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Paper

IMPACT OF RESIDUAL STRESSES ON ACCURACY OF AWJ CUTTING

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ABSTRACT

As the accuracy of abrasive waterjet (AWJ) machines is improving, a wider range of process variables are receiving attention regarding their impact on the accuracy of AWJ cut parts. Residual stress is one of these process variables. In this experimental study, AWJ tests cutting steel samples with and without residual stresses were conducted. The results indicated a strong link between residual stresses and part accuracy. An annealing process was used effectively to eliminate the residual stresses. A practical test was created to determine residual stress conditions and help decide if stress relief operations are necessary.

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1. INTRODUCTION

Thanks to the technological advances in machine building, software optimization, and error mapping, the latest abrasive waterjet machines can achieve ±0.025 mm (±0.001”) positioning accuracy. However, to our surprise, on one of these high precision machines, a round disc of 152 mm (6”) in diameter that was cut out of a 6.4 mm (¼”) thick steel plate had a 0.18 mm (0.007”) circularity error. After extensive efforts in troubleshooting the source of this error, residual stresses in the material became the primary suspect. Therefore, a series of experiments were conducted to verify this suspicion.

2. EXPERIMENTS

These experiments used an OMAX 2626 xp machine that was verified to have less than ±0.025 mm (±0.001”) positioning error over its entire working envelope. The following configurations were used: 345 MPa (50 kpsi) pressure, 0.3556 mm (0.014”) orifice, 0.762 mm (0.030”) mixing tube, Barton 80 HPX garnet at 0.34 kg/min (0.75 lb/min) of flow rate, and a 1.5 mm (0.06”) stand-off. Experiments were conducted using six different scenarios described in details below.

Case (1): Material with intentionally created residual stresses

A piece of 3.175 mm (1/8”) thick mild steel was hammered randomly on a portion of its top surface to create residual stresses (see Figure 1).

Figure 1. Steel plate was hammered to create residual stresses.

Then, a 3” round disc was cut with half of the disc on the hammered portion (Figure 2). The jet started and stopped at the spot marked with a “V” (at the 9 o’clock position), and the jet moved clockwise. Measurements of the diameters around the cut disc using a micrometer were recorded on its surface. The smallest diameter is near the 9 o’clock position (just ahead of stop), and the largest diameter is near the 4 o’clock position. The circularity error is 0.096 mm (0.0038”).

Figure 2. Disc cut on the hammered portion of the steel plate.

Case (2): Intensifying Effect of an open contour

Another disc was cut on the same steel plate as in Case (1), but on the portion not having been hit with the hammer. The program unintentionally cut through the edge of the plate (Figure 3a), resulting in an open contour. The circularity error was measured at 0.201 mm (0.0079”) (Figure 3b). This showed that the error associated with residual stresses can be intensified by an open contour.

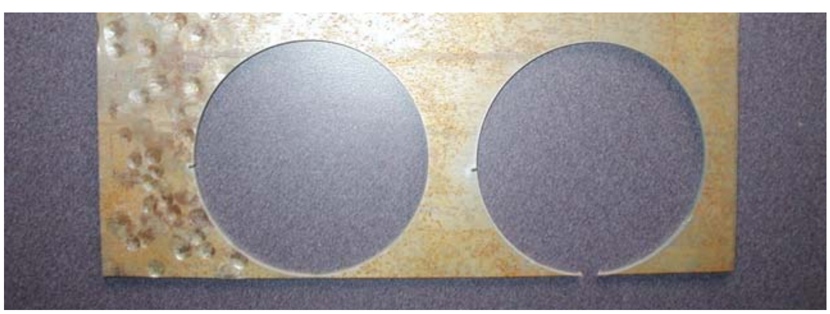

Figure 3a. Disc cut through the edge on the un-hammered portion of the steel plate (to the right).

Figure 3b. Disc cut through the edge on the un-hammered portion of the steel plate.

Case (3): Material with unknown status of residual stresses

Another disc was cut using a piece of the same material without being hammered. The circularity error was 0.015 mm (0.0006”) (Figure 4).

Figure 4. Disc cut on material with unknown status of residual stresses.

Case (4): Material with intentionally created residual stresses was stress-relieved

A material like that used in Case (1) was stress-relieved prior to cutting. The stress relief was done by heating the plate in an oven to 593°C (1100°F) for ½ hour, and then letting it cool in the oven to 427°C (800°F), followed by air cooling to room temperature. The part cut on the stress-relieved material had a circularity error of 0.028 mm (0.0011”), an improvement from 0.096 mm (0.0038”) as shown in Figure 5.

Figure 5. Disc cut on the hammered plate with stress relief.

Case (5): Effect of stress relief on an open contour

A material like that used in Case (2) was stress-relieved and then cut intentionally through the edge. The measured circularity error was 0.018 mm (0.0007”), an improvement from 0.201 mm (0.0079”) as shown in Figure 6.

Case (6): Effect of stress relief on material with unknown status of residual stresses

A material with an unknown residual stress status, like in Case (3), was stress-relieved, and then the round disc was cut. The measured circularity error was 0.010 mm (0.0004”), an improvement from 0.018 mm (0.0007”) as shown in Figure 7.

Figure 6. Disc cut through the edge on material with stress relief.

Figure 7. Disc cut on material with stress relief.

Results of the experiments are summarized in Table 1.

