Investigation of strain hardening effects in CNC milling and chemical etching of Al 7075: A comparative study

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ABSTRACT: *Data representation on the components can be done by engraving on the metal. This operation on the test specimen was done by two ways. CNC milling and chemical etching were done on aluminium 7075 to represent data on the test sample. Cuboid shaped aluminium 7075 was chosen as a test sample. The procedures for these 2 operations are explained. Then the merits, demerits and limitations for each of the chosen method were discussed. Strain hardening effects were detected by Vickers hardness profiling in the CNC milled and chemically etched samples. Thus data representation on aluminium 7075 components in the automobile and aerospace industries can be done by one of the suitable methods.*

Keywords: *Aluminium 7075, Chemical etching, CNC Milling, Engraving of metals, NaOH as etchant.*

I. INTRODUCTION

1.1 A survey of CNC Milling

J. Sun, Y.B. Guo made a comprehensive experimental study on surface integrity by end milling Ti–6Al–4V [1]. J. Xie et al carried out dry micro-grooving on Si wafer using a coarse diamond grinding [2]. Justin S. Mecomber et al executed enhanced machining of micron-scale features in microchip molding masters by CNC milling [3]. Toshiyuki Obikawa et al performed high-speed grooving with applying MQL [4]. Mariana Dotcheva et al. explained about the application of tolerance analysis to the theoretical and experimental evaluation of a CNC corner-milling operation [5]. Min-Yang Yang et al performed hybrid adaptive control based on the characteristics of CNC end milling [6]. Aleksandra Bierla et al. performed mechanical and physico-chemical study of sulfur additives effect in milling of high strength steel [7]. Soichi Ibaraki published a paper on the removal of critical cutting regions by trochoidal grooving [8]. Yih-Fang Chang performed parametric curve machining of a CNC milling EDM [9]. Ali Lasemi et al. presented a recent development in CNC machining of freeform surfaces [10]. Lihui Wang et al. did a remote real-time CNC machining for web-based manufacturing [11]. Zezhong C. Chen et al. made an automated surface subdivision and tool path generation for 3 ½ ½ axis CNC machining of sculptured parts [12]. Therefore it is found that engraving data on the metals by using CNC machine is possible.

1.2 A survey of Chemical etching

Fadaei Tehrani et al. found a new etchant for the chemical machining of St304 [13]. T.K.K.R. Mediliyegedara et al. made a preliminary study on an intelligent pulse classification system for electro-chemical discharge machining [14]. S. Ho, T. Nakahara et al. did chemical machining of nano crystalline Ni [15]. J.P. Choi et al. performed chemical-assisted ultrasonic machining of glass [16]. K.L. Bhondwe presented finite element prediction of material removal rate due to electro-chemical spark machining [17]. Ching-Chuan Mai, Jehnming Lin performed supersonic flow characteristics in laser grooving [18]. F. Klocke et al. performed technological and economical comparison of roughing strategies via milling, EDM and ECM for Titanium- and Nickel-based Blisks [19]. Sanjay K. Chak, P. Venkateswara Rao performed trepanning of Al_2O_3 by electro-chemical discharge machining (ECDM) process using abrasive electrode with pulsed DC supply [20]. Hereby it is found that etching can be done in order to create pattern on the metal by using chemicals.

1.3 Our main focus

In order to perform CNC milling operations on the test specimen, perfect jig and fixtures are needed. More than that, electrical energy is needed to run the CNC machine. In a CNC, additional electrical equipment like motor, driller and tools are needed. It requires skilled labor to carry out the milling operation to form patterns.

But in the case of chemical etching we need no electric power, and other electrical equipment. Only chemicals are used to carry out the milling operation. Therefore it requires only chemical agents to carry out the etching process.

Finally the hardness values with respect to depth from the milled and etched surfaces are plotted. Standard deviation and variance were calculated for the values obtained.

