern Manufacturing Methods and Processing Techniques, Elsevier, 2020, pp. 1–30.
[27] Z. Shao, n. Li, J. Lin, T.a. Dean, Development of a new BiaxiAl testing system for generating forming limit diagrams for sheet MetAls under hot stamping conditions, Exp. Mech. 56 (9) (2016) 1489–1500.
[28] G. Patel, G. Kakandikar, Investigations on effect of thickness and rolling direction of thin metAl foil on forming limit curves in microforming process, in: Modern Manufacturing Processes, Elsevier, 2020, pp. 145–155.
[29] G.M. Goodwin, Application of Strain anAlysis to Sheet MetAl Forming Problems in the Press Shop, 1968, 680093.
[30] S.P. Keeler, Circular Grid System—A VAluable Aid for EvAluating Sheet MetAl Formability, 1968, 680092.
[31] R. Zhang, et al., A review on modelling techniques for formability prediction of sheet metAl forming, Int. J. Lightweight Mater. Manuf. (2018).
[32] a. Hijazi, n. Yardi, V. Madhavan, Determination of Forming Limit Curves Using 3d Digital Image Correlation and In-Situ Observation vol. 14, 2004.
[33] P. Vacher, a. Haddad, R. arrieux, Determination of the forming limit diagrams using image anAlysis by the corelation method, CIRP Annal. 48 (1) (1999) 227–230.
[34] Y. Lou, H. Huh, Y. Ko, J. Ha, Comparative Study of the Ductile Fracture Criteria on the Prediction of FLDs for Aluminum Alloys vol. 7, 2010.
[35] S.M. MirfAlah-nasiri, a. Basti, R. Hashemi, Forming limit curves anAlysis of Aluminum Alloy considering the through-thickness normAl stress, anisotropic yield functions and strain rate, Int. J. Mech. Sci. 117 (2016) 93–101.
[36] a. Ghazanfari, a. assempour, CAlibration of forming limit diagrams using a modified Marciniak–Kuczynski model and an empiricAl law, Mater. Des. 34 (2012) 185–191.
[37] E. Cyr, M. Mohammadi, a. Brahme, R.K. Mishra, K. InAl, Modeling the formability of Aluminum Alloys at elevated temperatures using a new thermo-elasto-viscoplastic crystAl plasticity framework, Int. J. Mech. Sci. 128–129 (2017) 312–325.
[38] D. Banabic, S. Bouvier, G. Ferron, I. Ungureanu, G. Sindila, I. Tabacu, Contribution à la simulation du processus de déformation plastique à froid des tôles vol. 159, 2007.
[39] J. Pavan kumar, R. Uday kumar, B. Ramakrishna, B. Ramu, K. Baba Saheb, Formability of sheet metAls – a review, IOP Conf. Ser. Mater. Sci. Eng. 455 (2018), 012081.
[40] Z. Chen, G. Fang, Determination of forming limit for Aluminium Alloy sheet eliminating the interferences of through-thickness stress and non-linear strain path, IOP Conf. Ser. Mater. Sci. Eng. 418 (2018), 012051.
[41] ISO 12004-2, MetAllic materials–sheet and strip–determination of forming-limit curves–part 2 determination of forming-limit curves in the laboratory, Int. Stand. ISO 1 (2008) 1–27.
[42] M. Dilmec, H.S. Halkaci, F. Ozturk, H. LivatyAli, O. Yigit, Effects of sheet thickness and anisotropy on forming limit curves of AA2024-T4, Int. J. Adv. Manuf. Technol. 67 (9–12) (2013) 2689–2700.
[43] a.J. Martínez-Donaire, F.J. García-Lomas, C. Vallellano, New approaches to detect the onset of locAlised necking in sheets under through-thickness strain gradients, Mater. Des. 57 (2014) 135–145.
[44] M. Merklein, a. Kuppert, M. Geiger, Time dependent determination of forming limit diagrams, CIRP Annal. 59 (1) (2010) 295–298.
[45] C. Zhang, L. Leotoing, D. Guines, E. Ragneau, TheoreticAl and numericAl study of strain rate influence on AA5083 formability, J. Mater. Process. Technol. 209 (8) (2009) 3849–3858.
