Dynamic softening mechanism of 2 vol.% nano-sized SiC particle reinforced Al-12Si matrix composites during hot deformation

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Abstract

The hot deformation behavior of the 2 vol.% nano-SiCp/Al-12Si composites prepared by powder metallurgy is complicated due to the simultaneous presence of nano-sized SiC particles and micro-sized precipitated Si particles. In this paper, the isothermal heat compression test and the transmission electron microscope analysis technique were used to analyze the softening mechanism of the 2 vol.% nano-SiCp/Al-12Si composites based on Z parameters and deformation temperature, and the nucleation mechanism of dynamic recrystallization of the 2 vol.% nano-SiCp/Al-12Si composites was analyzed. The results showed that, when LnZ > 55.02, T ≤ 753 K, the cross slip of dislocation was the main softening mechanism; when LnZ < 55.76, T ≥ 733 K, the softening mechanism mainly includes the cross slip, climbing of dislocation, and untangling of three-dimensional dislocation network; when LnZ ≤ 53.65, T ≥ 773 K, the dynamic recovery and dynamic recrystallization were the main softening mechanism of the composites. The dynamic recrystallization nucleation mechanisms of the 2 vol.% nano-SiCp/Al-12Si composites include the sub-grain combination nucleation and grain boundaries bulging nucleation.

1. Introduction

SiC particle-reinforced aluminum matrix composites have been applied in rail transit, electronic packaging, aerospace, automobile industry, and other fields due to their excellent mechanical and physical properties, [1–3]. Traditionally, SiCp/Al composites are reinforced with micron-sized SiC particles. However, the application of micron-sized SiCp/Al composites in the industrial field is limited, because the micron-sized SiC particles improve the material strength while reducing the material plasticity [4–8]. Recently, some studies have found that the strength of the material is greatly improved while the plasticity can be retained when adding nano-sized hard particles to the aluminum alloy [9–12]. For instance, Qiu et al [9] studied the influence of the addition of nano-sized SiC particle on the mechanical properties of Al–Cu alloy, and found that when 3 wt.% SiC was added to Al–Cu alloy, the tensile strength and fracture strain increased from 310 MPa and 4.1% to 410 MPa and 6.3%, respectively. Hamedan et al [12] studied the mechanical properties of 1.0 wt.% nano-SiC particles reinforced A356, and found that the tensile strength of the composite material increased from 140 MPa to 173 MPa while maintaining ductility.

SiCp/Al composites fabricated by powder metallurgy usually need to undergo secondary processing such as hot rolling and extrusion before being used as components. The hot deformation process results in a more homogeneous distribution of reinforcement particles and microstructural refinement, which improves the mechanical properties of the composites [13]. In recent years, many researchers have conducted a large number of studies on the dynamic softening mechanism of many alloys and composites due to the significant influence of dynamic softening mechanism during hot deformation on the final structure and properties of materials [14–17]. Wan et al [14] studied the dynamic softening mechanism of GH4720Li alloy by conducting the isothermal compression test, and found that the micron-size precipitate phase in the alloy pinned dislocation...
during the hot deformation to form sub-grain boundary and the substructure with high-density dislocation, thereby promoting the occurrence of continuous dynamic recrystallization. Deng et al [17] found that the addition of submicron-sized hard particles, on the one hand, may hinder the movement of dislocations to increases the driving force for dynamic recrystallization, and on the other hand, may pin the migration of grain boundaries to hinder the occurrence of recrystallization.

In this paper, the microstructure of 2 vol.% nano-SiCp/Al-12Si composite material was observed by a transmission electron microscope, to analyze the influence of hot deformation conditions on the dynamic softening mechanism of the 2 vol.% nano-SiCp/Al-12Si composites, and therefore provides a theoretical basis for the engineering application of the composite material.

2. Experimental procedure

The experimental materials were fabricated by powder metallurgy, and the average diameters of the reinforcement particles and alloy powder were 80 nm and 7 μm, respectively. The Gleeble-1500D thermal simulation tester was used to thermally compress the 2 vol.% nano-SiCp/Al-12Si composite material at the strain rate of 0.1, 1, 5, and 10 s⁻¹, and temperature of 733 K, 753 K, 773 K, and 793K. The sample size is 8 mm in diameter and 12 mm in height, and the amount of deformation is 40% of engineering strain. The lubricant made from graphite mixed with oil is evenly applied to both ends of the hot-pressed sample to reduce friction between the sample and the equipment. The sample was quenched immediately with water after compression to retain the deformed structure. The structural evolution of 2 vol.% nano-SiCp/Al-12Si composites during thermal deformation were observed with the JEM-2100 transmission electron microscope.

