Evaluation of Fatigue Behavior and Surface Characteristics of Novel Machining Process: Rotary Chemical Machining (RCM)

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Received: 26 January 2021, Revised: 21 April 2021, Accepted: 25 April 2021

Abstract: In this study, Rotational Chemical Machining (RCM) as a novel machining process is introduced. The properties such as surface roughness and residual stress as well as fatigue strength of the RCM process are evaluated, discussed and compared to the conventional turning process. In this sense, Scanning Electron Microscope (SEM) and Atomic Force Microscope (AFM) were utilized. The results show the superiority of the RCM method over the conventional method and eliminate limits of process such as low surface quality and improve fatigue strength. The Amplitude Distribution Curve has a balanced Gaussian shape in RCM indicating the balanced distribution of peaks and valleys on machined surface. Due to the absence of machining force in the RCM process, in comparison to the turning process, maximum residual stress is significantly decreased from 363Mpa to 71Mpa; surface roughness reduced from 3.1µm to 1.5 µm as well as the fatigue strength improved 20% approximately.

Keywords: Fatigue Strength, Hybrid Micromachining Process, Residual Stress, Surface Roughness

How to cite this paper: Pooya Bahrami, Ali Khoshanjam, and Abdolhamid Azizi, "Evaluation of Fatigue Behavior and Surface Characteristics of Novel Machining Process: Rotary Chemical Machining (RCM)", Int J of Advanced Design and Manufacturing Technology, Vol. 14/No. 3, 2021, pp. 17–24.
DOI: 10.30495/admt.2021.1921815.1247

Biographical notes: Poya Bahrami and **Ali Khoshanjam** received their MSc in Manufacturing Engineering from University of IAU Kermanshah Branch in 2015. They are interested in machining and finishing processes and have done many researches in this area and are currently doing research in these fields. **Abdolhamid Azizi** received his BSc MSc and PhD in Manufacturing Engineering from Amirkabir University of Technology in 2003, 2005 and 2009, respectively. He is currently Associate Professor at the Department of Engineering, Ilam University, Ilam, Iran. His current research interest includes grinding and finishing processes.

1 INTRODUCTION

The corrosion of metals is phenomenon which causes many harmful effects on industrial parts. But also, it can be applied as a practical technique for shaping and removing chips to manufacture parts. This technique was first utilized by the ancient Egyptians for decorative purpose [1]. It has been further developed in the past century by M.C. Sanz in 1956; he published a patent entitled “chemical milling” or “chem-mill” [2]. This method has been identified by researchers by different terms, such as chemical machining (CHM), chemical etching, chemical polishing, wet etching [3], photochemical machining [4] etc.

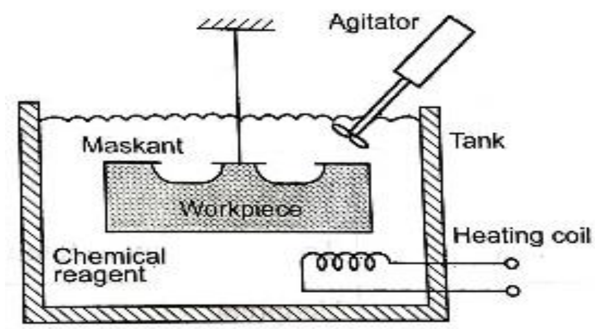
Meanwhile, throughout this paper it will be termed “chemical machining”. Chemical machining is a nontraditional manufacturing process that is widely used for shaping thin and complex geometrical materials and producing accurate parts [5]. This can also be utilized to weaken weight-strength ratio of the work materials, e.g. aircraft wings. The absence of residual stress in the specimen is the most important superiority of chemical machining process in comparison to other traditional manufacturing operations. It is due to the absence of any mechanical force or thermal stress during the chip removal process.

Although chemical machining offers a great deal of advantages over conventional methods, it also carries some disadvantages, such as, low material removing rates and environmental pollution [6]. In order to investigate the chemical machining process, many attempts have been implemented for example, Chakir et al. [7] machined Al 7075 and Cu workpieces using $FeCl_3$ and CuCl etchants, respectively. They examined the influence of temperature on the work and reported that by increasing the etchant temperature, the surface roughness and the depth of etch increase.

