SLOT MACHINING EFFECTS ON RESIDUAL STRESS MEASUREMENTS USING THE CRACK COMPLIANCE METHOD

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Abstract. The main aim of this paper was to evaluate the practical aspects and compare two of the most common machining techniques employed in the crack compliance method for the determination of residual stresses, namely WEDM and circular abrasive saws. For the circular saws, the effect of the rotational speed and blade thickness was also evaluated. Results show that the associated level of errors introduced during thin saw machining can be as low as the results obtained by WEDM machining. However, for practical reasons, WEDM machining offers a better control of cut increment length than sawing techniques. Additionally, higher rotational saw speeds are likely to introduce larger errors in strain readings probably due to higher frictional heat and plasticity generation ahead of the slot tip.

Keywords: *crack compliance method, residual stress, machining, WEDM, saw cut*

1. Introduction

The crack or cut compliance method is a powerful and easy to implement technique employed to determine both near surface and through the thickness residual stress profiles. It is based on the fact that when a cut, simulating a crack, is incrementally introduced into a part, the residual stresses are relieved on the slot surfaces created, causing the part to deform. Such deformation can be measured by strain gauges attached to specific regions of the part (Fig. 1) and the residual stress profile that originally existed can be evaluated (Prime, 1999).

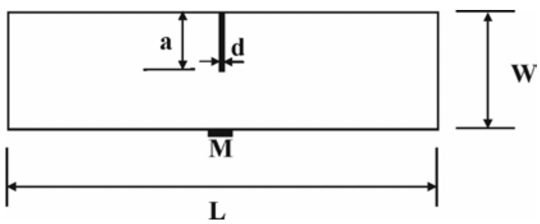


Figure 1. Rectangular plate containing a cut along its center plane, strain measurement taken at the point M.

Assuming a narrow slot (d<<a), linear elastic fracture mechanics equations can be employed to establish a relationship between the measured strains, ε, and the corresponding residual stress intensity factor, K_r (Schindler, 1995):

$$K_{Ir}(a) = \frac{E'}{Z(a)} \frac{d\varepsilon_M}{da} \quad (1)$$

where ε_M is the measured strain at point M during the cutting procedure, a is the slot length, E´ is the generalized form of the Young´s modulus (E´=E for plane stress and E´=E/(1-υ^2) for plane strain) and Z(a) is the “influence function” which depends on the testpiece geometry, cut plane location and strain measurement position, but it is independent on the residual stress profile.

For a rectangular plate, where L>2W, and taking strain measurements at the back face point M, Z(a) is given as (Schindler and Bertschinger, 1997):

for a/W<0.2

$$Z(a) = \frac{-2{,}532}{(W-a)^{1.5}}\sqrt{1-25.\left(\frac{a}{W}-0.2\right)^2}.\left[5.926.\left(0.2-\frac{a}{W}\right)^2 - 0.288.\left(0.2-\frac{a}{W}\right)+1\right] \tag{2}$$

for 0.2<a/W<1

$$Z(a) = \frac{-2.532}{(W-a)^{1.5}} \tag{3}$$

$K_{Ir}(a)$ and the normal residual stresses, $\sigma_r(x)$, that existed prior to the cutting (where the x axis is coincident with the cut plane) can be correlated by the following expression:

$$K_{Ir}(a) = \int_{a_o}^{a} h(x,a).\sigma_r(x).dx \tag{4}$$

where $h(x,a)$ is the weight function, which is available for several geometries (Fett and Munz, 1997). In particular, for a single edge crack in a finite width rectangular plate, the weight function is given as:

$$h(x,a) = \sqrt{\frac{2}{\pi a}}\frac{1}{\sqrt{1-x/a}}\left[1+\frac{1}{(1-a/W)^{3/2}}\sum_{\upsilon,\mu} A_{\upsilon,\mu}(a/W)^{\mu}(1-x/a)^{\upsilon+1}\right] \tag{5}$$

where $A_{v,\mu}$ values are found in Table 1.

Table 1.Weight function coefficients for rectangular testpieces (Fett and Munz, 1997).