3. Results and discussion

3.1. Hot deformation characteristics

Figure 1 shows the peak stress of 2 vol.% nano-SiCp/Al-12Si composite under different deformation conditions, which is higher than that of the Al-7Si alloy reported in the literature [18]. The higher peak may be ascribed to the nano-sized SiC particles hindering the movement of dislocations and the migration of grain boundaries during hot deformation, thereby increasing the deformation resistance of the composite [19]. The investigation from Pirlari et al [13] indicated that the yield strength and hardness of Al5083-TiB₂ composites increased with the increase of TiB₂ content. Figure 1 shows that the peak stress decreases with the increase of deformation temperature. On the one hand, the thermal vibration amplitude of atoms increases and the bonding force between atoms decreases with the increase of temperature, which reduces the critical shear stress for dislocation slipping. On the other hand, the mobility of dislocations increases with the increase of temperature [20, 21].

The dynamic softening mechanism of metal materials is related to the temperature compensated strain rate factor Z parameter, which can fully reflect the influence of deformation temperature and strain rate. The
expression of the Z parameter is [22–25]:

$$Z = \dot{\varepsilon} \exp \left( \frac{Q}{RT} \right) = A \left[ \sinh \left( \alpha \sigma \right) \right]^n$$

(1)

Where, A, α, n are material constants, \( \dot{\varepsilon} \) stands for strain rate, R stands for the gas constant, T stands for deformation temperature, \( \sigma \) stands for true stress, and Q stands for thermal deformation activation energy.

The value of Q can be obtained by formula (2) [26]. According to calculation, the hot deformation activation energy of 2 vol% nano-SiC/Al-12Si composites under the experimental conditions is 330.02 kJ mol\(^{-1}\), which is slightly higher than for micron-sized SiC particles reinforced Al–Si matrix composites (263 KJ mol\(^{-1}\)) [27]. Similar results can be found by comparing the studies of Cerri \textit{et al} [28] with those of Ezatpour \textit{et al} [29]. Cerri \textit{et al} [28] found that the Q value of 6061 aluminum matrix composites reinforced with 20% micro-sized Al\(_2\)O\(_3\) was 156 KJ mol\(^{-1}\), while Ezatpour \textit{et al} [29] found that the Q value of 6061 aluminum matrix composites reinforced with 0.5% nano-sized Al\(_2\)O\(_3\) was 285 KJ mol\(^{-1}\). The Q value obtained by adding 0.5% nano-sized Al\(_2\)O\(_3\) to the 6061 aluminum alloy matrix is much larger than that obtained by adding 20% micro-sized Al\(_2\)O\(_3\), which may be ascribed to that the nano-sized particles delay the dynamic softening. The nano-sized particles hinder the movement of dislocation, pinning the migration of grain boundaries and sub boundaries to delay the occurrence of dynamic softening, while the presence of micro-sized particles will introduce a large number of geometrically necessary dislocations to promote the occurrence of dynamic softening with particle-stimulated nucleation mechanism (PSN) [30].

$$Q = R \left\{ \frac{\partial \ln \left[ \sinh \left( \alpha \sigma \right) \right]}{\partial (1/T)} \right\} \left\{ \frac{\partial \ln \dot{\varepsilon}}{\partial \left[ \sinh \left( \alpha \sigma \right) \right]} \right\}$$

(2)

The Z value was calculated by substituting the hot deformation activation energy and the strain rate into equation (1), and the natural logarithm of the Z parameter was calculated, which was shown in table 1. As can be seen from table 1, the variation of lnZ value is similar to the peak stress characteristic with the change of deformation conditions, that is, as the deformation temperature increases, the lnZ value gradually decreases, and as the strain rate increases, the lnZ value increases.