[46] M.B. Silva, a.J. Martínez-Donaire, G. Centeno, D. MorAles-Palma, C. Vallellano, P.a.F. Martins, Recent approaches for the determination of forming limits by necking and fracture in sheet MetAl forming, Procedia Eng. 132 (2015) 342–349.
[47] D. Swapna, C. Rao, Srinivasa, S. Radhika, A review on deep drawing process, Int. J. Emerg. Res. Manag. Technol. 6 (6) (2018) 146.
[48] P. Janaki Ramulu, Aluminum alloys behavior during forming, in: K. Omar Cooke (Ed.), Aluminium Alloys and Composites, IntechOpen, 2020.
[49] R. Padmanabhan, M.C. Oliveira, J.L. Alves, L.F. Menezes, Influence of process parameters on the deep drawing of stainless steel, Finite Elem. Anal. Des. 43 (14) (2007) 1062–1067.
[50] R. Dwivedi, G. agnihotri, Study of deep drawing process parameters, Mater. Today Proc. 4 (2) (2017) 820–826.
[51] E.J. Obermeyer, S.a. Majlessi, A review of recent advances in the application of blank-holder force towards improving the forming limits of sheet metAl parts, J. Mater. Process. Technol. 75 (1–3) (1998) 222–234.
[52] M. Colgan, J. Monaghan, Deep drawing process: anAlysis and experiment, J. Mater. Process. Technol. 132 (1–3) (2003) 35–41.
[53] H. Choi, M. Koc, J. ni, Determination of optimAl loading profiles in warm hydroforming of lightweight materials, J. Mater. Process. Technol. 13 (2007).
[54] H. Zein, M. El-Sherbiny, M. abd-Rabou, M. El Shazly, Effect of die design parameters on thinning of sheet MetAl in the deep drawing process, Am. J. Mech. Eng. 1 (2) (2013) 20–29.
[55] E. Doege, L.-E. Elend, Design and application of pliable blank holder systems for the optimization of process conditions in sheet metAl forming, J. Mater. Process. Technol. 111 (1–3) (2001) 182–187.
[56] K. Manabe, H. Koyama, S. Yoshihara, T. Yagami, Development of a combination punch speed and blank-holder fuzzy control system for the deep-drawing process, J. Mater. Process. Technol. 125–126 (2002) 440–445.
[57] K. Bouchaâla, E. Essadiqi, M. Mada, M.F. Ghanameh, M. Faqir, M. Meziane, Prediction of Earing in cylindricAl Deep Drawing of Aluminum Alloys Using Finite Element anAlysis vol. 8, 2018.
[58] R. Padmanabhan, M.C. Oliveira, J.L. Alves, L.F. Menezes, numericAl simulation and anAlysis on the deep drawing of LPG bottles, J. Mater. Process. Technol. 200 (1–3) (2008) 416–423.
[59] S. Dou, J. Xia, anAlysis of sheet MetAl forming (stamping process): a study of the variable friction coefficient on 5052 aluminum alloy, Metals 9 (8) (2019) 853.
[60] K.K. Saxena, J. Mukhopadhyay, K.V. Ramesh, Formability Characterization Of Aluminum Lithium Alloys Used In Spacecraft Industry vol. 6, 2014.
[61] H. Kleemola, J. Kumpulainen, A cAlculation method for determining the limit of flange wrinkling in the deep-drawing of cylindricAl steel shells without blankholding, Metall. Trans. A 11 (10) (1980) 1701–1710.
[62] C. Won, Wrinkling prediction for GPa-grade steels in sheet metAl forming process, Int. J. Adv. Manuf. Technol. 15 (2019).
[63] B.W. Senior, Flange wrinkling in deep-drawing operations, J. Mech. Phys. Solid. 4 (4) (1956) 235–246.
[64] X. Li, n. Song, G. Guo, Z. Sun, Prediction of forming limit curve (FLC) for Al–Li Alloy 2198-T3 sheet using different yield functions, Chin. J. Aeronaut. 26 (5) (2013) 1317–1323.
[65] M. Khelifa, M. Oudjene, numericAl damage prediction in deep-drawing of sheet metAls, J. Mater. Process. Technol. 200 (1–3) (2008) 71–76.