ν	μ =0	μ = 1	μ = 2	μ = 3	μ = 4
0	0.4980	2.4463	0.0700	1.3187	-3.067
1	0.5416	-5.0806	24.3447	-32.7208	18.1214
2	-0.19277	2.55863	-12.6415	19.7630	-10.986

Knowledge of $K_{Ir}(a)$ profile (obtained by Eq. (1)) makes possible to calculate $\sigma_r(x)$ profile through the inversion of Eq. (4). One of the methods used for such purpose is the incremental stress method (Schindler 1995), where the stress profile is approximated by a series of small steps as depicted schematically in Fig. 2. The stress level in each step can be calculated by applying Eq. (4) to a hypothetical, incrementally prolonging crack. This leads to a discrete form of Eq. (4):

$$K_{Ir}(a_i) = \sum_{j=1}^{i}\sigma_j \int_{a_{j-1}}^{a_j} h(x,a_i)dx \tag{6}$$

Using Eq. (6) sequentially allows each σ_j to be determined and the stress profile can be determined. The resulting stress distribution converges to the exact solution $\sigma_r(x)$ as Δa→0.

The procedure described above is able not only to determine the initial residual stress profile that was present in the material before the slot was introduced, but also the redistributing stress profiles ahead of the slot tip, by simply changing the integration limits in Eq. (6).

Machining the slot is a critical step in the crack compliance method. Several methods have been used to introduce the slot such as saws (Lim et al, 2003; Vaidyanathan and Finnie, 1971 and Kang and Seol, 1996), milling cutters (Cheng and Finnie, 1985 and Ritchie and Leggatt, 1987) and wire electro discharge machining (WEDM) (Schindler and Bertschinger, 1997; Rankin et al, 2003; Reid, 1988; Cheng et al, 1994 and Prime and Hellwig, 1997). The general consensus is that WEDM in finishing mode is the best choice for introducing the slot because it is likely to introduce lower levels of additional stresses. However, to the knowledge of the authors, no systematic study has been performed so far comparing different machining techniques.

Therefore, the main aim of this paper was to evaluate the practical aspects and compare two of the most common machining techniques employed in the crack compliance method for the determination of residual stresses, namely WEDM and circular abrasive saws. For the circular saws, the effect of the rotational speed and blade thickness was also evaluated.

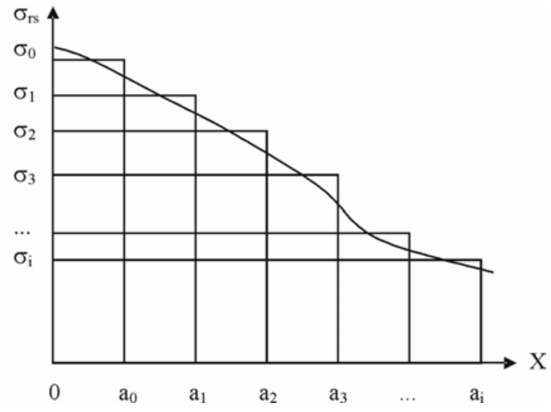


Figure 2. Stress profile approximation using small constant stress steps.

2. Experimental procedures

Testpieces of AA2024-T3, 1.6mm thick were machined by WEDM into 60x120mm2 rectangular plates. The testpieces were subjected to a temperature of 350oC, for 3h, to completely remove any residual stresses that could mask the actual machining effects on strain readings. A strain gauge was glued to the back face of each testpiece, in a configuration similar to the one presented in Fig. 1. A plastic resin was applied on top of the strain gauge and wires to avoid contact with the environment. Shielded wires were used to connect the strain gauges to the strain data acquisition apparatus in order to minimize electromagnetic interferences.

Two different circular abrasive saws with thickness of 0.7mm and 1.7mm were used in the tests. Both saws present a diameter of 180mm. For both thicknesses, a rotational speed of 100RPM was applied during the tests. For the thin saw, additional tests were performed under 150RPM for the purpose of comparison. WEDM slotting was performed in finishing mode. For all tests, increments of approximately 2mm were chosen for each step and the readings were taken 5min after the slotting procedure in each step had finished. In all cases, as required by the method, the testpieces were fixed to the equipment on one side only, leaving the testpiece free to deform.

After the strain data was obtained as a function of the slot length, a best fit polynomial function was found and derived to input $d\varepsilon/da$ values in Eq. (1). After K_r values were found, the residual stress profile was determined by the incremental stress method, using a routine created in Mathcad software.

