Journal of
INDUSTRIAL
TECHNOLOGY

Volume 25, Number 4 - October 2009 through December 2009

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Peer-Refereed
Applied Papers

KEYWORD SEARCH

Manufacturing
Materials & Processes
Materials Testing

Mapping of Superficial Residual Stresses in Machined Components

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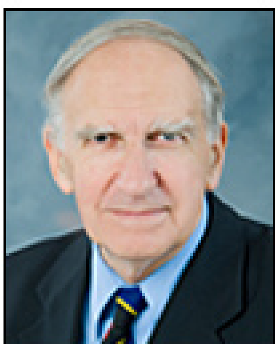

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Abstract

The paper describes how the superficial residual elastic strains present after machining AA 6061-T6511 bar stock using a 63.5 mm (2½") diameter face mill at various cutting speeds were measured using a recently developed low cost technique intended for workshop use. The technique enables the distribution of such strains to be mapped over a wide area by following the change in spacing of a previously generated grid of hardness indents, which have been placed on the components, then examined after stress relieving. The indents were generated using an indenter attached to the spindle of the machining center upon which the samples were machined. A microscope also mounted on the spindle, to which a video camera was attached, facilitated this measurement. Finite Element Analysis (FEA) was not employed in this series of experiments as this is a preliminary investigation.

The results reveal a consistent pattern of residual strains which vary between tensile and compressive forces as the cutter rotates.

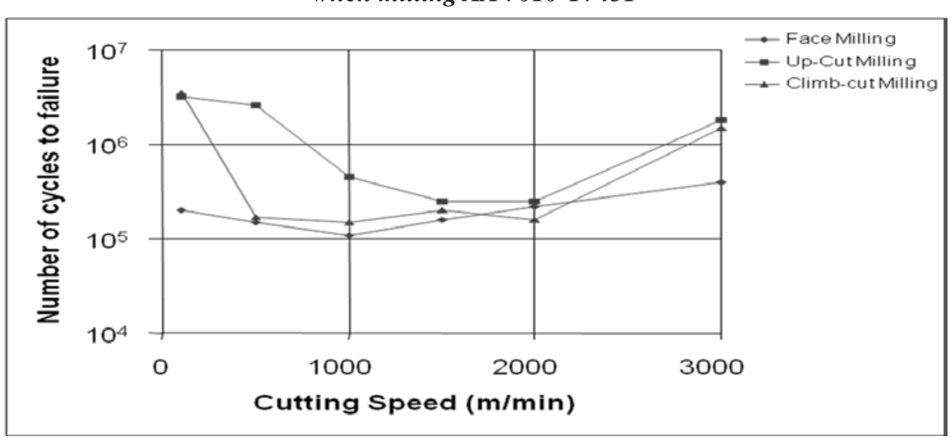
Introduction & Background

The measurement of residual stress patterns associated with machining, in particular milling, is well documented (Field & Kales 1964, Arndt 1971, Liu, Lin & Barash 1984, El-Khabeery & Fattouh 1985, Fu & Wu 1995, Jacobus, DeVor & Kapoor 1999 & 2001). The effects of such machining induced stress patterns on fatigue life have also been noted (Matsumoto et al. 1991, Jordan 2007) for both ferrous and non-ferrous alloys.

However, the motivation for the present study sprang from two reports pertaining to the surface integrity of both aluminum-based alloys and steel as affected by high speed machining (HSM). The first report was concerned with work at Svenska Aeroplan Aktiebologat (SAAB) Aerospace company in Sweden, and involved the effects of cutting speeds up to 3000 m/min (9843 sfm) on the fatigue life of pocket-milled structural panels of AA 7010-T7451 (Ansell 1999) as shown in figure 1.

The second report also focused on HSM. In this case both an aluminum

Figure 1. SAAB Aerospace work showing the effect of cutting speed on fatigue life when milling AA 7010-T7451



alloy and a low alloy steel were machined (Siems, Dollmeier & Warnecke 2000). The authors observed what they claimed was superficial melting at the surfaces of both AA 7075-T6 and AISI 1045 at cutting speeds up to 8000 m/min (26248 sfm), obtained using specialized equipment.