II. PREPARATION OF TEST SAMPLE

2.1 CNC Milling

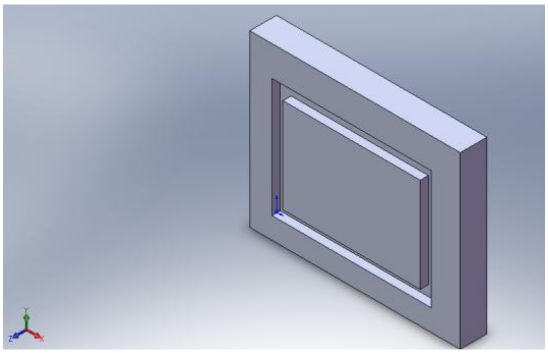

Fig 1 Isometric view of the test specimen that is to be used for CNC machining

The test specimen which is cuboidal in shape is 102x82x13mm in dimension. The shape to be milled is as shown in the Fig 1. It was created using SOLIDWORKS^{TM} modeling software. The G code for the milling process was generated using EDGECAM^{TM} software. Many patterns were created using the 3 axis CNC milling machine. One of them is chosen for the study of hardness variation.

2.2 Chemical etching

The test specimen which has to be chemically milled was modeled using SOLIDWORKS^{TM} with the alphabet "T" was written on it.

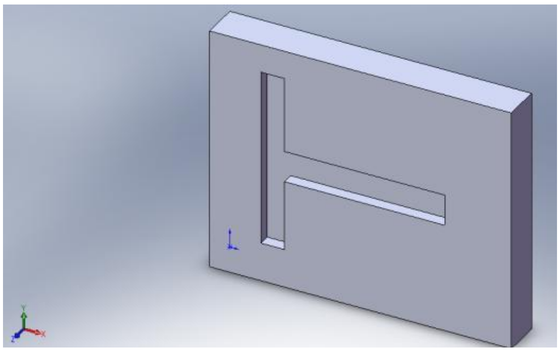

Fig 2 Trimetric view of the test specimen that is to be used for chemical machining

III. EXPERIMENTATION OF THE MILLING PROCESS

3.1 CNC Milling

A 3 axis CNC milling machine as shown in Fig 3 was used. The G codes were fed. The aluminium 7075 workpiece was fed to the jig and fixtures of the machine in order to hold the test sample firmly. The different patterns were obtained after machining.

Fig 3 The CNC Milling machine

3.2 Concept

The test specimen was fixed to the CNC milling machine using the jig and fixtures. Then the tool traversed on the global XY plane. It also has a driller type of projection and hence it has 3 degrees of freedom (3DOF).

3.3 Results of CNC milling

The 3DOF CNC milling was done on different Aluminium 7075 pieces. Drawing curves, straight lines, arcs were possible. It is as shown in Fig 4.

Fig 4 Various lines and curves done using the 3 DOF CNC milling

IV. COMPOSITION OF Al 7075 ALLOY

The chemical composition of the aluminium 7075 is as shown in the Table 1.

Table 1: Composition of Al 7075 alloy

Element (%)	Alloy 7075
Zn	5.10 - 6.10
Mg	2.10 - 2.90
Cu	1.20 - 2.00
Cr	0.18 - 0.28
Fe	0.50 (Max.)
Si	0.40 (Max.)
Mn	0.30 (Max.)
Ti	0.20 (Max.)
Others	0.05 (Max.) each 0.15 (Max.) total
Remainder	Aluminium

V. CHEMICAL ETCHING

5.1 Concept

The workpiece was covered with a maskant. Then the area exposed to the atmosphere was fully covered with NaOH pellets. The pellets were changed once in every 120 minutes and the sequence was repeated 5 times. The schematic of the chemical etching is as shown in the Fig 5.

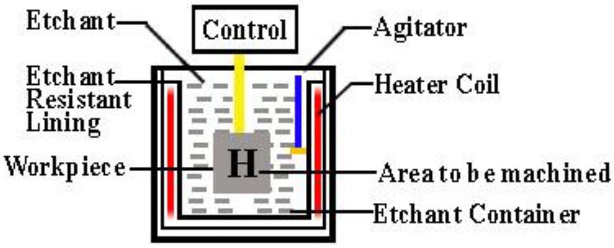

Fig 5 Schematic of chemical etching/machining [21]

5.2 Preparation of the test specimen

The test specimen was exposed to the atmosphere and the maskant was applied to it. The cross sectional view of the masked test specimen is as shown Fig 6.