3. Results and discussions

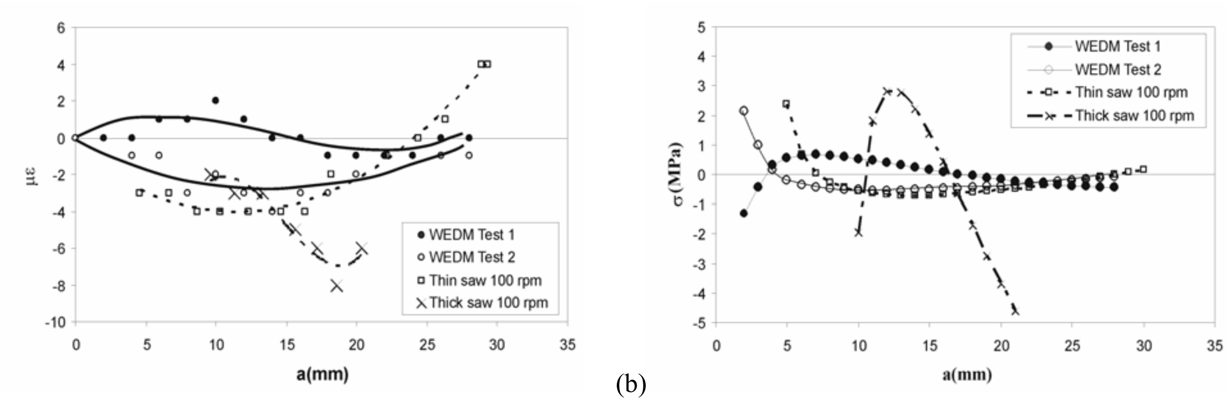
Slot machining using circular abrasive saws is easy to perform and readily available in any mechanical workshop. However, some practical disadvantages were found when compared to WEDM. First, contrary to WEDM, it is very difficult, if not impossible, to impose exactly equal length increments in each step of the machining procedure; this is particularly important if one intends to use the secant method for the derivation of strain values. Second, a lot of vibration was observed during saw cutting which in some cases led to fracture of the strain gauge wire. Moreover, saw cutting is more likely to locally heat the testpiece and longer periods of time have to be allowed for the testpiece to cool completely. On the other hand, WEDM proved to be very efficient in controlling the length of each increment and giving very accurate digital readings of total slot length. However, care must be taken to avoid contact between the refrigerating fluid and the strain gauge wires, which in turn could affect the readings.

Since Eq. (1) is based in linear elastic fracture mechanics relationships, the length of the slot, a, must be significantly larger than its width, d, in order to simulate a crack. Therefore, strain data points corresponding to a slot length smaller than 5d were excluded from the analysis. Table 2 presents the exclusion length for each of the machining procedures used in this work. The exclusion length is much smaller for the WEDM machining technique because the wire is very thin and consequently fewer data points have to be discarded in the analysis. The zero data point (a=0 and ε=0) was included in the WEDM analysis because the gap between this contour condition and the first valid point is very small.

Tabel 2. Slot width and initial exclusion length for strain data points.

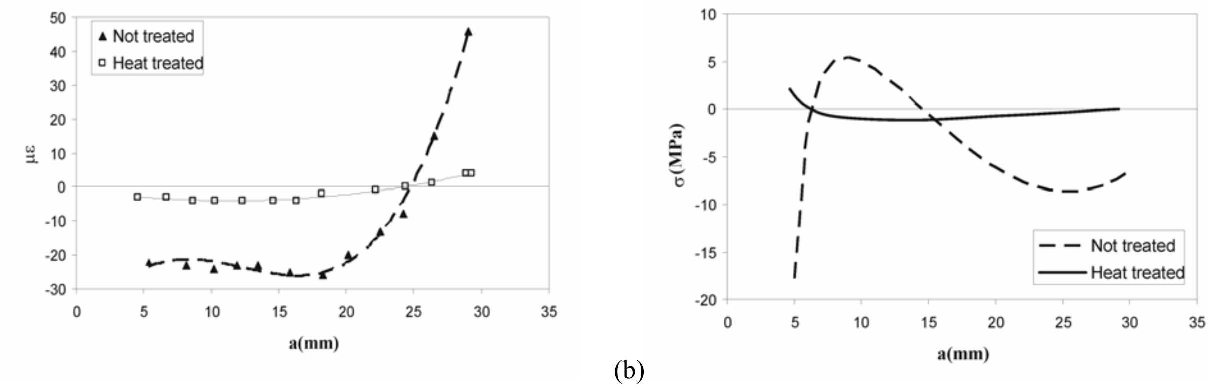
	Slot width, *d* (mm)	Exclusion length, *5d* (mm)
WEDM	0.2	1.0
Thin saw	0.7	3.5
Thick saw	1.7	8.5