[66] P. Koowattanasuchat, n. Mahayotsanun, S. ngernbamrung, S. Mahabunphachai, Formability effects of variable blank holder force on deep drawing of stainless steel, MaTEC Web Conf. 80 (2016), 15005.
[67] Z. Tekıner, An experimentAl study on the examination of springback of sheet metAls with severAl thicknesses and properties in bending dies, J. Mater. Process. Technol. 145 (1) (2004) 109–117.
[68] M. Lee, D. Kim, C. Kim, M. Wenner, R. Wagoner, K. Chung, Spring-back evAluation of automotive sheets based on isotropic-kinematic hardening laws and non-quadratic anisotropic yield functions Part II: characterization of material properties, Int. J. Plast. 21 (5) (2005) 883–914.
[69] M.Y. Demeri, M. Lou, M.J. Saran, A Benchmark Test for Springback Simulation in Sheet MetAl Forming, 2000, 2000-01–2657.
[70] R. Hino, Y. Goto, F. Yoshida, Springback of sheet metAl laminates in draw-bending, J. Mater. Process. Technol. 139 (1–3) (2003) 341–347.
[71] T. Liu, Y. Wang, J. Wu, X. Xia, J. Wang, S. Li, S. Wang, J. Wang, G. Han, Minimum bending radius of Al-Li alloy extrusions in stretch bending, Proc. IME B J. Eng. Manufact. 232 (2) (2018) 281–295.
[72] M. Ueda, K. Ueno, M. Kobayashi, A study of springback in the stretch bending of channels, J. Mech. Work. Technol. 5 (3–4) (1981) 163–179.
[73] T. Intarakumthornchai, S. Jirathearant, S. Thongprasert, P. Dechaumphai, FEa-based optimization of blank holder force and pressure for hydromechanical deep drawing of parabolic cup using greedy search and RSM methods, Eng. J. 14 (2) (2010) 15–32.

[74] S. Yaghoubi, F. Fereshteh-Saniee, Optimization of the geometricAl parameters for elevated temperature hydro-mechanical deep drawing process of 2024 Aluminum Alloy, in: Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 2020, 095440892094936.
[75] T. Maeno, K. Mori, T. nagai, Improvement in formability by control of temperature in hot stamping of ultra-high strength steel parts, CIRP Annal. 63 (1) (2014) 301–304.
[76] D. Acar, M. Türköz, H. Gedikli, H. Selçuk Halkaci, Ö. necati Cora, Warm hydromechanical deep drawing of AA 5754-O and optimization of process parameters, J. Eng. Mater. Technol. 140 (1) (2017), 011012.
[77] M. Ghosh, Warm deep-drawing and post drawing anAlysis of two Al–Mg–Si Alloys, J. Mater. Process. Technol. 12 (2014).
[78] M. Tajally, E. Emadoddin, Mechanical and anisotropic behaviors of 7075 Aluminum Alloy sheets, Mater. Des. 32 (3) (2011) 1594–1599.
[79] R.K. Desu, S.K. Singh, a.K. Gupta, Comparative study of warm and hydromechanical deep drawing for low-carbon steel, Int. J. Adv. Manuf. Technol. 85 (1–4) (2016) 661–672.
[80] X. Yang, Influence of Process Parameters on Deep Drawing of 2060 Al-Li Alloy under Hot Stamping Process vol. 7, 2020.
[81] H. Takuda, K. Mori, I. Masuda, Y. abe, M. Matsuo, Finite element simulation of warm deep drawing of Aluminium Alloy sheet when accounting for heat conduction, J. Mater. Process. Technol. 120 (1–3) (2002) 412–418.
[82] C. Gao, Z. Zhu, J. Han, H. Li, Correlation of microstructure and mechanical properties in friction stir welded 2198-T8 Al–Li Alloy, Mater. Sci. Eng. 639 (2015) 489–499.
[83] C. Gao, Y. Ma, Y. Pei, S. Li, J. Li, J. Dong, The Effect of Thermo-Mechanical Coupling on Microstructures and Tensile Properties of Al-Li2198-T8 Alloy via Friction Spot Welding vol. 879, 2016, p. 7.
[84] H. Rong, Thermal forming limit diagram (TFLD) of AA7075 Aluminum Alloy based on a modified continuum damage model: ExperimentAl and theoreticAl investigations, Int. J. Mech. Sci. 15 (2019).