### 3.2. The relationship between the softening mechanism and Z parameters

TEM images of the tested composite with different Z parameters are shown in figure 2. When lnZ = 56.46 (733 K, 10 s\(^{-1}\)), as shown in figure 2(a), the high-density dislocations generated during the hot deformation at the low temperature and high strain rate, the dislocation entanglement structure is formed when cross-slip of dislocation is blocked, and thus a large number of cellular substructures with high-density dislocation are developed in the composite material. The cell wall is composed of high-density dislocation, and the dislocation density in the cell is low. In this case, cross-slip of dislocation is the main softening mechanism. When lnZ = 55.76 (733 K, 5 s\(^{-1}\)), as shown in figure 2(b), the dislocation density within the cellular structure decreases, and the cell wall gradually becomes clear with the decrease of the strain rate. Dislocations offset each other by the cross-slip of dislocations, meanwhile, the dislocations located in the cell wall begin to climb to make the cell wall gradually clear. However, dislocation climbing occurs to a small extent at this time, and dislocation cross-slip is still the main mechanism to control deformation.

When lnZ = 55.02 (753 K, 10 s\(^{-1}\)), As shown in figure 2(c), the density of vacancy increased with the increase of deformation temperature, which results in increasing the ability of dislocation climbing. The dislocations moving to the cell wall are regularly arranged at the cell wall by climbing, so that the cell wall appears clearer. It is worth noting that there is a nano-sized SiC particle adjacent to the cellular substructure, indicating that nano-sized SiC particles may pin the cell wall and hinder the increase of the cellular substructure size. Many similar studies suggested that dispersed fine particles may hinder the migration of sub-grain boundary to result in hindering the occurrence of dynamic recrystallization [31–33]. When lnZ = 54.32 (753 K, 5 s\(^{-1}\)), As shown in figure 2(d), the dislocation density of the cellular substructure decreased significantly, the cell wall was clear, and the sub-grain was formed gradually. This is due to the gradual untangling of the three-dimensional dislocation

| T/K  | 0.1 s\(^{-1}\) | 1 s\(^{-1}\) | 5 s\(^{-1}\) | 10 s\(^{-1}\) |
|------|---------------|------------|------------|-------------|
| 733  | 51.85         | 54.15      | 55.76      | 56.46       |
| 753  | 50.41         | 52.71      | 54.32      | 55.02       |
| 773  | 49.05         | 51.35      | 52.96      | 53.65       |
| 793  | 47.75         | 50.06      | 51.67      | 52.36       |

Table 1. The value of lnZ of 2 vol.% nano-SiCp/Al-12Si composite at different deformation conditions.
network, and the annihilation of some dislocations by cross-slip, and the regular rearrangement of some dislocations by climbing in the cell wall. The softening mechanism of the composites under this deformation condition is mainly the cross slip, climbing of dislocation, and untangling of the three-dimensional dislocation network.

When \( \ln Z = 53.65 \) (773 K, \( \dot{\varepsilon} = 10 \text{ s}^{-1} \)), as shown in figure 2(e), the sub-grain boundary is straight, and there are still a few dislocations in the sub-grain, which are the result of dislocation cross-slip and climbing. At the same time, the low angle grain boundary (LAGB) between the two sub-grains in the left half of the image is relatively vague, and the two sub-grains tend to develop into a DRXed grain through the mechanism of sub-grain combination. Besides, the dislocation density of the grain in the middle of the TEM image is low, and the contrast between the grain and the surrounding grains is obviously different, indicating that dynamic recrystallization has occurred. The softening mechanism of the composite is controlled by dislocation slip, climbing, untangling, and dynamic recrystallization under this deformation condition. When \( \ln Z = 49.05 \) (773 K, \( \dot{\varepsilon} = 0.1 \text{ s}^{-1} \)), as shown in figure 2(f), the contrast of different grains is different and the grain boundaries are clear, there are almost no dislocations in the grains, indicating that dynamic recrystallization grains have formed.
There is a nano-sized SiC particle distributed around the grains in the lower-left corner of figure 2, indicating that the nano-sized SiC particles may hinder the migration of grain boundaries to result in hindering the occurrence of grain boundaries bulging and the growth of DRXed grains. There is a nano-sized SiC particle which is around by dislocation in the upper right corner of figure 2, indicating that the dislocation motion is hindered at the nano-sized SiC particles, and the dislocation has a tendency to bypass the particle to move. The softening mechanism of the composite is controlled by dynamic recrystallization and dynamic recovery under this deformation condition.