The present authors attempted to repeat the experiments of the Swedish investigators using similar cutting conditions surface speeds up to 2000 m/min (6562 sfm) but using AA 6061-T6511, rather than the AA 7010-T7451 alloy. Figures 2 & 3 compare the measurements made of superficial residual stress upon samples machined at various cutting speeds with the results of fatigue life testing of the Swedish group (Ansell 1999). The data shown in figure 2 is from experimental work undertaken by the authors. The reason for using AA 6061-T6511 is that it is readily available. Figure 3 shows the results from the SAAB face milling experiment. They employed the aerospace alloy AA 7010-T7451. These are two distinctly different alloys as can be seen in Table 1. These materials were employed so as to make a broad comparison of the face milling operation. The comparison appears to indicate that materials with the highest tensile strength have the shortest fatigue life. This is corroborated by the remarks made in a summary of the SAAB work (Ansell 1999) which states that their results were explained by measurements of residual stress and other metallurgical procedures (Blom & Palmberg 2001). In work conducted at Mississippi State University (MSU) on the residual stress measurements were made by a new low cost technique which will next be described.

Details of Measurement Technique and its Application

As detailed earlier, the existence of unfavorable residual stress patterns in engineered components has long been associated with fatigue life. Those stress patterns may be affected by all of the stages in processing a particular component.

Aerospace industry units and their suppliers are especially aware of the

Figure 2. Superficial residual stress measured on AA 6061-T6511for face milling.

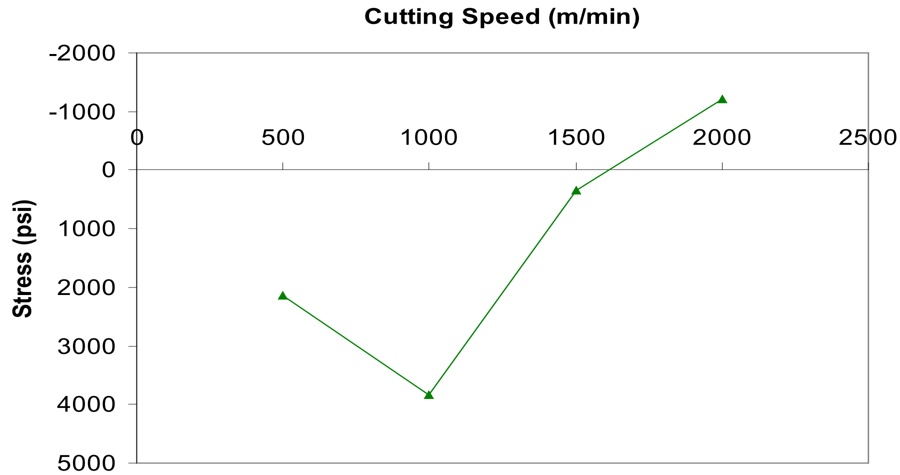


Figure 3. Fatigue life curves for AA 7010-T7451 undertaken by SAAB when face milling.

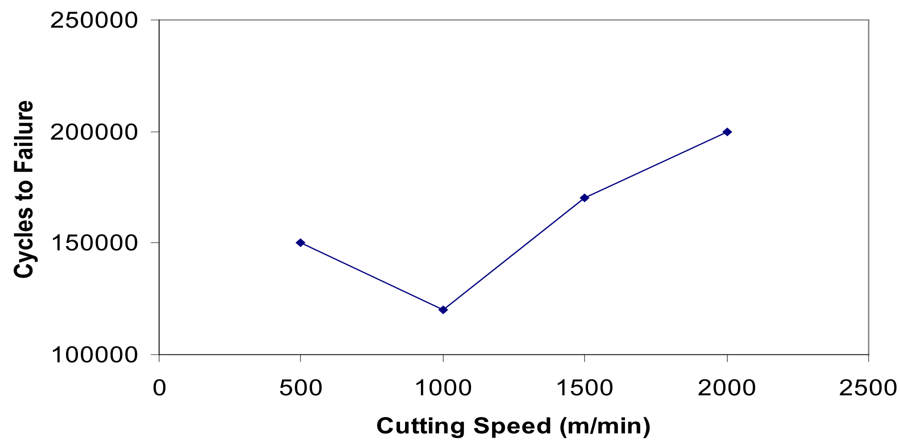


Figure 4. Deflections measured from the release of residual stresses in aluminum alloy 6061-T6511. Points 1, 2, and 3 are the measured deflections of the released slab at a distance of 3" (75mm) from the constrained end. Points 4, 5, and 6 are the measured deflections of the released slab at a distance of 10" (250mm) from the constrained end.