[85] Ho Choi, Muammer Koç, Jun ni, A study on warm hydroforming of Al and Mg sheet materials: mechanism and proper temperature conditions, J. Manuf. Sci. Eng. 14 (2008).
[86] G. Cai, C. Wu, Z. Gao, L. Lang, S. Alexandrov, Research on Al-Alloy sheet forming formability during warm/hot sheet hydroforming based on ellipticAl warm bulging test, AIP Adv. 8 (5) (2018), 055023.
[87] G. Palumbo, Warm HydroForming of the Heat Treatable Aluminium Alloy aC170PX vol. 9, 2015.
[88] K.V. Wong, a. Hernandez, A review of additive manufacturing, ISRN Mechan. Eng. 2012 (2012) 1–10.
[89] Reiner Anderl, Martin Kage, Hans-Joachim Schmid, Michael Cornelius Hermann Karg, Additive Manufacturing.Pdf, German nationAl academy of Sciences Leopoldina, 1978.
[90] D. Liu, B. Yürekli, T. Ullsperger, G. Matthäus, L. Schade, S. nolte, M. Rettenmayr, MicrostructurAl aspects of additive manufacturing of Al Li Alloys with high Li content, Mater. Des. 198 (2021), 109323.
[91] S. Singamneni, Y. Lv, a. Hewitt, R. ChAlk, W. Thomas, D. Jordison, Additive manufacturing for the aircraft industry: a review, J. Aeronaut. Aero. Eng. 8 (1) (2019).
[92] L. Yang, K. Hsu, B. Baughman, D. Godfrey, F. Medina, M. Menon, S. Wiener, Microstructure, mechanical properties, and design considerations for additive manufacturing, in: L. Yang, K. Hsu, B. Baughman, D. Godfrey, F. Medina, M. Menon, S. Wiener (Eds.), Additive Manufacturing of MetAls: the Technology, Materials, Design and Production, Springer International Publishing, 2017, pp. 45–61.
[93] I.D. Harris, Development and implementation of metAls additive manufacturing, in: a.B. Badiru, V.V. VAlencia, D. Liu (Eds.), Additive Manufacturing Handbook, first ed., CRC Press, 2017, pp. 215–224.
[94] M. Jiménez, L. Romero, I.a. Domínguez, M. Espinosa del, M. Domínguez, Additive manufacturing technologies: an overview about 3D printing methods and future prospects, Complexity 2019 (2019) 1–30.
[95] H. Zhong, B. Qi, B. Cong, Z. Qi, H. Sun, Microstructure and mechanical properties of Wire + arc additively manufactured 2050 Al–Li alloy WAll deposits, Chin. J. Mech. Eng. 32 (1) (2019) 92.
[96] n.T. Aboulkhair, M. Simonelli, L. Parry, I. ashcroft, C. Tuck, R. Hague, 3D printing of Aluminium Alloys: additive Manufacturing of Aluminium Alloys using selective laser melting, Prog. Mater. Sci. 106 (2019), 100578.
[97] J. Shao, G. Yu, X. He, S. Li, R. Chen, Y. Zhao, Grain size evolution under different cooling rate in laser additive manufacturing of superAlloy, Opt Laser. Technol. 119 (2019), 105662.
[98] B. Yürekli, L. Schade, T. Ullsperger, B. Seyfarth, H. Kohl, G. Matthäus, D. Liu, M. Rettenmayr, S. nolte, Additive manufacturing of binary Al-Li alloys, Procedia CIRP 94 (2020) 69–73.
[99] I. Raffeis, F. Adjei-Kyeremeh, U. Vroomen, S. Richter, a. Bührig-Polaczek, Characterising the microstructure of an additively built Al-Cu-Li alloy, Materials 13 (22) (2020) 5188.
[100] Xin Wang, Liu Dong, Xu Cheng, Effect of heat treatment process on microstructures and mechanical properties of laser additive manufactured Al-Li alloys, Chin. J. Lasers 45 (5) (2018), 0502004.
[101] S. Jiao, LiuS. haoyin, Dong Liu, Cheng Xu, *Heat treatment structure and TB phase precipitation of laser additive manufacturing aluminum-lithium alloy* (nationAl engineering laboratory of additive manufacturing for large MetAllic components beihang university beijing 100191 China, Chin. J. Lasers 45 (5) (2018).