According to the above analysis, the dynamic softening mechanism of the 2 vol.% nano-SiCp/Al-12Si composites under experimental conditions is as follows: when \( \ln Z > 55.02 \), \( T = 753 K \), the cross slip of dislocation was mainly softening mechanism; when \( \ln Z < 55.76 \), \( T > 733K \), the softening mechanism mainly includes the cross slip, climbing of dislocation, and untangling of three-dimensional dislocation network; when \( \ln Z \leq 53.65 \), \( T > 773K \), the dynamic recovery and dynamic recrystallization were the main softening mechanism of the composites. The dynamic recrystallization nucleation mechanisms of the 2 vol.% nano-SiCp/Al-12Si composites include the sub-grain combination nucleation and grain boundaries bulging nucleation.

3.3. Dynamic recrystallization nucleation mechanism

Figure 3. TEM images of 2 vol.% nano-SiCp/Al-12Si composites at deformation temperature of 793 K. (a) \( \dot{\varepsilon} = 0.1 s^{-1} \) (\( \ln Z = 47.75 \)); (b) \( \dot{\varepsilon} = 1 s^{-1} \) (\( \ln Z = 50.06 \)); (c) \( \dot{\varepsilon} = 5 s^{-1} \) (\( \ln Z = 51.07 \)); (d) \( \dot{\varepsilon} = 10 s^{-1} \) (\( \ln Z = 52.36 \)).

 TEM images of the 2 vol.% nano-SiCp/Al-12Si composites at a deformation temperature of 793 K are shown in figure 3. When the strain rate is \( 0.1 s^{-1} \) (\( \ln Z = 47.75 \)), as shown in figure 3(a), there is still a small number of dislocations in the two sub-grains located in the middle of figure 3(a). The low angle grain boundary (LAGB) between the two sub-grains gradually disappears by the sub-grain combination nucleation mechanism. When the strain rate is \( 1 s^{-1} \) (\( \ln Z = 50.06 \), as shown in figure 3(b), the dislocation density of the two sub-grains in the left half of figure 3(b) is high, and the low angle grain boundary (LAGB) between the two sub-grains is fuzzy. The dislocation at the small-angle grain boundary continuously moves to the surrounding sub-grains by cross slip and climbing, the dislocation density at the low angle grain boundary gradually decreases, eventually, the two sub-grains become one grain. The dislocation density of the grain in the middle of figure 3(b) is low, and the high angle grain boundary (HAGB) gradually migrates to the sub-grain with higher dislocation density, so that the new grain without distortion is formed by the mechanism of grain boundaries bulging nucleation.
When the strain rate is $5 \text{s}^{-1} (\ln Z = 51.67)$, as shown in figure 3(c), the dislocation density in the two sub-grains is high, the sub-grain boundaries are clear, and the low angle grain boundaries (LAGB) between the two sub-grains are fuzzy. The dislocation at the low angle grain boundaries moves to the surrounding sub-grain boundaries by cross-slip, resulting in the disappearance of the sub-grain boundaries and the dislocation density at the surrounding sub-grain boundaries increases, so that the difference in the crystal orientation of the surrounding sub-grain increases, and the sub-grain gradually transforms into grain. The TEM image of the test composite at $10 \text{s}^{-1} (\ln Z = 52.36)$ is shown in figure 3(d). The combination and growth of the sub-grains are still not completed. The dislocation density of the two sub-grains in the upper left of figure 3(d) is low, the difference in the crystal orientation between the sub-grains is small. The common grain boundary between the two sub-grains is fuzzy, which may be ascribed to the low angle grain boundary (LAGB) gradually disappears due to the mechanism of sub-grains combination. The density of the combined sub-grain is greatly reduced, and the difference in the crystal orientation with the surrounding sub-grains is large, the sub-grain boundary gradually evolves into a large angle grain boundary during the deformation. The dislocation density in the DRXed grain in the upper right of figure 3(d) is low, and the grain boundaries tend to migrate away from the center of its curvature, thereby achieving the growth of dynamic recrystallized grain. According to the above analysis, the dynamic recrystallization nucleation mechanism of the 2 vol.% nano-SiCp/Al-12Si composites include the sub-grain combination nucleation and grain boundaries bulging nucleation.