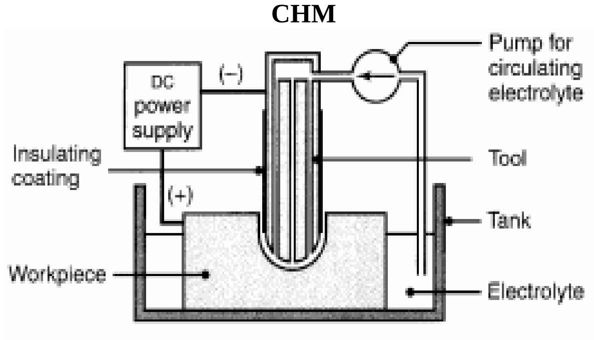
Many works have been done for improving machining capability and efficiency of the CHM process. For instance, a new hybrid machining process which is called Grinding Assisted Chemical Etching (GACE) was introduced by combining the conventional grinding process with CHM [5]. In this method by applying etchant in machining area, improvement in surface roughness and material removing was achieved. In other researches, Magnetic Abrasive Finishing (MAF) process was combined with chemical etching to improve surface finishing of silicon wafer [8]. Mohamadian et al. investigated surface finishing of Inconel 625 by using combined chemical-abrasive flow polishing process. They found that applying chemical etchant in abrasive polishing improved the surface roughness and material removal rate [9].

Laser-Chemical Machining (LCM) is another recent development in the chemical machining process. It is a novel method that improves the efficiency of laser machining by using a chemical etchant in the machining zone [10]. Consequently, the utilization of this method results in increasing the material removing and reducing residual stress [11]. Furthermore, another study named Spark Assisted Chemical Engraving (SACE) was introduced to achieve high precision parts and to cut cost of the machining process [12].

Electro-chemical machining is another advanced machining process which is based on principle of electrolysis for metal removal. Two electrodes are placed in a bath containing liquid (electrolyte) and when a direct potential is applied across electrodes, the metal can be depleted from anode and plated on the cathode. However, Chemical Machining (CHM) performed based on controlled chemical erosion and material removal occurs through contact with a strong chemical etchant. Figure 1 shows a schematic diagram of ECM and CHM process.



CHM



ECM

Fig. 1 Comparison of Chemical Machining (CHM) and Electrochemical Machining (ECM).

In this research, an innovative chemical machining method called RCM for round parts machining is presented. In the following, by examining the surface properties and mechanical properties of the machined specimen, the superiority of the presented method over the traditional machining methods is proved. Another research innovation is that in addition to conventional parameters such as arithmetic mean deviation (R_a) and maximum height of profile (R_z), more precise parameters such as skewness and Kurtosis are used to investigate the machined surface quality and sharpness.

2 MATERIALS AND EXPERIMENTAL PROCEDURE

The material used in these experiments is Al 7075. It is widely used in aerospace and automotive industries due to its light weight along with its elevated mechanical properties. The chemical compositions of Al 7075 are reported in "Table 1". Many etchants have been studied by researchers and the majority of results reported that $FeCl_3$ is the most appropriate etchant for chemical machining of aluminum and aluminum alloys. It is relatively inexpensive and can be used to better control the material removal process. On the other hand, due to the possibility of its regeneration, it is also used more in the industry. The details of the experiments are described in "Table 2".

Table 1 Chemical composition of EN AW-7075 aluminum

Chemical elements (%)									
Al	Si	Fe	Cu	MN	Mg	Cr	Zn	Ti	Others
96	0.4	0.5	1.2–2.0	0.3	2.1–2.9	0.18–0.28	5.1–6.1	0.2	0.05

Table 2 Experimental conditions

Specimen	Al-EN AW-7075
temperature	25
etchant	$FeCl_3$
Concretion	25 %wt.
Fatigue test frequency	30 Hz
Stress Ratio (R)	Reverse (zero mean stress, R = -1)
Roughness Measurement standard	ISO 1997
Cutoff	2.5 mm
Filter	GAUSS

In the previous methods of chemical machining, the specimen is usually immersed in the etchant which results in solving the unwanted material in the solution. It is a good way for shaping flat specimen; however, there are limitations in shaping the circular parts. Figure 2a shows the schematic of the RCM process. First, the aluminum specimen was cleaned by removing grease, oil, heavy oxides and other contaminations from the surface then a special corrosion resistant material (maskant) was used to cover the ends of the specimen. Maskants are commonly used to protect parts of the specimen where the chemical dissolution action is not required [13]. Synthetic or rubber base materials are commonly used for this purpose and in this study Epoxy resin was applied.