[102] D.J. Politis, n.J. Politis, J. Lin, T.a. Dean, A review of force reduction methods in precision forging axisymmetric shapes, Int. J. Adv. Manuf. Technol. 97 (5–8) (2018) 2809–2833.
[103] C.G. Dalbhagat, D.K. Mahato, H.n. Mishra, Effect of extrusion processing on physicochemicAl, functionAl and nutritionAl characteristics of rice and rice-based products: a review, Trends Food Sci. Technol. 85 (2019) 226–240.
[104] R.F. Wall, Ground transportation, J. Air Transp. Div. 85 (3) (1959) 57–62.
[105] D.K. Denzer, R.J. Rioja, G.H. Bray, G.B. Venema, E.L. Colvin, The Evolution of Plate and Extruded Products with High Strength and Fracture Toughness vol. 6, 2012.
[106] F. Boey, H.F. Lee, K.a. Khor, T. Sano, CIP extruded Aluminium-lithium Alloy composite: interfacial compatibility and mechanical properties, J. Mater. Process. Technol. 38 (1–2) (1993) 337–349.
[107] Chen, et al., Method of Heat Treating Aluminum Lithiumalloy to Improve Formability. United States Patent, Patent no.: US 9,365,917 B1, 2016.
[108] Y. Wang, G. Zhao, Hot extrusion processing of Al–Li alloy profiles and related issues: a review, Chin. J. Mech. Eng. 33 (1) (2020) 64.
[109] ISO 25239-1:2011(fr), Soudage Par Friction-mAlaxage—Aluminium—Partie 1: Vocabulaire, 2011. https://www.iso.org/obp/ui/#iso:std:iso:25239:-1:ed-1:v1:fr.
[110] K.S. Arora, S. Pandey, M. Schaper, R. Kumar, Effect of process parameters on friction stir welding of Aluminum Alloy 2219-T87, Int. J. Adv. Manuf. Technol. 50 (9–12) (2010) 941–952.
[111] P.L. Threadgill, Terminology in friction stir welding, Sci. Technol. Weld. Join. 12 (4) (2007) 357–360.
[112] S. Boopathi, K. Moorthi, Review On Effect Of Process Parameters-Friction Stir Welding Process, 2017.
[113] Prashant Pratap Mall, Jitender Panchal, Modern institute of engineering technology, Kurukshetra, Haryana (India), Int. J. Eng. Res. V6 (6) (2017), IJERTV6IS060029 friction stir welding process parameters: a review.
[114] Y.X. Huang, L. Wan, S.X. Lv, J.C. Feng, Novel design of tool for joining hollow extrusion by friction stir welding, Sci. Technol. Weld. Join. 18 (3) (2013) 239–246.
[115] B. Venu, I. BhavyaSwathi, L.S. Raju, G. Santhanam, A review on Friction Stir Welding of various metAls and its variables, Mater. Today Proc. 18 (2019) 298–302.
[116] V. Calogero, G. Costanza, S. Missori, a. Sili, M.E. Tata, A weldability study of Al–Cu–Li 2198 alloy, Metallurgist 57 (11–12) (2014) 1134–1141.
[117] H. Sidhar, n.Y. Martinez, R.S. Mishra, J. Silvanus, Friction stir welding of Al–Mg–Li 1424 Alloy, Mater. Des. 106 (2016) 146–152.
[118] H.-S. Lee, J.-H. Yoon, J.-T. Yoo, K. no, Friction stir welding process of aluminum-lithium alloy 2195, Procedia Eng. 149 (2016) 62–66.
[119] O. Hatamleh, Effects of peening on mechanical properties in friction stir welded 2195 Aluminum Alloy joints, Mater. Sci. Eng. 492 (1–2) (2008) 168–176.

[120] Y. Lin, Z. Zheng, MicrostructurAl evolution of 2099 Al Li Alloy during friction stir welding process, Mater. Char. 123 (2017) 307–314.
[121] M. Masoumi KhAlilabad, Y. Zedan, D. Texier, M. Jahazi, P. Bocher, Effect of heat treatments on microstructurAl and mechanical characteristics of dissimilar friction stir welded 2198/2024 Aluminum Alloys, J. Adhes. Sci. Technol. 36 (3) (2022) 221–239.