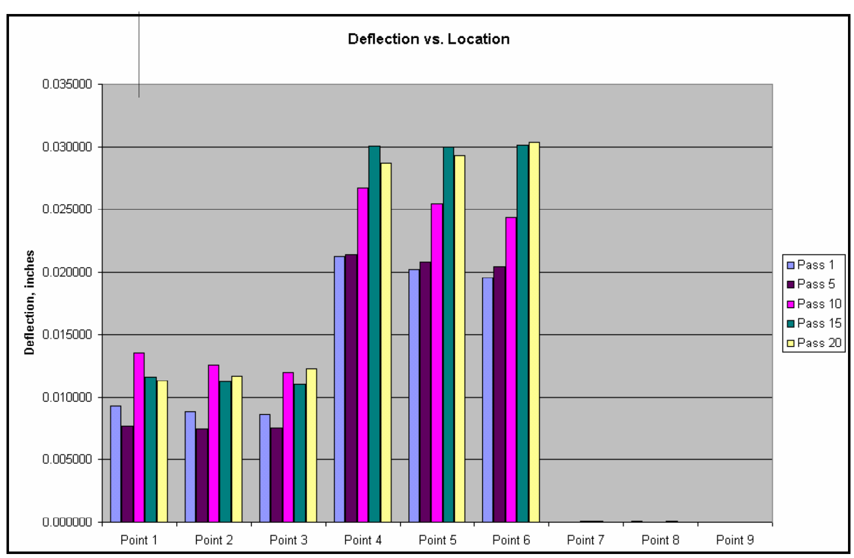


Table 1. A comparison of the mechanical properties and chemical content of AA 6061-T651 and AA 7010-T7451 alloys (Matweb 2009)

Mechanical and Physical Properties of AA 6061-T651 & AA 7010–T7451						
	Density (lb/in^3)	UTS (ksi)	Tensile Yield Strength (ksi)	Elongation (%)	Modulus of Elasticity (ksi)	Shear Strength (psi)
AA 6061-T651	0.0975	42.0	37.0	12	10000	27000
AA 7010-T7451	0.102	76.0	68.0	11	10400	44000

Chemical Composition (by %) of AA 6061-T651 & AA 7010-T7451						
	Al	Cr	Cu	Fe	Mg	Mn
AA 6061-T651	95.8-98.6	0.04-0.35	0.15-0.4	<=0.7	0.8-1.2	<=0.15
AA 7010-T7451	87.3-90.3	<=0.04	2.0-2.6	<=0.15	1.9-2.6	<=0.1

Chemical Composition (by %) of AA 6061-T651 & AA 7010-T7451						
	Other Each	Other Total	Si	Ti	Zn	Zr
AA 6061-T651	<=0.05	<=0.15	0.4-0.8	<=0.15	<=0.25	-
AA 7010-T7451	<=0.05	<=0.15	<=0.12	<=0.06	5.7-6.7	0.08-0.15