Next, the specimen was clamped to the rotational spindle and was immersed in the etchant and finally, the specimen was formed into the desired shape due to the chemical reaction with the etchant. Figure 2b illustrates the comparison between the specimens shaped by the RCM and the turning processes. As it is shown, the specimen shaped by RCM contains a brownish colour surface which is called "reacted layer" that has occurred during the chemical machining process [14]. Fatigue experiments were accomplished in vitro at ambient temperature, applying a closed loop rotating beam fatigue test machine (Model RBF200) ("Fig. 2c").

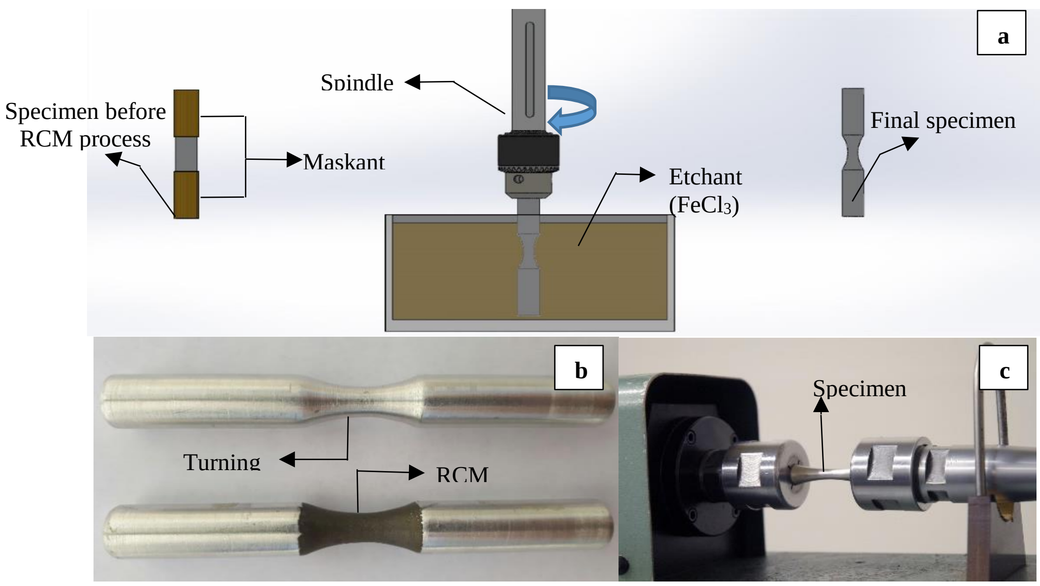


Fig. 2 (a): RCM procedure, (b): Turning and RCM specimens, and (c): Rotating beam fatigue test setup.

Surface analysis of the specimens was performed providing a SEM apparatus shown in “Fig. 3” and a Mitutoyo stylus roughnessmeter. The cut-off length was set at 2.5 mm. In order to study the surface quality more accurately, the Atomic Force Microscopy (AFM) device shown in “Fig. 4” was also used.

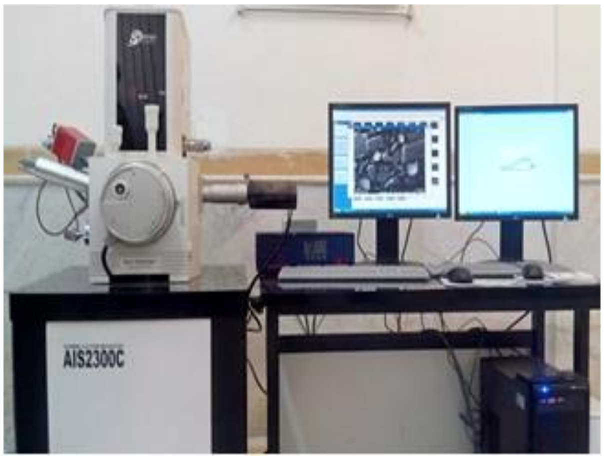


Fig. 3 SEM surface Image apparatus.