[122] F. De Geuser, B. Malard, a. Deschamps, Microstructure mapping of a friction stir welded AA2050 Al–Li–Cu in the T8 state, Phil. Mag. 94 (13) (2014) 1451–1462.
[123] B. Malard, F. De Geuser, a. Deschamps, Microstructure distribution in an AA2050 T34 friction stir weld and its evolution during post-welding heat treatment, Acta Mater. 101 (2015) 90–100.
[124] W. Xu, J. Liu, G. Luan, C. Dong, Microstructure and mechanical properties of friction stir welded joints in 2219-T6 Aluminum Alloy, Mater. Des. 30 (9) (2009) 3460–3467.
[125] M.R. Sonne, C.C. Tutum, J.H. Hattel, a. Simar, B. de Meester, The effect of hardening laws and thermal softening on modeling residuAl stresses in FSW of Aluminum Alloy 2024-T3, J. Mater. Process. Technol. 213 (3) (2013) 477–486.
[126] C.B. Fuller, M.W. Mahoney, M. Calabrese, L. Micona, Evolution of microstructure and mechanical properties in naturally aged 7050 and 7075 Al friction stir welds, Mater. Sci. Eng. 527 (9) (2010) 2233–2240.
[127] Y.C. Chen, J.C. Feng, H.J. Liu, Precipitate evolution in friction stir welding of 2219-T6 Aluminum Alloys, Mater. Char. 60 (6) (2009) 476–481.
[128] S. Benavides, Y. Li, L.E. Murr, D. Brown, J.C. McClure, Low-temperature friction-stir welding of 2024 Aluminum, Scripta Mater. 41 (8) (1999) 809–815.
[129] M.P. Alam, a. n. Sinha, Fabrication of third generation Al–Li Alloy by friction stir welding: a review, Sādhanā 44 (6) (2019) 153.
[130] M. Sahul, On the microstructure and mechanical properties of aW2099 Aluminium lithium Alloy joints produced with electron beam welding, Mater. Lett. 5 (2020).
[131] G.J. Kulkarni, D. Banerjee, T.R. Ramachandran, PhysicAl metAllurgy of aluminum-lithium alloys, Bull. Mater. Sci. 12 (3–4) (1989) 325–340.
[132] a. a. Csontos, E.a. Starke, The effect of processing and microstructure development on the slip and fracture behavior of the 2.1 wt pct Li aF/C-489 and 1.8 wt pct Li aF/C-458 Al-Li-Cu-X Alloys, Metall. Mater. Trans. 31 (8) (2000) 1965–1976.
[133] B. Ahmed, S.J. Wu, Aluminum lithium alloys (Al-Li-Cu-X)-new generation material for aerospace applications, Appl. Mech. Mater. 440 (2013) 104–111.
[134] S. Ya Betsofen, V.V. antipov, M.I. Knyazev, Al–Cu–Li and Al–Mg–Li Alloys: phase composition, texture, and anisotropy of mechanical properties (Review), Russ. Metall. (4) (2016) 326–341, 2016.
[135] (2320) Minoru Furukawa, Yasuhiro Miura, Minoru nemoto, Strengthening mechanisms in Al–Li alloys containing coherent ordered particles, Trans. Japan Inst. Metals 26 (4) (1985) 230–235.
[136] N. Eswara Prasad, amol a. GokhAle, R.J.H. Wanhill, Chapter 3 Al-Li Alloys, Springer Science+Business Media Singapore, 2017, pp. 53–72.
[137] n. Nayan, K.S. Govind nair, M.C. MittAl, K.n. Sudhakaran, Studies on Al–Cu–Li–Mg–ag–Zr Alloy processed through vacuum induction melting (VIM) technique, Mater. Sci. Eng. 454–455 (2007) 500–507.
[138] H. Ning, J. Li, P. Ma, Y. Chen, X. Zhang, K. Zhang, R. Zhang, Evolution of aging precipitates in an Al–Li Alloy with 1.5 wt% Li concentration, Vacuum 182 (2020) 109677.
[139] a. Hekmat-ardakan, E.M. ElgAllad, F. ajersch, X.-G. Chen, MicrostructurAl evolution and mechanical properties of as-cast and T6-treated AA2195 DC cast Alloy, Mater. Sci. Eng. 558 (2012) 76–81.
