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Flow stress prediction for hot deformation processing of 2024Al-T3 alloy

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Abstract: Isothermal compression tests were conducted to predict the hot deformational flow stress behaviour of 2024Al-T3 alloy with respect to a wide range of strain rates (0.001−100 s^{-1}), strains (0.1−0.5) and temperatures (573−773 K). The prediction capabilities of various constitutive models for 2024Al alloys and a recently developed constitutive model were evaluated using statistical parameters such as the average absolute relative error (AARE) and the correlation coefficient (R). Models recorded the lowest AARE (4.6%) and the highest correlation coefficient (R=0.99) were developed compared with the other models. Hence, this model can track the deformational behaviour of 2027Al-T3 alloy more accurately compared with other models throughout the entire processing domain investigated.

Key words: isothermal compression; 2024Al alloy; constitutive model; flow stress

1 Introduction

2024 aluminium alloys are used extensively within the aerospace industry to fabricate structural components such as aircraft fuselage and wing panels due to their high strength to mass ratio [1,2]. Finite element (FE) methods have been successfully used to analyze and optimize bulk metal deformation processes [3], metal machining processes [4,5] and solid state joining processing [6] of these aluminium alloys. During the development of a FE simulation, the constitutive model of the workpiece material was used as an input to simulate material deformation behaviour under specified loading conditions [7]. Therefore, the precision of the numerical simulation depends on how accurately the deformation behaviour of the material is represented by the constitutive model [8]. Usually, the constitutive model is a mathematical representation describing the relationship among flow stress, strain, strain rate and temperature [9].

Many constitutive models have been proposed or modified to describe the flow stress behaviour of 2024Al alloys over different ranges of temperatures and strain rates. Table 1 highlights previous research publications in this area. In terms of aluminium alloys, one of the earliest and most common constitutive models is the hyperbolic sine Arrhenius-type model proposed by ZENER and HOLLOMON [10], and SELLARS and TEGART [11]. SHEPPARD and JACKSON [12] performed hot compression and hot torsion tests to determine the flow stress behaviour of 2024Al alloy using this Arrhenius-type model. Hot torsion tests were conducted by CEPEDA-JIMENEZ et al [13] to determine the flow stress behaviour of 2024Al-T351 alloy also using the Arrhenius-type model. More recently, HAO et al [14] used the Arrhenius-type model to establish the flow stress behaviour of 35%SiC_p/2024 aluminium metal matrix composite. A major disadvantage of the Arrhenius model is that the effect of strain is not considered. LIN et al [15] proposed a modified Arrhenius-type model with strain compensation to encapsulate the effect of strain to establish the flow stress behaviour of 42CrMO steel.

The Johnson−Cook model is another example of a well-established constitutive model. JOHNSON and COOK [16] used their proposed model to determine the flow stress behaviour of 2024Al-T351 alloy by performing isothermal and adiabatic torsion tests. LESUER [17] performed high strain rate compression tests on 2024Al-T3 alloy using a split Hopkinson pressure bar (SPHB) system to determine new constants for the Johnson−Cook model. However, SPHB tests at different temperatures were not completed. SEIDT and GILAT [18] performed a number of tension, compression and torsions tests on 2024Al-T351 alloy test pieces at

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Table 1 Highlight of previous research on developing constitutive models for 2024 aluminium alloys