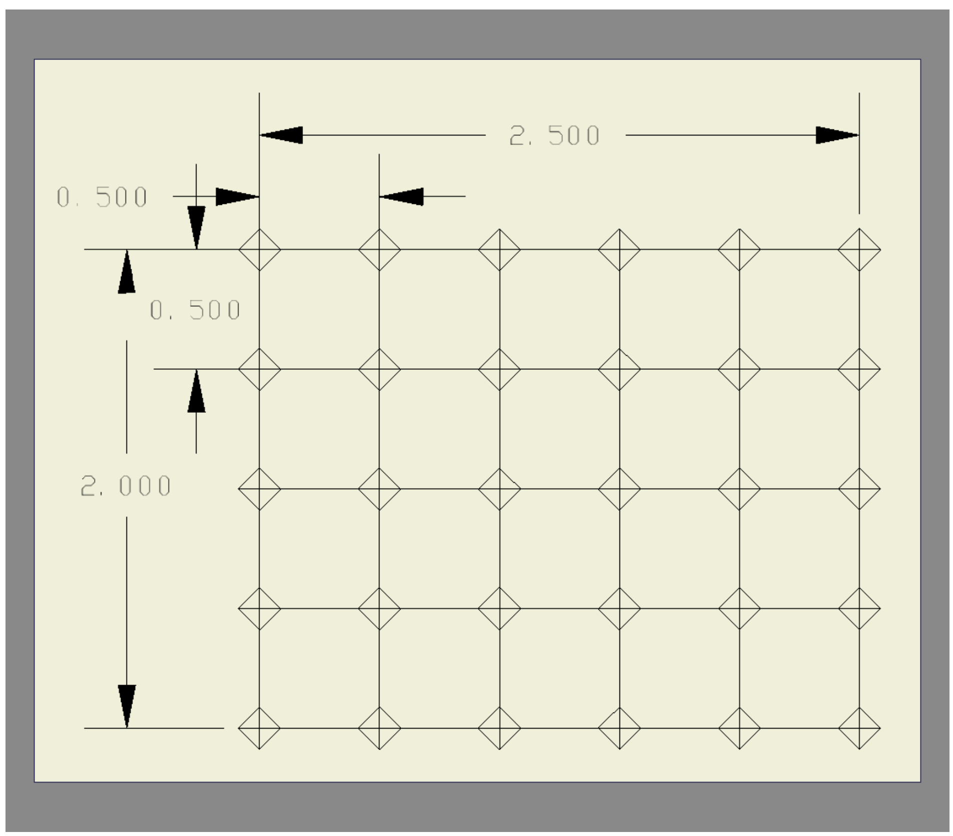
problems affecting very large components where the relief of stresses contained in the as-received billet can lead to serious distortion problems (Heymes et al. 1997). The present authors and their colleagues were able to confirm this in experiments involving the end milling of 37mm (1½”) thick, long slabs of AA 6061-T6511. Figure 4 illustrates the amount of distortion measured after milling the slab and releasing one end of the slab was compared with that of a small standard reference block which remained constrained (Wyatt et al. 2003).

Subsequent experiments, also involving AA6061-T651, were conducted to examine these residual stress patterns in more detail.

The technique described briefly below was used to measure these stresses. The technique is described in more detail by Berry & Wyatt (2005).

(i) stress relieve samples prior to machining.
(ii) mark the machined sample with a network of small indents (ex.

Figure 5. An illustration of the grid pattern employed in the described experiments



microhardness indents) as shown in figure 5.
(iii) measure the spacing between the indents.
(iv) conduct a thermal stress relief (alternatively vibratory stress relief could be employed)
(v) measure the change in the spacing of the network pairs in orthogonal directions.
(vi) compute ε_{xx} and ε_{yy}, the residual strains.
(vii) hence from appropriate values of Young's Modulus and Poisson's Ratio, the superficial residual stresses σ_{xx} and σ_{yy} can be estimated.

The technique has something in common with that used to determine strain distributions in sheet forming where a pattern of circles is printed onto the blank prior to forming. After forming the resulting major and minor strains can be determined by reference to the changes in the circle pattern.

In the present technique mapping is undertaken through the measurement of the changes in the spacing of the indents which may be negative or positive depending on the sense of the residual stress (tension or compression). Figure 5 shows a grid pattern prior to stress relief.

Both the generation of the grid patterns and the measurement of the indent pair spacing before and after stress relief are undertaken on a state-of-the-art CNC machining center, where a micro-hardness indenter and an optical microscope (reflected-light type) fitted with a small video camera are attached to the machine spindle.

The initial grid was made post machining and then measured on the CNC machine to give the distances between each indent. This mapping technique works in reverse as this is the residual stress state after machining. Next the component was stress relieved and the spacing between the indents was measured again. This stress relieved state is what will become the original state of stress or L_o. The difference between the two sets of indent spacing's is ΔL.

Figure 6. The micro-hardness indenter mounted in the CNC machine tool spindle.