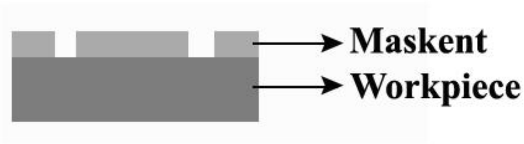

Fig 6 The workpiece and the maskant

5.3 Preparation of the maskant

A paper was taken and the alphabet "T" was drawn on it as shown in Fig 7. Then the shape was cut out as shown in Fig 7. Then the shape was placed on the test specimen.

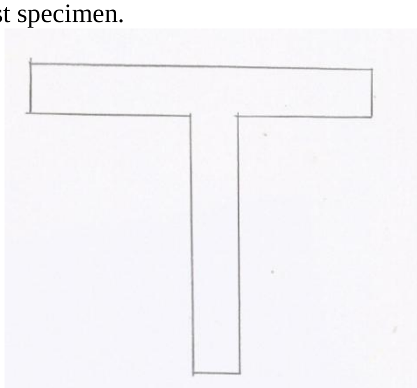

Fig 7 The alphabet "T" to be chemically etched

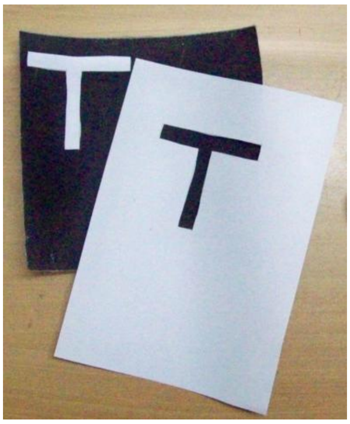

Fig 8 The "T" shape cut out as a maskant for the chemical etching

5.4 Testing the Aluminium 7075 with chemicals

The test specimen was exposed to HNO_3 and NaOH for 30 minutes. We found that NaOH was able to etch the Aluminium 7075 metal. Hence NaOH was chosen as the etchant. It is as shown in Fig 9.

Fig 9 Red box denotes the area where reaction of NaOH on the Al metal has happened

5.5 Masking the Aluminium 7075 metal

A white paper was held close to the Aluminium 7075 metal. The molten wax was poured on to the region except the region that had a "T" shaped paper. Then the "T" shaped paper was removed. Then the region was as shown in Fig 10.

Fig 10 Wax applied as a maskant on the Al test specimen

5.6 Result of chemical etching

The region exposed to the atmosphere was filled with NaOH pellets. The NaOH was exposed to the masked Aluminium 7075 for about 600 minutes. The "T" shape was formed on the test sample. It is as shown in the Fig 11. The chemical reaction is as follows.

$2\,Al + 2\,NaOH + 2\,H_2O \rightarrow 2\,NaAlO_2 + 3\,H_2$

Fig 11 The chemically etched test specimen (the formation of the T structure)

VI. INTRODUCTION TO DEFORMATION AND ITS DEPENDENCE ON GRAINS OF A MATERIAL

Hardness of a material is a measure of its resistance to deformation. Deformation occurs by the movement of dislocation lines through the crystal lattice of materials. So, a material having higher hardness resists the movement of dislocations in its crystal. Single crystal (or single grain) materials that are homogeneous in nature with a uniform arrangement of atoms throughout the body of the material offer the least resistance to dislocation movement. The unit cell arrangement of the material is followed throughout the material allowing for easy displacement of atoms from their original lattice sites. However, materials we use in everyday life are not all single crystals. They are made up of a huge number of tiny single crystals called grains inside which a uniform orientation of the unit cells is followed, but the material as a whole does not have a common orientation. These materials are called polycrystalline materials, since they are composed of many single crystalline grains. The common area of contact between two adjacent grains is called the grain boundary. At any grain boundary, there is a mis-match in the orientation of the crystal between the two grains that form the grain boundary. As a result, a dislocation line trying to move from one grain to another has to make some extra effort to move into the next grain. If both the grains have the same orientation, they would be just one grain by theory. The bigger the difference in orientation between two adjacent grains, the harder it is for a dislocation line to move from one to the other. This concept of grain boundaries impeding dislocation movement is used to make materials stronger. It is called grain boundary strengthening or Hall-Petch strengthening. Since dislocation movement is impeded by the presence of a grain boundary, increasing the total grain boundary area would make deformation more difficult. So, the average grain size is minimized, thus increasing the net grain boundary area.

