Materials Science & Engineering A 630 (2015) 125–130

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

The effect of machining-induced residual stresses on the creep characteristics of aluminum alloys

Timothy W. Spence [a], Makhlouf M. Makhlouf [b,*]

[a] BAE Systems Electronics and Integrated Solutions, P.O. Box 868, NHQ3-2145, Nashua, NH 03061, USA
[b] Department of Mechanical Engineering, Worcester Polytechnic Institute, Worcester, MA 01601, USA

ARTICLE INFO

Article history:
Received 15 October 2014
Received in revised form
3 February 2015
Accepted 9 February 2015
Available online 18 February 2015

Keywords:
Dimensional stability
Creep
Mathematical modeling
Machining-induced residual stress
Aluminum alloys

ABSTRACT

Precision components, such as those used in optical systems, often experience distortion of their shape during service. This distortion occurs because of residual stresses that are introduced into the surface of the components during machining and lead to creeping of the material when the component is subjected to elevated temperatures for prolonged periods of time. In this paper, a creep model is developed and used to describe how the residual surface stresses created by milling and by fly cutting affect the geometry of an aluminum alloy component as it creeps. The model is verified by applying it to components that are manufactured from two different aluminum alloys; namely 4032-O and 6061-T6; and then it is used to design efficient stress relief schedules for these alloys.

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1. Background

Dimensional stability of materials is of paramount importance in the fabrication of precision components such as those used in optical systems. Changes in the geometry of these parts over time are unacceptable; particularly if the changes cause the parts to no longer meet the required tolerance. Many sources of dimensional instability have been identified and studied over the years, important among them is residual stresses induced by machining operations; and although stress relief procedures have been developed for many alloys in order to control these stresses, dimensional instability caused by surface stresses due to machining operations has not been thoroughly characterized and a comprehensive understanding of the magnitude of dimensional changes and the kinetics of the strains that develop in the material over time spans and temperature ranges does not exist. Nevertheless, several studies have been performed to characterize the magnitude of residual stress caused by machining operations. Noteworthy among them is an investigation by Brunet [1] in which he characterized the residual stresses induced in an aluminum alloy (7075-T7351) by milling operations. He found that residual stresses always peaked at the surface of the part and that the milling parameters significantly affect the magnitude of the residual stress. For example, he found that up-milling results in a residual stress that is 100 MPa less in magnitude than down milling, he also found that reducing the cutting speed by 10 times reduces the residual stress by about 200 MPa and reducing the feed speed by 3 times reduces the residual stress by about 150 MPa. Similarly, Field [2] characterized the residual stresses induced in 4340 steel by grinding operations and found that "gentle" grinding produced small compressive stresses at the surface and virtually no internal stresses, while more aggressive grinding produced large tensile stresses at the surface balanced by compressive stresses deeper within the metal's bulk. Also Frommer and Lloyd [3] characterized the residual stresses in heat treated aluminum alloys that have been subjected to different machining operations. They used x-rays to measure the magnitude of surface stresses and acid etching to estimate the depth of the stressed layer. Their findings are summarized in Table 1. Therefore, it is evident that machining operations invariably produce surface stresses in the machined components and that these stresses can range in magnitude from being insignificant to being highly significant. Moreover, the magnitude and sense of these surface stresses depend to a large extent on the machining operation.

2. Development of the model

Generally speaking, material that is in a state of sustained stress will creep and there are two unique characteristics to this situation:

* Corresponding author. Tel.: +1 508 831 5647; fax: +1 508 831 5993.
E-mail address: mmm@wpi.edu (M.M. Makhlouf).

http://dx.doi.org/10.1016/j.msea.2015.02.020
0921-5093/Published by Elsevier B.V.

Table 1
Summary of findings by Frommer and Lloyd related to surface stresses produced by various machining operations.

Machining operation	Process details	Stress (MPa)	Depth (mm)
Turning	Flat surface finished with a fine finishing cut (0.038 mm/rev., 0.127 mm depth of cut).	45	0.051
	Cylindrical surface turned with a rough cut (575 rpm, 0.305 mm/rev., 1.27 mm depth of cut).	98	0.381
	Surface faced off under conditions that produce chatter marks.	282	0.610
Recessing	Recess made with a flat bottom drill (290 rpm, 0.127 mm/rev.).	94	0.102–0.381
Surface milling (cutter not enclosed by material)	Flat surface side-milled with a 50.8 long 9.525 diameter end-mill (220 rpm, 0.01 mm/rev., 3.175 mm depth of cut).	Nil	Nil
	Flat surface milled with a straddling end-mill (220 rpm, 0.254 mm/rev., 3.175 mm depth of cut).	Nil	Nil

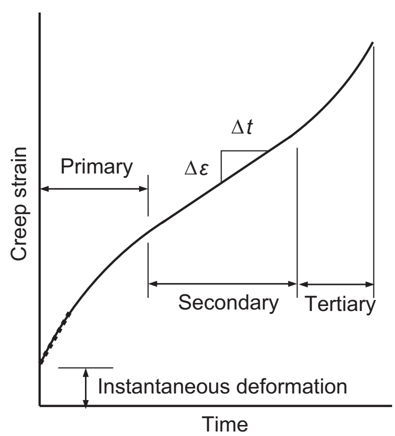

Fig. 1. Hypothetical creep strain vs. time plot showing (as a dashed line) the region of interest when considering creep induced by residual stresses that are caused by machining operations [10].