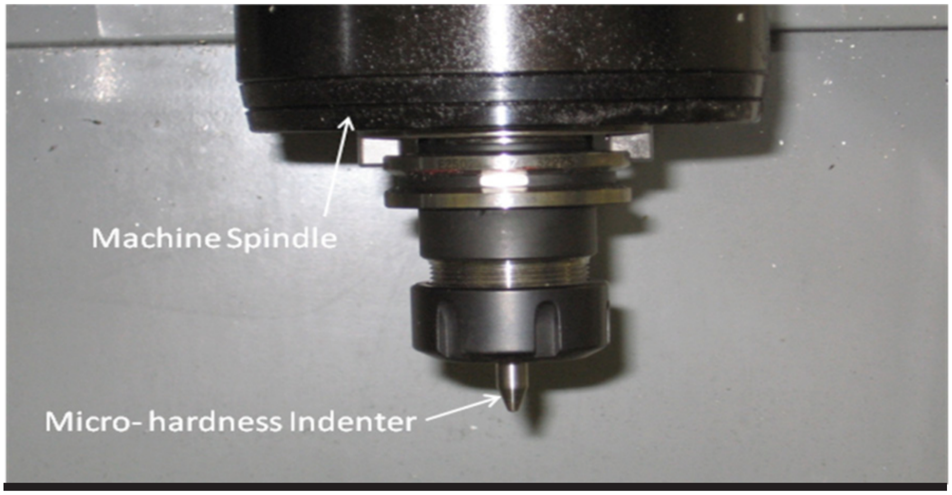


Figure 7. The optical microscope mounted in the CNC machine tool spindle

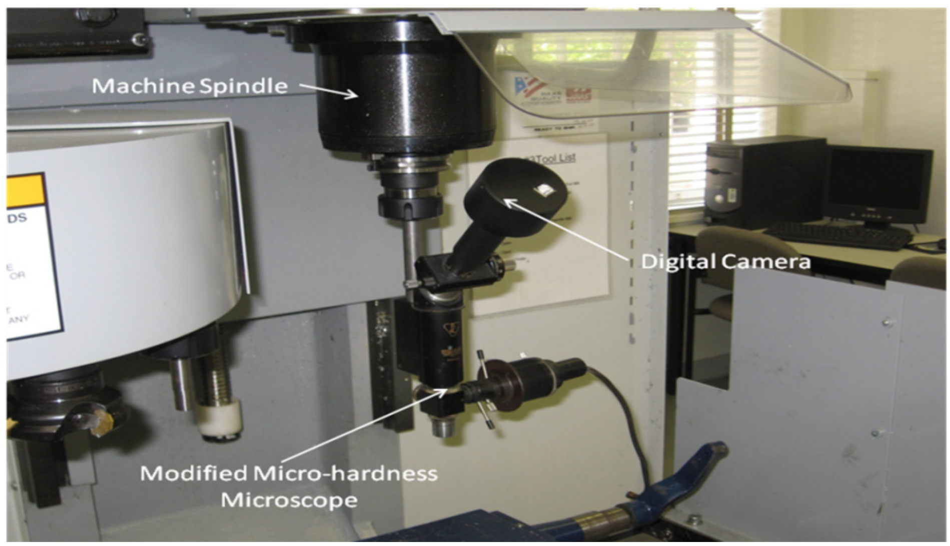
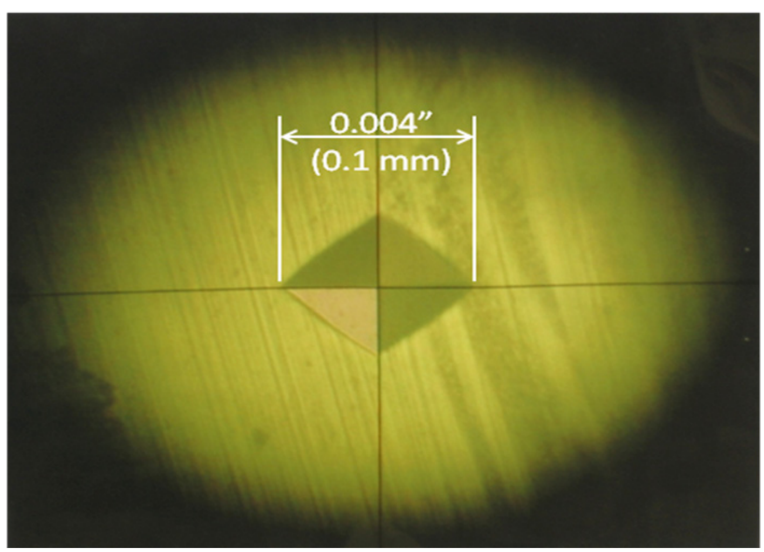