This concept is quantified by the Hall-Petch relationship which relates the yield strength of a material to its average grain diameter.

$$\sigma_y = \sigma_0 + \frac{k}{d^{0.5}}$$

where

σ_y is the yield stress

σ_o is a materials constant for the starting stress for dislocation movement (or the resistance of the lattice to dislocation motion)

k is the strengthening coefficient (a constant unique to each material)

d is the average grain diameter.

Mechanical strength of a material is also increased by strain hardening. Mechanical processes like machining, forging, rolling, etc. have been studied and are proven to increase the residual strain in the material. This also contributes to higher hardness values, but it also increases the brittleness along with it. The increase in hardness is attributed to the deformation of grains, breaking them down to smaller grains, thus increasing the net grain boundary area.

VII. VICKERS HARDNESS

The effects of mechanical strain hardening by CNC milling has been investigated by measuring hardness values in the direction perpendicular to the milling direction. An attempt has been made to generate a hardness value profile with respect to depth as a result of the milling. Vickers hardness measurement was done using a VM-50 model Vickers hardness tester manufactured by Fuel Instruments and Engineers Pvt. Ltd.

The metal samples whose hardness profile was to be measured was cut and the surface at which the polishing is to be done was subject to emery paper polishing ranging from size 320 (coarsest) to 1500 (finest)(changing the direction of polishing by 90 degrees for consecutive papers). After this, the sample surface was polished on a cloth using Magnesium Oxide powder of particle size ~ 1 micron, to obtain a scratch free surface for hardness measurement.

The hardness values were measured with a load of 1kgf(kilogram force) along a slanted line approximately 30° to the direction of milling in order to avoid strain hardening effects of nearby prior indentations. It was taken care that the points where readings were taken always fell within the region below the CNC milled region so that the hardness value vs depth could be plotted.

Fig 12 (Left) The cross section area where indentation was made to measure the hardness. (Right) Vickers Hardness tester

To get the reading at the surface of the milled region (i.e. at height=0), the top plane was subjected to a less intense polishing in order to leave the strain hardened region unaffected, and the hardness measured.

The Vickers Hardness is calculated as $HV = \frac{1.854\ xF}{D^2}$

Where

F is the load applied in kgf

D is the average length of the diagonals of the square indentation

VIII. RESULTS AND DISCUSSION

Three sets of data were collected for both the chemical etching and mechanically milled samples.