[140] Y. Yang, G.Y. Tan, P.X. Chen, Q.M. Zhang, Effects of different aging statuses and strain rate on the adiabatic shear susceptibility of 2195 Aluminum–lithium Alloy, Mater. Sci. Eng. 546 (2012) 279–283.
[141] W. Walker, R. Marloth, Y.T. Hein, O.S. Es-Said, The Effect of Incomplete Solution Treatment on the Tensile Behavior and Mechanical Anisotropy of 2195 Aluminum Lithium Alloy vol. 22, 2019, p. 9.
[142] V. Proton, J. Alexis, E. andrieu, J. Delfosse, a. Deschamps, F. De Geuser, M.-C. Lafont, C. Blanc, The influence of artificiAl ageing on the corrosion behaviour of a 2050 Aluminium–copper–lithium Alloy, Corrosion Sci. 80 (2014) 494–502.
[143] I. Häusler, C. Schwarze, M.U. BilAl, D.V. Ramirez, W. Hetaba, R.D. KamachAli, B. Skrotzki, Precipitation of T1 and θ Phase in Al-4Cu-1Li-0.25Mn during Age Hardening: MicrostructurAl Investigation and Phase-Field Simulation vol. 21, 2017.
[144] C. Yu, D. Yin, F. Zheng, X. Yu, Effects of solution treatment on mechanical properties and microstructures of Al-Li-Cu-Mg-ag Alloy, J. Cent. S. Univ. 20 (8) (2013) 2083–2089.
[145] a.K. Jha, S.K. Singh, M. Swathi Kiranmayee, K. Sreekumar, P.P. Sinha, Failure anAlysis of titanium Alloy (Ti6Al4V) fastener used in aerospace application, Eng. Fail. Anal. 17 (6) (2010) 1457–1465.
[146] Y. Xinxiang, Y. Dengfeng, Y. Zhiming, Effects of Cerium and zirconium MicroAlloying addition on the microstructures and tensile properties of novel Al-Cu-Li alloys, Rare Met. Mater. Eng. 45 (8) (2016) 1917–1923.
[147] Y. Ma, X. Zhou, G.E. Thompson, T. Hashimoto, P. Thomson, M. Fowles, Distribution of intermetAllics in an AA 2099-T8 aluminium alloy extrusion, Mater. Chem. Phys. 126 (1–2) (2011) 46–53.
[148] E. Nizery, Influence of Particles on Short Fatigue Crack Initiation in 2050-T8 and. 7, 2014.
[149] K.S. Prasad, n.E. Prasad, a. a. GokhAle, Microstructure and precipitate characteristics of aluminum–lithium alloys, in: Aluminum-lithium Alloys, Elsevier, 2014, pp. 99–137.
[150] Ø. Ryen, B. HolmedAl, O. nijs, E. nes, E. Sjölander, H.-E. Ekström, Strengthening mechanisms in solid solution Aluminum Alloys, Metall. Mater. Trans. 37 (6) (2006) 1999–2006.
[151] M.J. Starink, P. Wang, I. Sinclair, P.J. Gregson, Microstrucure and strengthening of Al–Li–Cu–Mg alloys and MMCs: I. anAlysis and modelling of MicrostructurAl changes, Acta Mater. 47 (14) (1999) 3841–3853.
[152] K.S. Kumar, F.H. Heubaum, The Effect of Li Content on the Natural Aging Response of Al-Cu-Li Mg-Ag-Zr Alloys, Elsevier S&&e Ltd Printed, Great Britain, 1997.
[153] K. Kumar, The effect of Li content on the naturAl aging response of Al_Cu_Li_Mg_ag_Zr Alloys, Acta Mater. 45 (6) (1997) 2317–2327.
[154] Y. Lin, Z. Zheng, S. Li, X. Kong, Y. Han, Microstructures and properties of 2099 Al-Li alloy, Mater. Char. 84 (2013) 88–99.
[155] J. Han, Z. Zhu, H. Li, C. Gao, MicrostructurAl evolution, mechanical property and thermal stability of Al–Li 2198-T8 Alloy processed by high pressure torsion, Mater. Sci. Eng. 651 (2016) 435–441.