Figure 8. An image of a micro-hardness indent taken by the optical microscope mounted on the CNC machine tool.



From this the residual strain between each indent pair can be described as:

$$\varepsilon = \Delta L/L_o$$

From the results of the residual strains between the micro-hardness indents, areas of interest on the component can then be investigated with higher resolution techniques, such as x-ray diffraction. This new technique is a convenient method when undertaking residual stress analysis to confirm FEA. Also it can be employed by small shops to look at residual stresses in components before committing to more expensive x-ray diffraction techniques for final analysis.

This makes for a relatively simple determination of the stress level present in the component at the time of manufacture. This method can be applied to any component that can have the indents placed upon it, and can be stress relieved. This means that is suitable for fabrications and weldments as well as machined, cast and forged components. Future work will also be undertaken in these areas.

The positioning resolution of the CNC machining center referred to above is 0.0025mm (0.0001") which is sufficiently sensitive to accomplish the objective in hand. Figures 6 and 7 show respectively the indenter and the optical microscope mounted on the machine spindle, while figure 8 shows the optical image of an indent.

The method described has been applied to measurement of as-cast superficial residual stresses present in sand castings (Wyatt, Berry & Williams 2007) as well as to those of machined surfaces.

Figure 9. Lateral (cutting) strains for AA 6061-T6511 when face milled at 762 m/min (2500 sfm).

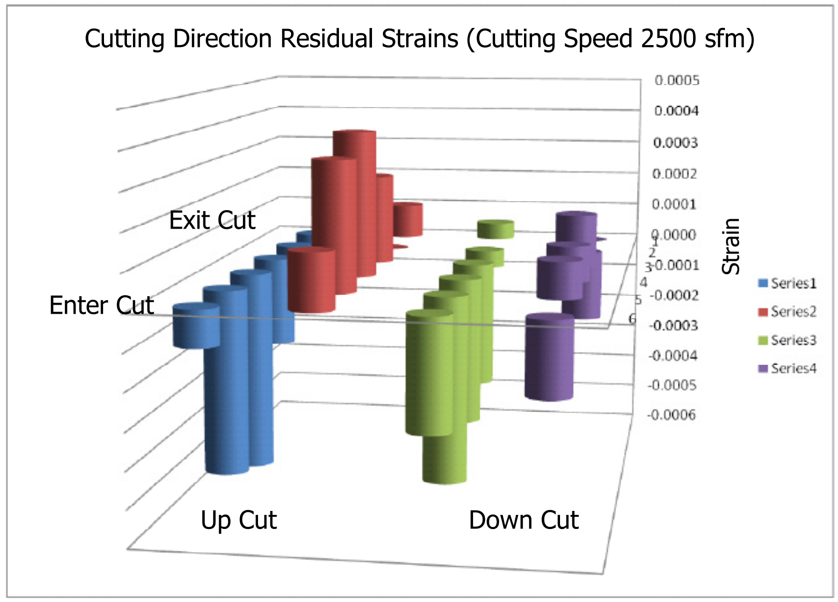
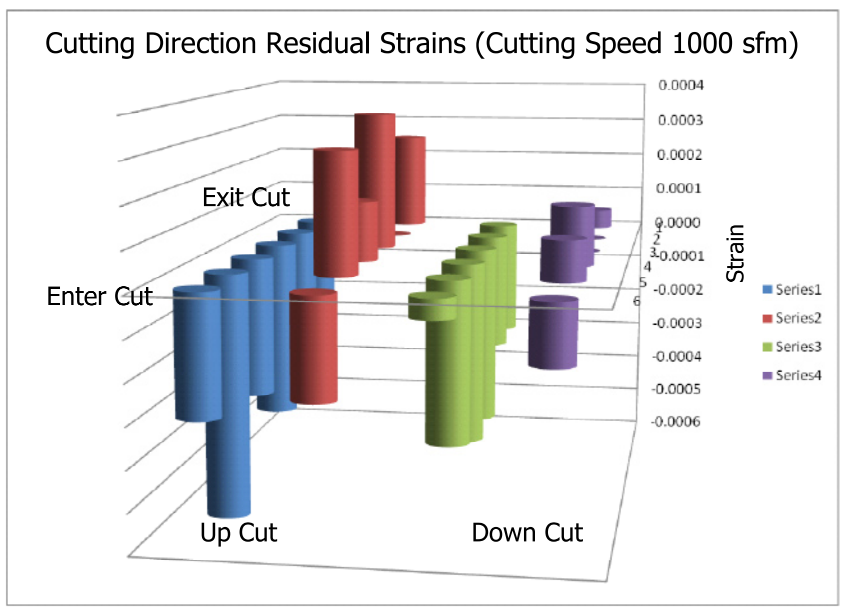