Table 1. The Impacts of Stress Conditions on Circularity Errors for Parts

Circularity Errors	Hammered to Create Residual Stresses		Not Hammered (Unknown Stress Condition) and Closed Contour
	Closed Contour	Open Contour	
Without Stress Relief	0.096 mm (0.0038”) Case (1)	0.201 mm (0.0079”) Case (2)	0.015 mm (0.0006”) Case (3)
With Stress Relief	0.028 mm (0.0011”) Case (4)	0.018 mm (0.0007”) Case (5)	0.010 mm (0.0004”) Case (6)

3. COUNTER MEASURES

3.1 Stress Relief

It is clear that residual stresses, when present, dominate the circularity errors in these cases. Stress relief from the cut portion causes distortion of the uncut material and thus causes the circularity errors. When the disc was cut through the edge (an open contour situation), distortion of the uncut material was magnified, leading to a larger circularity error. Intentional stress relief prior to cutting is effective in removing such errors. Information about stress relief for metals is available in most metallurgy literature.

These cases demonstrate the influence of residual stresses resulting from mechanical deformation, such as the case of cold-worked steels. Residual stress may also come from other sources such as uneven thermal loading or cooling. Processes like forging, casting, and welding may retain a high level of residual stresses. These residual stresses can be removed in an annealing operation. Sometimes, if the annealing operation has no other purpose, a much lower temperature than that required for annealing can be used for stress relief. Residual stresses may be partly removed at room temperature, but it may take a long time like months. By heating the part to a temperature that is below the critical temperature of steel (assuming the material is steel), these residual stresses can be removed in a few minutes.

3.2 Stress Detection

To prevent scrapping a critical part because of residual-stresses-related errors, a test part can be cut that determines if it is necessary to carry out a stress relief operation on the material. A program that works well for test cutting parts (“StressCheck.ord”) is illustrated in Figure 8. A split ring cut on the subject material will reveal material distortion caused by residual stresses. A single-pass slot cut near the split is useful for kerf comparison. Either or both of these two phenomena will indicate the existence of residual stresses: (1) the kerf width at the split is different from that at the slot; (2) the two ends of the split ring are no longer positioned on the same plane.

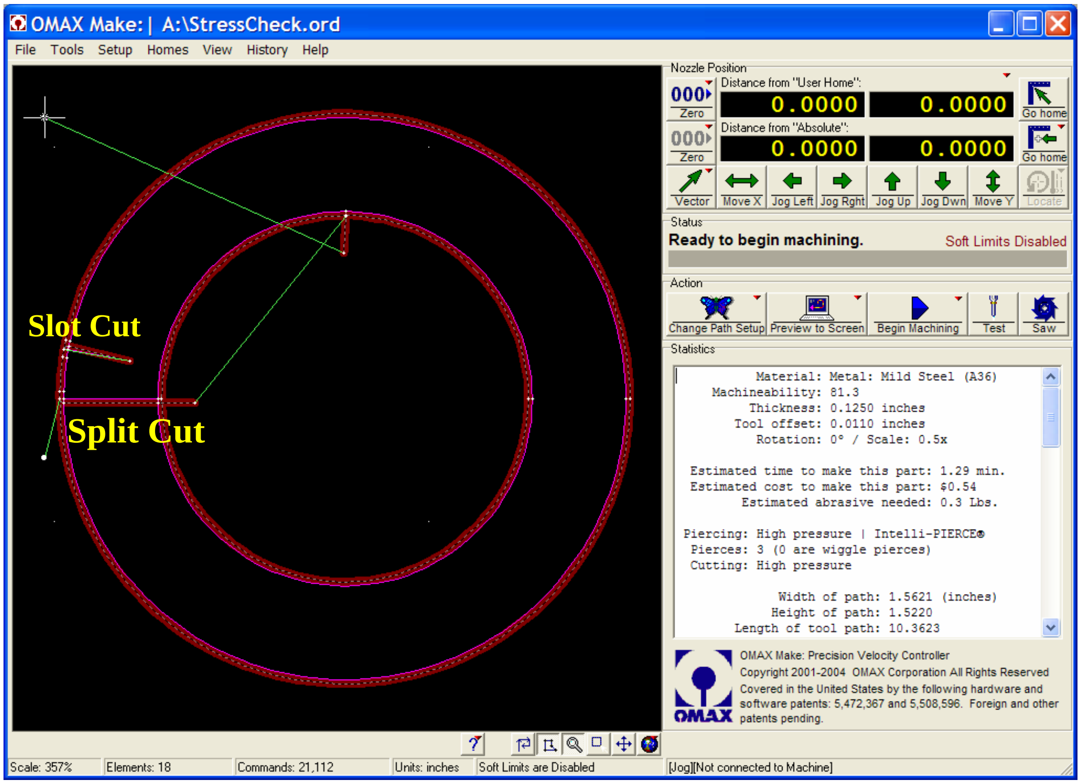

Figure 8. Split ring test part to detect residual stresses.

To prove that this is an effective method of detecting residual stresses, two split rings were cut on materials with and without residual stresses. One was cut on the same material as in Case (6) (with stress relief). The kerf width on the split exactly matches that on the slot and the two ends of the split are evenly on the same plane (no warping) (Figure 9).

The other split ring was cut on the same material used in Case (1) (hammered to create residual stresses and without stress relief). The kerf width at the split is 0.508 mm (0.020") vs. 0.635 mm (0.025") at the slot. In addition, the two ends of the split have a height mismatching error of 1.32 mm (0.052") (Figure 10). This indicates that the material has residual stresses and should be stress-relieved prior to cutting.

Figure 9. Split ring cut on stress relieved material.

Figure 10. Split ring cut on material having residual stresses.

4. CONCLUSIONS

1) Residual stresses play a very significant role in the part accuracy of abrasive waterjet cutting.
2) Parts with an open contour are affected more by residual stresses.
3) Stress relief techniques can effectively remove errors caused by residual stresses.
4) A split ring test part can be used to effectively detect residual stresses and help decide whether a stress relief operation is necessary.

5. ACKNOWLEDGMENTS

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