[156] T. Laitinen, K. Wallin, VAltion teknillinen tutkimuskeskus., MultiscAle Modelling and Design for Engineering Application, 2013.
[157] a.B. Nellippallil, P. Mohan, J.K. Allen, F. Mistree, An inverse, decision-based design method for robust concept exploration, J. Mech. Des. 142 (8) (2020), 081703.
[158] M. Suresh, a. Sharma, a.M. More, n. nayan, S. Suwas, Effect of Scandium addition on evolution of microstructure, texture and mechanical properties of thermo-mechanical ly processed Al-Li alloy AA2195, J. Alloys Compd. 740 (2018) 364–374.
[159] T.-L. Liu, J.-F. Li, D.-Y. Liu, Y.-L. Ma, Microstructure evolution and mechanical properties of the 2195 Al-Li alloy via different anneAling and ramp heating-up treatments, Metals 10 (7) (2020) 910.
[160] J. Augustyn-Pieniążek, H. adrian, S. Rzadkosz, M. Choroszyński, Structure and mechanical properties of Al-Li alloys as cast, Arch. Foundry Eng. 13 (2) (2013) 5–10.
[161] R.-G. Guan, D. Tie, A review on grain refinement of aluminum alloys: progresses, ChAllenges and prospects, Acta Metall. Sin. 30 (5) (2017) 409–432.
[162] V. Singh, a. a. GokhAle, Melting and casting of aluminum–lithium alloys, in: Aluminum-lithium Alloys, Elsevier, 2014, pp. 167–185.
[163] Y. Ma, J. Li, F. Sang, H. Li, Z. Zheng, C. Huang, Grain structure and tensile property of Al-Li alloy sheet caused by different cold rolling reduction, Trans. Nonferrous Metals Soc. China 29 (8) (2019) 1569–1582.
[164] K. InAl, R.K. Mishra, O. Cazacu, Forming simulation of Aluminum sheets using an anisotropic yield function coupled with crystal plasticity theory, Int. J. Solid Struct. 47 (17) (2010) 2223–2233.
[165] H.-Y.L. Ou, Z.-Q. Zheng, Study on the Anisotropy of 2195 Al-Li Alloy, 2005, pp. 31–34 (10).
[166] S.J. Hales, R.a. Hafley, Texture and anisotropy in Al-Li alloy 2195 plate and near-net-shape extrusions, Mater. Sci. Eng. 257 (1) (1998) 153–164.

[167] K. Bouchaâla, M.F. Ghanameh, M. Faqir, M. Mada, E. Essadiqi, numericAl investigation of the effect of punch corner radius and die shoulder radius on the flange earrings for AA1050 and AA1100 Aluminum Alloys in cylindricAl deep drawing process, Heliyon 7 (4) (2021), e06662.
[168] R. Hill, (193 C.E.). A Theory of the Yielding and Plastic Flow of Anisotropic metAls, 1948.
[169] F. Barlat, J.C. Brem, J.W. Yoon, K. Chung, R.E. Dick, D.J. Lege, F. Pourboghrat, S.-H. Choi, E. Chu, Plane stress yield function for Aluminum Alloy sheets—part 1: Theory, Int. J. Plast. 19 (9) (2003) 1297–1319.
[170] F. Barlat, H. aretz, J.W. Yoon, M.E. Karabin, J.C. Brem, R.E. Dick, Linear transfomation-based anisotropic yield functions, Int. J. Plast. 21 (5) (2005) 1009–1039.
[171] F. Bron, J. Besson, A yield function for anisotropic materials application to Aluminum Alloys, Int. J. Plast. 20 (4–5) (2004) 937–963.
[172] K. Bouchaâla, M.F. Ghanameh, M. Faqir, M. Mada, E. Essadiqi, Prediction of the impact of friction's coefficient in cylindricAl deep drawing for AA2090 Al-Li alloy using FEM and Taguchi approach, IOP Conf. Ser. Mater. Sci. Eng. 664 (2019), 012004.
[173] K. Bouchaâla, M.F. Ghanameh, M. Faqir, M. Mada, E. Essadiqi, EvAluation of the effect of contact and friction on deep drawing formability anAlysis for lightweight aluminum lithium alloy using CylindricAl cup, Procedia Manuf. 46 (2020) 623–629.