Figure 10. Lateral (cutting) strains for AA 6061-T6511 when face milled at 305 m/min (1000 sfm).



Results and Discussion

The results which describe a series of experiments on 3"x 3" x ½" (75mm x 75mm x 13mm) samples of AA 6061-T6511 which were face milled at a variety of cutting speeds are shown in figures 9 through 11. The results are displayed in the form of lateral and longitudinal strains. The longitudinal direction is that of the feed of the milling spindle.

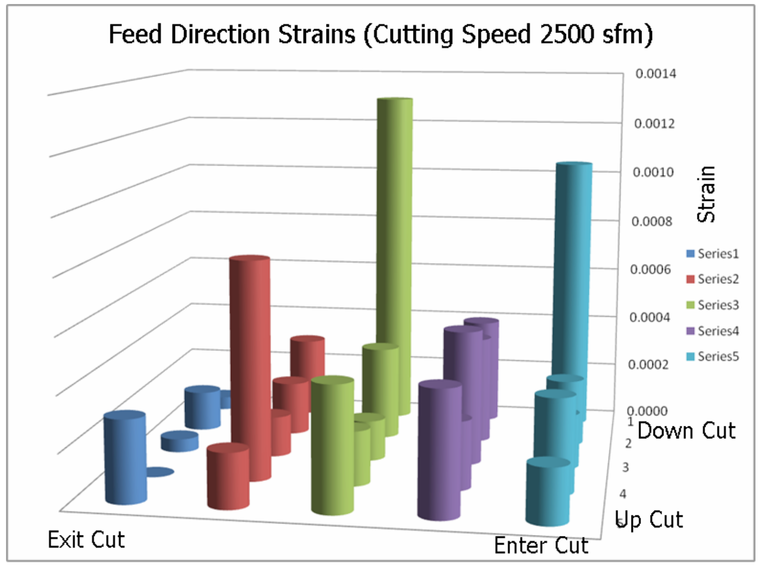
The cuts concerned were made with a 63.5mm (2.5") diameter face mill containing four carbide inserts. The depth of cut was 1.78mm (0.070"). The first two figures (9 and 10) show the cutting direction residual strain (i.e. lateral strains) for 762 m/min (2500 sfm) and 305 m/min (1000 sfm) respectively.
It is noteworthy that the two patterns (at both the minimum and maximum speeds) are almost identical in general shape.

The alternation between compression and tension in the residual strain pattern are associated with the rotational action of the face mill where a 'pushing' and a 'pulling' action as the cutter rotates can be anticipated.

It should also be noted that the often accepted picture that 'up-cutting' produces tensile residual strains and that 'climb milling' produces compressive residual strains is not seen here. This can be explained on the basis of the fact that the process of face milling is a hybrid of conventional and climb milling. The major effects that are observed in the face milling operation are those of the linear feed of the cutter and the chip thickness. Therefore, the cyclic nature of this phenomenon may be interpreted in terms of the change in uncut chip thickness which is dependent on the feedrate and the rotational motion of the cutter.