Material	Temperature/K	Strain rate/s^{-1}	Model	Constant		Ref.
2024Al	533, 573, 613, 653, 693	0.008, 0.08, 8, 80	$\dot{\varepsilon}=A[\sinh(\alpha\sigma)]^n\exp\left(\frac{-Q}{RT}\right)$	α=0.016 MPa^{-1}, n=4.27	Q=148880 J/mol, ln A=19.6 s^{-1}	[12]
2024Al-T3	551, 588, 633, 681, 740	2.1, 4.5, 9.6, 25.6	$\dot{\varepsilon}=A[\sinh(\alpha\sigma)]^n\exp\left(\frac{-Q}{RT}\right)$	α=0.0103 MPa^{-1}, n=6.1	Q=179000 J/mol, ln A=31.36 s^{-1}	[13]
35%SiC_p/2024Al	623, 673, 723, 773	0.01, 0.1, 1, 10	$\dot{\varepsilon}=A[\sinh(\alpha\sigma)]^n\exp\left(\frac{-Q}{RT}\right)$	α=0.013 MPa^{-1}, n=9.075	Q=225400 J/mol, ln A=35.48 s^{-1}	[14]
2024Al-T351	−	1, 10, 100	$\sigma=(A+B)^n(1+C\ln\dot{\varepsilon}^*)(1-T^{*m})$	A=265 MPa, B=426 MPa, C=0.015	n=0.34, m=1.0	[16]
2024Al-T3	−	4000, 8000	$\sigma=(A+B)^n(1+C\ln\dot{\varepsilon}^*)(1-T^{*m})$	A=369 MPa, B=684 MPa, C=0.0083	n=0.73, m=1.7	[17]
2024Al-T351	223, 293, 423, 573, 723	0.0001, 0.01, 1, 500, 1800	$\sigma=(A+B)^n(1+C\ln\dot{\varepsilon}^*)(1-T^{*m})$	A=304 MPa, B=478 MPa, C=0	n=0.406, m=2.1	[18]
2024Al-T3	−	−	$\sigma=(A+B)^n(1+C\ln\dot{\varepsilon}^*)(1-T^{*m})$	A=325 MPa, B=414 MPa, C=0.015	n=0.2, m=1	[19]
2024Al	573, 623, 673, 723, 773	0.1, 1, 10, 100	$\sigma=(P+Q\varepsilon^n)\dot{\varepsilon}^{*r}\cdot\left[1+\left\{\frac{\sigma_m}{\sigma_y}-1\right\}\exp(-\alpha T^{*\beta})\right]$	P=78, Q=−12.13, n=0.796	r=0.095, α=0.522, β=0.582	[21]
2024Al	573, 623, 673, 723, 773	0.1, 1, 10, 100	$\sigma=\sigma_0+d\sigma_1+d\sigma_2$, $\sigma_0=\sigma_r\dot{\varepsilon}^{*m}\left[1+\left\{\frac{\sigma_m}{\sigma_y}-1\right\}\exp(-\alpha T^{*\beta})\right]$, $m=\gamma_{11}T+\gamma_{12}$, $d\sigma_1=(\gamma_{21}T+\gamma_{22})\Delta\varepsilon$, $d\sigma_2=(\gamma_{31}T+\gamma_{32})\Delta\varepsilon\Delta\dot{\varepsilon}_0$	α=0.399, β=0.722, γ_{11}=0.0002, γ_{12}=−0.375	γ_{21}=0.0172, γ_{22}=−22.497, γ_{31}=0.003, γ_{32}=−2.819	[22]
2024Al-T351	233, 296, 358, 422, 505	0.0001, 0.001, 1, 1500, 2400	$\sigma=[A+B\exp(-C_2\dot{\varepsilon}^*)T^{*m_2}\ \varepsilon^{n_0}]\cdot[\exp^{C_1\dot{\varepsilon}^*}-C_2(T)\exp^{-K_2\dot{\varepsilon}}]T^{*m_2}$	A=275.98, B=700.43, C_1=0.0001726, C_3=0.002752, n_0=0.4208	K_1=64.68, m_1=1.368, m_2=0.3939, m_3=0.3589	[23]

different specimen orientations to determine the flow stress behaviour using the Johnson−Cook model. However, the effect of temperature was investigated at one strain rate only. AMIR et al [19] performed machining investigations based on Ref. [20] to further refine the original constants of the Johnson−Cook model for 2024Al-T351 alloy.

More recent constitutive models have focused on the modification of existing models or the development of new constitutive models. MAHESHWARI et al [21] proposed a modified Johnson−Cook model to describe the flow stress behaviour of 2024Al alloy from experimental compression data. It was found that in most cases, the modified model correlated better with experimental results compared with the original Johnson−Cook model. More recently, MAHESHWARI [22] proposed a new phenomenological constitutive model which correlated even better with experimental data compared with that previously proposed modified Johnson−Cook model [21]. KHAN and LIU [23] performed compression tests on 2024Al-T351 alloy and proposed a new phenomenological model to describe the flow stress behaviour. LIN et al [24] proposed a new constitutive model to predict the hot tensile deformation behaviour of Al−Cu−Mg, Al−Zn−Mg−Cu [25] and 7075Al [26] alloy based on the original Johnson−Cook model. The authors reported greater prediction capability compared with the Johnson−Cook model. TRIMBLE and O'DONNELL [27] have also recently developed a new constitutive model to describe the flow stress behaviour of 7075Al.

The objective of this study was to establish the flow stress behaviour of 2024Al-T3 through isothermal compression tests. This was achieved by evaluating the