4. Conclusions

(1) The dynamic recovery mechanism of the 2 vol.% nano-SiCp/Al-12Si composite can be divided into: when $\ln Z > 55.02, T \leq 753 \text{K}$, the cross slip of dislocation was mainly softening mechanism; when $\ln Z < 55.76, T > 733 \text{K}$, the softening mechanism mainly includes the cross slip, climbing of dislocation, and untangling of three-dimensional dislocation network.

(2) The dynamic recovery and dynamic recrystallization were the main softening mechanism when the hot deformation of the 2 vol.% nano-SiCp/Al-12Si composite was conducted at $\ln Z \leq 53.65$ and $T \geq 773 \text{K}$.

(3) The dynamic recrystallization nucleation mechanisms of the 2 vol.% nano-SiCp/Al-12Si composites include the sub-grain combination nucleation and grain boundaries bulging nucleation.

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References

[1] Wang T, Xie L and Wang X 2015 Simulation study on defect formation mechanism of the machined surface in milling of high volume fraction SiCp/Al composite Int. J. Adv. Manuf. Tech. 79 1185–94
[2] Ren S, Qu X, Guo J, He X, Qin M and Shen X 2009 Net-shape forming and properties of high volume fraction SiCp/Al composites J. Alloy. Compd. 484 256–62
[3] Cui Y, Jin T, Cao L and Liu F 2016 Aging behavior of high volume fraction SiCp/Al composites fabricated by pressureless infiltration J. Alloy. Compd. 681 233–9
[4] Soltan S, Khoreshahi R A, Mousavian R T, Jiang Z Y, Boostani A F and Brabazon D 2017 Stir casting process for manufacture of Al–SiC composites Rare Met. 36 581–90
[5] Sun Y, Xie J, Hao S, Wang A, Liu P and Li M 2015 Dynamic recrystallization model of 30% SiCp/Al composite J. Alloy. Compd. 649 665–71
[6] Song J, Guo Q, Ouyang Q, Su Y, Zhang J and Lavernia E J 2015 Influence of interfaces on the mechanical behavior of SiC particulate-reinforced Al–Zn–Mg–Cu composites Mat. Sci. Eng. A 644 79–84
[7] Monazzah A H, Pouraliakbar H, Bagheri R and Reihani S M S 2017 Al–Mg–Si/SiC laminated composites: fabrication, architectural characteristics, toughness, damage tolerance, fracture mechanisms Compos Part B. Eng. 125 49–70
[8] Ghandvar H, Farahany S and Idris J 2015 Wettability enhancement of SiCp in cast A356/SiCp composite using semisolid process Mater. Manuf. Process. 30 1442–9
[9] Qiu F, Gao X, Jiang T, Gao Y, Shu S, Han X, Li Q and Jiang Q 2017 Microstructures and tensile properties of Al–Cu matrix composites reinforced with nano-sized SiCp fabricated by semisolid stirring process Metals 7 89
[10] Zhang L J, Qiu F, Wang G and Jiang Q C 2015 High strength and good ductility at elevated temperature of nano-SiCp/Al2014 composites fabricated by semi-solid stir casting combined with hot extrusion Mater. Sci. Eng. A 626 338–41
[11] Moussavian R T, Behnamfar S, Khoreshahi R A, Zavašnik I, Ghosh P, Krishnamurthy S and Brabazon D 2020 Strength-ductility trade-off via SiC nanoparticle dispersion in A356 aluminium matrix Mater. Sci. Eng. A 771 138639
[12] Xiong B, Xu Z, Yan Q, Cai C, Zheng Y and Lu B 2010 Fabrication of SiC nanoparticles reinforced Al matrix composites by combining pressureless infiltration with ball-milling and cold-pressing technology J. Alloy. Compd. 497 L1–4
[13] Pirlari A I, Emamny M, Amadeh A A and Naghizadeh M 2019 Elucidating the effect of TiB2 volume percentage on the mechanical properties and corrosion behavior of Al5083–TiB2 composites J. Mater. Eng. Perform. 28 6912–20
[14] Wan Z, Wang T, Sun Y, Hu L, Li Z and Li P 2019 Dynamic softening mechanisms of GH4720Li alloy during hot deformation Acta. Metall. Sin. 55 213–22