Figure 3 shows a comparison of the strain data and residual stress results obtained for WEDM and saw cutting (100RPM) methods. It is possible to observe than all values of calculated stresses are very low, regardless of the cutting technique employed. However, the thick saw results presented a larger range of stress values than both the thin saw and WEDM method, confirming the idea that thinner saws/wires are preferable for the crack compliance method because they are more representative of a true crack. The thin saw test results are as a low as the WEDM values, however, as mentioned previously, the WEDM technique gives a better control of slot increment and total length. It is important to emphasize that the calculated stress profiles presented in Fig. 3b do not represent a true residual stress profile that was present in the testpieces before the slot was introduced because no residual stresses are likely to be present as consequence of the heat treating procedure. In fact, as depicted in Fig. 4, the stress relief procedure employed was very successful in removing any residual stress of the testpieces. However, the results provide a good representation of the error band introduced in residual stress measurements expected for the crack compliance method, according to each machining technique employed.



(a) (b)

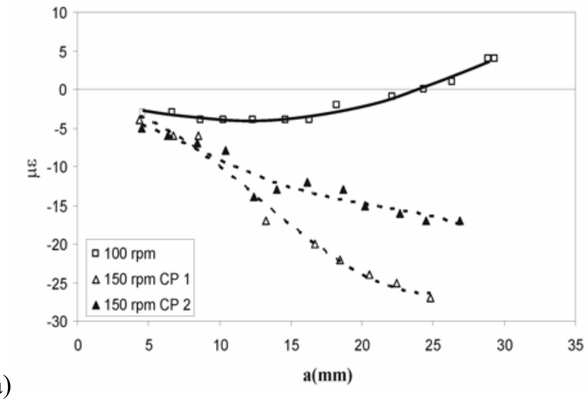
Figure 3. Comparison of the different machining techniques: (a) strain data; (b) calculated stress profiles.



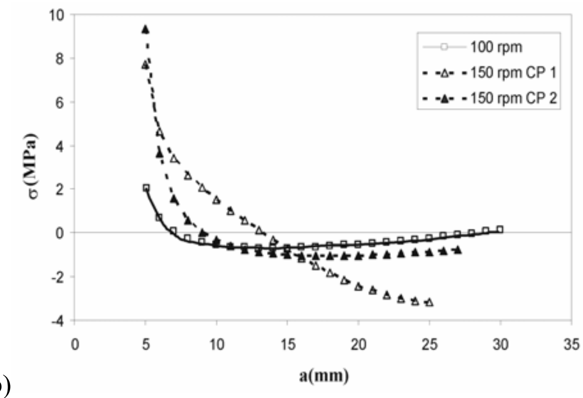
(a) (b)

Figure 4. Results of the stress relief heat treating procedure employed: (a) strain data; (b) calculated stress profiles. The slot was introduced using the thin saw, at 100RPM.

In relation to the rotational speed effects, Fig. 5 indicates that higher speeds are likely to introduce larger variations in strain readings, resulting in higher levels of calculated stresses. Although thermal analysis was not performed during the cutting procedure, it is possible that higher saw speeds increase the levels of heat generation and since the time interval between cutting and taking the strain measurements was kept constant in all tests, this could affect the readings. Moreover, higher rotational speeds may introduce a larger level of non-linear effects due to plasticity ahead of the slot tip.



(a)



(b)

Figure 5. Comparison of the effects of different rotational speeds: (a) strain data; (b) calculated stress profiles. The slot was introduced using the thin saw.

4. Conclusions

1. Thick saws are likely to introduce large errors in strain readings and more points have to be excluded from the analysis to assume the condition of d<<a, i.e., to simulate a crack.

2. The level of errors introduced during thin saw machining can be as low as the results obtained by WEDM machining. However, for practical reasons, WEDM machining offers a better control of cut increment length than sawing techniques.

3. Higher rotational saw speeds are likely to introduce larger errors in strain readings probably due to higher frictional heat and plasticity generation ahead of the slot tip.

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