8.1 Hardness in Chemically etched samples

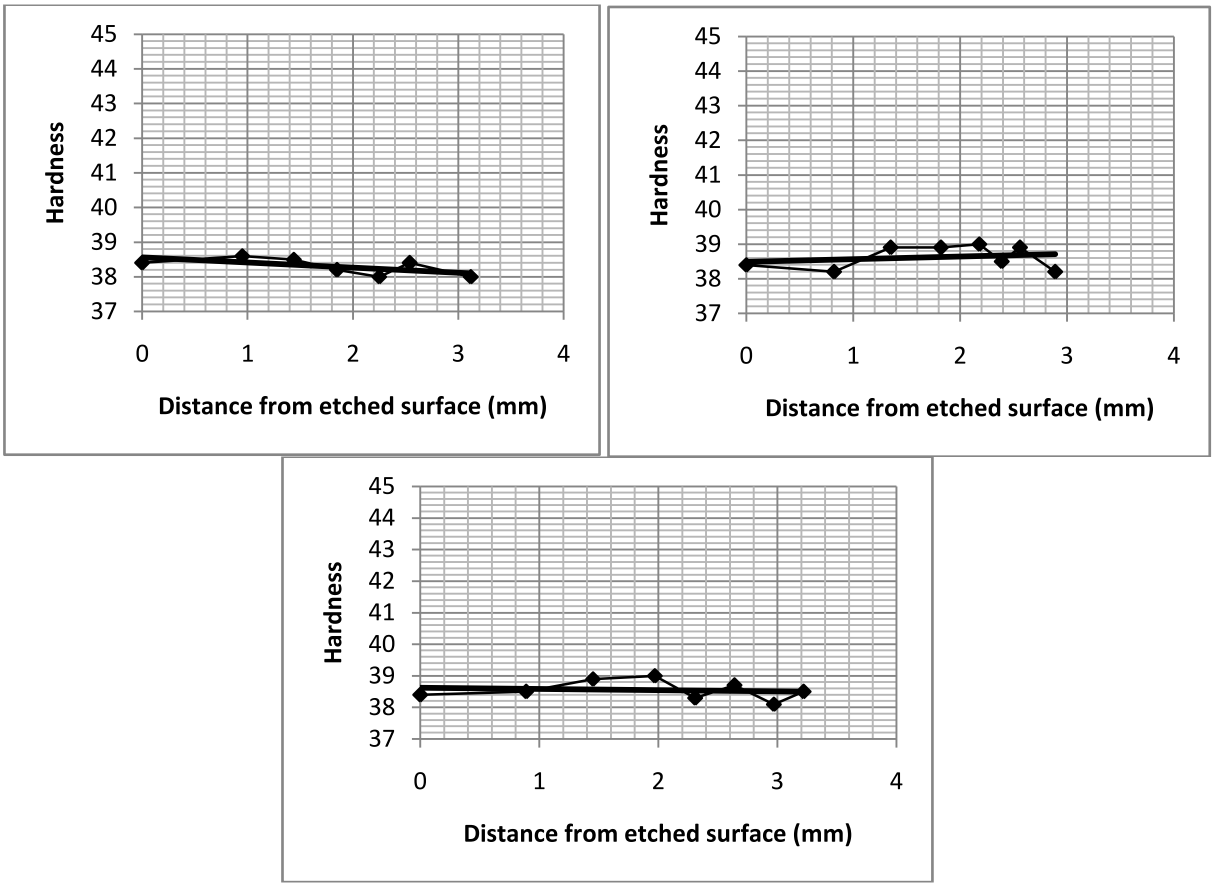

Fig 13. A plot between Hardness and Distance from etched surface

8.2 Hardness in CNC milled samples

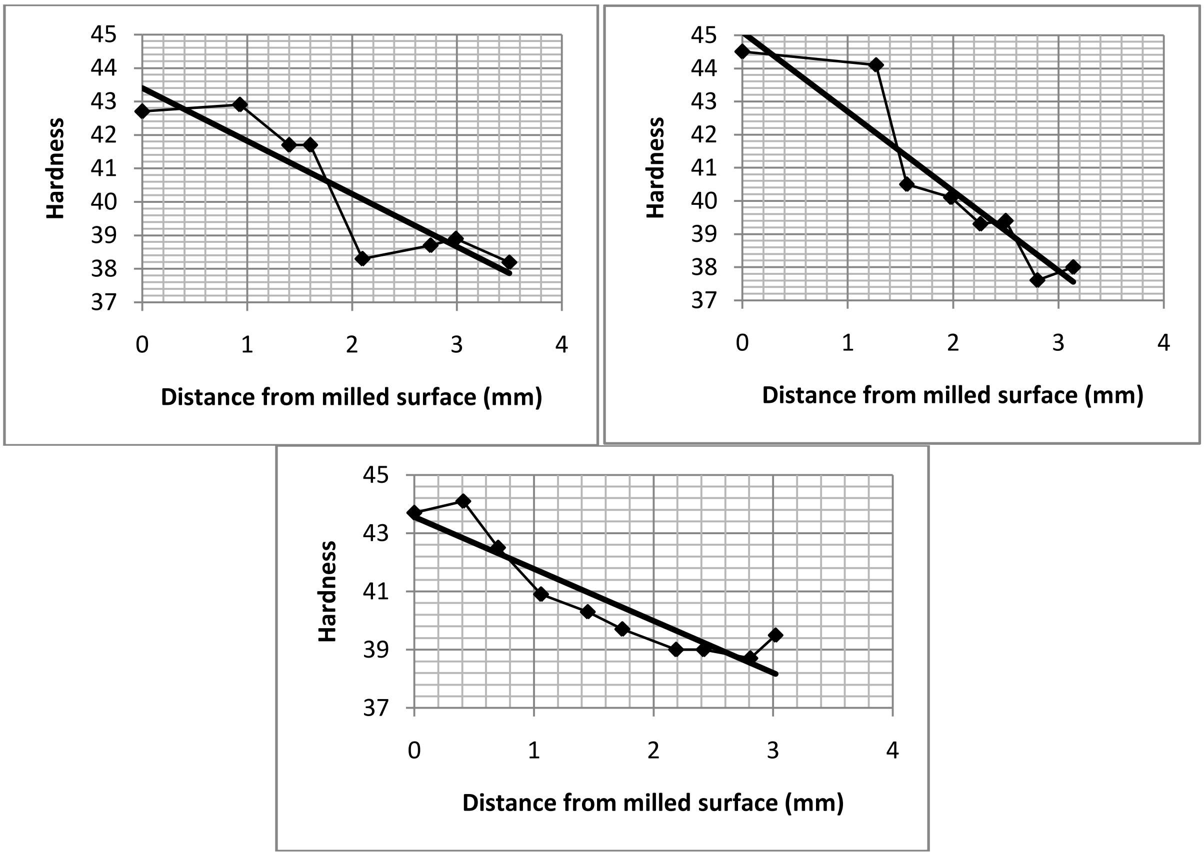

Fig 14. A plot between Hardness and Distance from milled surface

To plot the hardness data, identical scales are taken so as to see the difference in effect visually. Apart from the scatter plot of hardness value vs. depth, the trend line feature on Microsoft Excel has been used to see the pattern of the data points. Considering that the scale of the ordinate axis is taken equal in all plots, it is quite apparent that there is a good variation in the hardness values in the mechanically milled sample. To make a more quantitative analysis of this, the standard deviation and variance of the hardness values of all datasets has been calculated.

Table 2: Standard Deviation and Variance of the hardness values

Chemical		Mechanical	
Std. Deviation	Variance	Std. Deviation	Variance
0.238047614	0.056666667	2.046207293	4.18696429
0.337003603	0.113571429	2.574566538	6.62839286
0.302371578	0.091428571	2.005658662	4.02266667

Average variance of chemically etched sample hardness = 0.0872
Average variance of mechanically milled sample hardness = 4.946

It is evident from the difference of average variances that the CNC milling has in fact contributed to an increase in the hardness by producing strain hardening. The reason for this is that the chemical etching process is purely a non-mechanical process that involves no external pressure or stress on the sample.

IX. CONCLUSION

Milling and etching of metals is not so easy and involves a formation of new surfaces. Strong mechanical forces are involved in the process. This requires energy to break the bonds in the material. As mentioned previously, the chemical etching process took about 600 minutes, whereas the CNC milling is a much faster process. So, higher power is required to accomplish CNC milling and more energy is transferred to the material over a very short period of time, thus resulting in enormous forces acting on the milling surface. We would expect that the grains near the surface have been subjected to strong shear forces in the direction of milling as well as compressive forces perpendicular to the direction of milling. These forces are responsible for the deformation of the grains, leading to the accumulation of strain in them. Thus, when the region close to the CNC milled area is subjected to indentation during the Vickers hardness testing, the already strain hardened grains and higher grain boundary area offer better resistance to deformation, thus resulting in higher hardness values near the milled surface. Strain hardening effects contribute to increase in the brittleness of the material and thus make crack formation more probable at the surface. Chemical etching has not affected the properties of the material in any way, making it a safer method of engraving on metals. So, it is advisable to keep the material's properties in mind while doing CNC milling.

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