In the feed or longitudinal direction, all the strains observed were tensile in nature. It may be hypothesized that this tensile strain is caused by the linear feed of the cutter pushing the undeformed chip ahead of the cutter insert (Figure 11).

Figure 11. Longitudinal (feed) strains for AA 6061-T6511 when face milled at 762 m/min (2500 sfm).

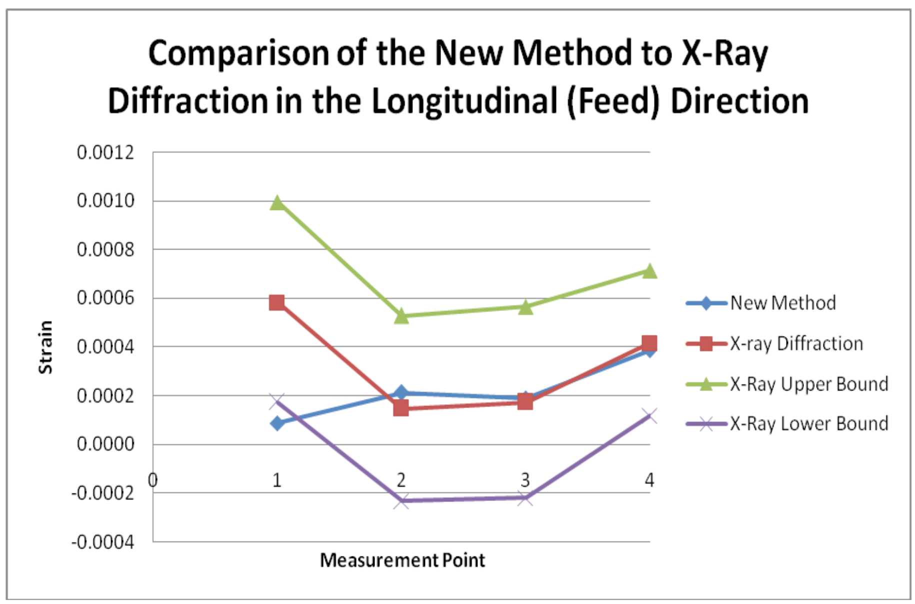


Comparison to X-ray Diffraction

The residual strains in the longitudinal (feed) direction were measured, between the markers of the grid (figure 5) by an independent laboratory using x-ray diffraction. The material was also stress relieved prior to machining and then sent to an independent laboratory. This data was supplied in the form of residual stresses. These values were then converted back to residual strains using information supplied by that laboratory.

The figure below (figure 12) shows how the average and the upper and lower uncertainty bounds of the x-ray measurements correspond to those determined by the new method. (Note: the upper and lower bounds as supplied, arise because of grain size and orientation effects). The x-ray diffraction based results essentially bracket those determined by the new method. It should also be noted that from the independent lab results, and figure 12, the tolerances of the measured strains were so high that the measured strain could either be tensile or compressive regardless of the figure given. This could be due to grain size effects which can disrupt the effectiveness of x-ray diffraction (Kandil, Lord et al. 2001).

Figure 12. Comparison of x-ray diffraction derived residual strains and those determined by the new method.



Conclusions and Recommendations

1. A simplistic low cost method of mapping superficial residual strains and stresses in machined components has revealed an interesting pattern in milled components.
2. The patterns revealed provide a detailed picture of the complex nature of the superficial residual stress distribution in milled components.
3. These observations may well account for the unusual behavior relating cutting speed to fatigue life previously reported.
4. It is recommended that further exploration of the observed effects over a wider range of cutting speeds be undertaken.

5. Together with suitable surface characterization and superficial temperature mapping, this may well provide a more basic understanding of the effects of machining on surface integrity.
6. This method has also been proven to be on a par with x-ray diffraction. However, it is best used as a precursor to the more expensive x-ray diffraction technique. It should be employed to identify which areas will require measurement via x-rays. This will save both time and money in expensive residual stress mapping of components using just x-ray diffraction.
7. The next stage will to be undertake FEA to predict residual stresses. These results would then be compared with those using the new method and by x-ray diffraction.

Acknowledgements

The authors would like to acknowledge the participation in this research of Mr. Andrew Westfall and Mr. August Johnson for their help in the execution of these experiments.

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