1. In general, creep models have a stress term that is raised to an exponent; and for metals, this exponent is larger than unity. Consequently, if a metallic specimen has a non-uniform stress, the more stressed regions will creep at exponentially higher rates than the less stressed regions.
2. As the material strains, the stress level becomes proportionally lower.

These two characteristics must be accounted for in any mathematical model that is intended for predicting the dimensional stability of metallic components due to machining residual stresses.

The temperature range of interest in this work is $-55\,^{\circ}$C to $+125\,^{\circ}$C. This is known as “the full military temperature range” because it is the service range for a wide variety of military components. The typical magnitude of residual stress caused by machining operations is in the range 100–200 MN/m^2 [1–7]. The creep mechanism map for aluminum shows that for this temperature and stress ranges, the operative creep modes are Dislocation Glide and Dislocation Creep [8]. The creep model that is applicable for Dislocation Glide and Dislocation Creep, and also accounts for both stress and temperature is the Power Law [9]. However, the Power Law creep model best represents Secondary Creep; while in this case, the constantly changing stress magnitude (due to creep strain) will keep the creep mode in the Primary Creep regime. Nevertheless, the strains associated with machining residual stresses are small enough and the time spans considered are short enough that a straight line approximation over the range of interest should introduce only a small error into calculations made with the Power Law as shown in Fig. 1.

The Power Law Creep equation for crystalline materials [9,11] is given by the following equation:

$$\dot{\varepsilon}=\frac{k}{T}\sigma^{m}e^{-\frac{Q_c}{RT}} \tag{1}$$

In Eq. (1), the variables that affect the strain rate $\dot{\varepsilon}$ are stress, σ, and absolute temperature, T. The coefficient k, the exponent m, and the activation energy Q_c have values that depend on the material and the creep mechanism. A unique condition of creep strain due to residual (not applied) stress in an un-restrained material is that stress is not constant but it is a function of strain, i.e.

$$\sigma_{res}=f(\varepsilon)$$

Given Hooke's Law

$$\varepsilon_1=\frac{1}{E}[\sigma_1-\nu(\sigma_2+\sigma_2)]$$

and if

$$\sigma_2=\sigma_3=0$$

then

$$\sigma_1=\sigma=E\varepsilon \tag{2}$$

A stress function is then defined with a linear relationship to strain and where the value of stress reduces to zero as strain reaches its final magnitude (ε_f) as shown in the following equation:

$$\sigma=\sigma_{in}\left(1-\frac{\varepsilon}{\varepsilon_f}\right) \tag{3}$$

Substituting Eq. (3) into Eq. (1), and integrating from an initial strain of zero at an initial time of zero, yields an expression that defines strain as a function of initial stress (σ_{in}), final strain (ε_f), stress exponent (m), activation energy (Q_c), a constant (k), and time (t) as shown in the following equation:

$$\int_{\varepsilon=0}^{\varepsilon=\varepsilon}\left(\sigma_{in}-\frac{\sigma_{in}\varepsilon}{\varepsilon_f}\right)^{-m}d\varepsilon=\int_{t=0}^{t=t}ke^{\frac{-Q_c}{RT}}dt$$

$$\varepsilon=\varepsilon_f-\frac{\varepsilon_f}{\sigma_{in}}\left[\frac{(m-1)\sigma_{in}}{\varepsilon_f}\frac{k}{T}te^{\left(\frac{-Q_c}{RT}\right)}+(\sigma_{in})^{1-m}\right]^{\frac{1}{1-m}} \tag{4}$$

It was found that, within the temperature range considered in this work, as the temperature increased, ε_f also increased. The theoretical maximum creep strain that would be recovered during an isothermal temperature exposure ($\varepsilon_{f,m}$) would be in accordance with Hooke's Law (assuming that the initial stress is completely converted to strain), i.e.

$$\varepsilon_{f,m}=\frac{\sigma_{in}}{E}.$$

In reality, the theoretical maximum strain is not reached, so an expression is developed to allow predicting ε_f. The expression includes a material constant, B, and a temperature dependence term, T^n, together with the modulus of elasticity for the material, E, as shown in following equation:

$$\varepsilon_f=B\frac{\sigma_{in}}{E}T^n. \tag{5}$$