[15] Ji H, Liu J, Wang R, Tang X, Lin J and Hua Y 2017 Microstructure evolution and constitutive equations for the high-temperature deformation of 5Cr21Mn9Ni4N heat-resistant steel J. Alloy. Compd. 693 674–87
[16] Wang Z, Wang A, Xie J and Liu P 2020 Hot deformation behavior and strain-compensated constitutive equation of nano-sized SiC particle-reinforced Al–Si matrix composites Materials 13 1812
[17] Deng K, Wang X, Zhang M and Wu K 2013 Dynamic recrystallization behavior during hot deformation and mechanical properties of 0.2 μm SiCp reinforced Mg matrix composite Mater. Sci. Eng. A 560 824–30
[18] Gangothi S, Gourav Rao A, Sabirov I, Kashyap B P, Prabhun N and Dreshmhk V P 2016 Development of constitutive relationship and processing map for Al-6.65Si-0.44Mg alloy and its composite with B4C particulates Mater. Sci. Eng. A 655 256–64
[19] Ezatpour H R, Chaichi A and Sajjadi S A 2015 The effect of Al2O3–nanoparticles as the reinforcement additive on the hot deformation behavior of 7075 aluminium alloy Mater. Design 88 1049–56
[20] Liu R, Wang W, Chen H, Zhang Y and Wan S 2019 Hot deformation and processing maps of B4C/6061Al nanocomposites fabricated by spark plasma sintering J. Mater. Eng. Perform. 28 6287–97
[21] Chen X H, Fan C H, Hu Z Y, Yang J J and Gao W L 2018 Flow stress and dynamic recrystallization behavior of Al-9Mg-1.1Li-0.5Mn alloy during hot compression process T Nonferr. Metal. Soc. 28 2401–09
[22] Li J, Li F and Cai J 2018 Constitutive model prediction and flow behavior considering strain response in the thermal processing for the TA15 titanium alloy Materials 11 1985
[23] Ashiani H R, Parsa M H and Bisadi H 2012 Constitutive equations for elevated temperature flow behavior of commercial purity aluminium Mater. Sci. Eng. A 545 61–7
[24] Mirzadeh H 2013 A simplified approach for developing constitutive equations for modeling and prediction of hot deformation flow stress Metall. Mater. Trans. A 46 4027–37
[25] Shao J C, Xiao B L, Wang Q Z, Ma Z Y, Liu Y and Yang K 2010 Constitutive flow behavior and hot workability of powder metallurgy processed 20 vol.% SiCp/204Al composite Mater. Sci. Eng. A 527 7865–72
[26] Senthilkumar V, Balaji A and Narayanasamy R 2012 Analysis of hot deformation behaviour of Al5083–TiC nanocomposite using constitutive and dynamic material models Mater. Des. 37 102–10
[27] McQueen H J, Mysliwetz M, Konopleva E and Sakaris A P 1998 High temperature mechanical and microstructural behavior of A356/15 vol% SiCp and A356 alloy Can. Metall. Q. 37 125–39
[28] Cerri E A, Spigarelli S B, Evangelista E B and Cavalliere P B 2002 Hot deformation and processing maps of a particulate-reinforced 6061 + 20% Al2O3 composite Mater. Sci. Eng. A 324 157–61
[29] Ezatpour H R, Sajjadi S A, Sabievar M H, Chaichi A and Ebrahimi G R 2017 Processing map and microstructure evaluation of AA6061/Al2O3 nanocomposite at different temperatures T Nonferr. Metal. Soc. 27 1248–56
[30] Jiang D, Yuan C, Li X and Yu H 2020 Hot deformation behavior and microstructure characteristic of 2055 Al–Li alloy during uniaxial compression Mater. Res. Express 7 076507
[31] Xiang S, Liu D Y, Zhu R H, Li J F, Chen Y L and Zhang X H 2015 Hot deformation behavior and microstructure evolution of 1460 Al–Li alloy T Nonferr. Metal. Soc. 25 3853–64
[32] Hu R, Liu Q, Li J, Xiang S, Chen Y and Zhang X 2015 Dynamic restoration mechanism and physically based constitutive model of 2050 Al–Li alloy during hot compression J. Alloys Compd. 650 75–85
[33] Ou L, Zheng Z, Nie Y and Jian H 2015 Hot deformation behavior of 2060 alloy J. Alloys Compd. 648 681–9