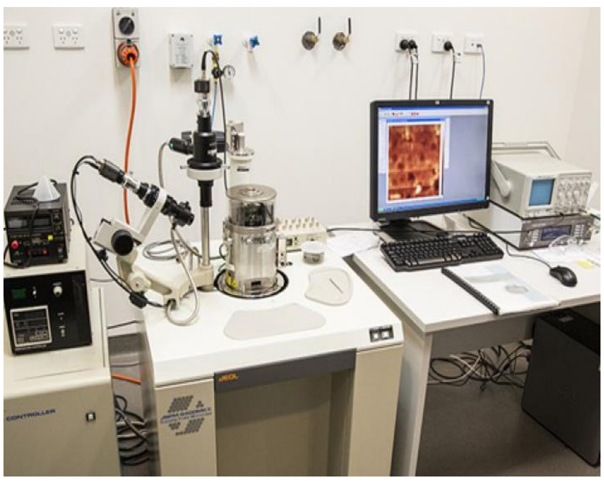


Fig. 4 AFM surface measurement apparatus.

3 RESULTS AND DISCUSSIONS

3.1. Surface Integrity

Figure 5 illustrates the two important surface roughness factors (Ra and R_z) for the RCM and the turning processes. Surface roughness is an important factor in the machining process. It is evident that in the RCM process, Ra and R_z are two times lower than those in the turning process. Additionally, the surface produced in the RCM process is smoother than that in the turning process.

Arithmetic mean deviation (Ra) and maximum height of profile (Rz) are necessary factors when comparing the surface roughness, but are not sufficient parameters to explain the surface properties. To distinguish the difference in shape or patterns of surfaces in the RCM and the turning processes, we need to have a more realistic understanding of the peaks and valleys created on the surface. The more elaborated the state of the roughness, the more critical the function of the surface, thus we need to measure parameters beyond Ra and Rz [13]. Many surface studies use the R_a parameter, while this parameter describes the mean value and cannot accurately describe the exact nature of the peaks and valleys on the surface. This is especially important when producing parts such as engine parts in which the presence of more valleys on the surface is important for proper lubrication. Therefore, it is important to use other parameters such as skewness (R_{sk}) and kurtosis ($R_{k\mu}$).

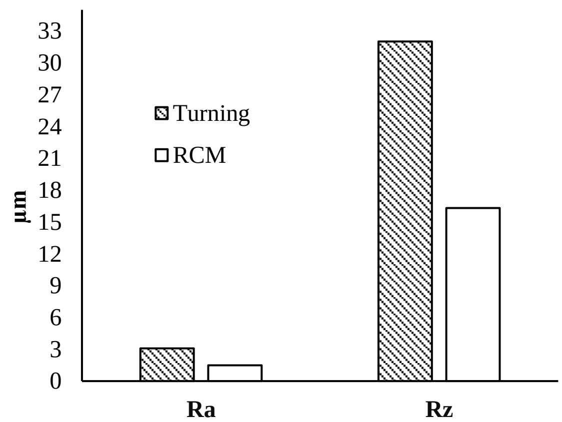


Fig. 5 Ra, Rz surface roughness of the RCM and the turning processes.

The probability that a point such as ‘x’ on the surface has height of ‘z’ is expressed by Amplitude Distribution Curve (ADC). The ADC function obtained from the roughness measurement has a normal distribution like other probability distribution curves. It should be noticed that R_t is the distance between the highest peak and the deepest valley. The ADC demonstrates ‘how much’ a peak or a valley, in a histogram is sensed. ADC, is generally described by dimensionless unit parameters: skewness and Kurtosis. Skewness is used to check the surface roughness symmetry about mean line, which is defined according to ASME B46.1. This parameter is used to evaluate the surface roughness quality. According to “Fig. 6”, surfaces where deep valleys are predominant, the skewness of these surfaces tend to be negative numbers and have better lubricating properties, and vice versa. Also, abrasion resistance is lower on surfaces with skewness greater than zero. The Kurtosis parameter indicates the intensity of the distribution of peaks and valleys on the surface, and if the distribution is normal, the value of Kurtosis will be equal to 3. If there is a stretch in the distribution of peaks and valleys on the surface, the value of Kurtosis will be greater than 3, otherwise it will be less than 3 (“Fig. 7”). Also, Kurtosis is therefore recognized as an important parameter in the study of surface sharpness. Figure 8 demonstrates the ADC of the RCM and the turning processes. The amount of skewness and Kurtosis are, respectively, 1.16, 4.94 for the turning process and -0.19, 2.97 for the RCM process. This implies that the RCM process produced lower valleys on the surface of the specimen in comparison to the turning process. Figure 9 demonstrates the 5 mm surface profile, AFM and SEM topography of Al 7075 specimens machined by the RCM and the turning processes. As can be seen, by applying RCM, smoother surface can be achieved. On the other hand, in specimens machined by turning process, many valleys (scratched marks) were observed.

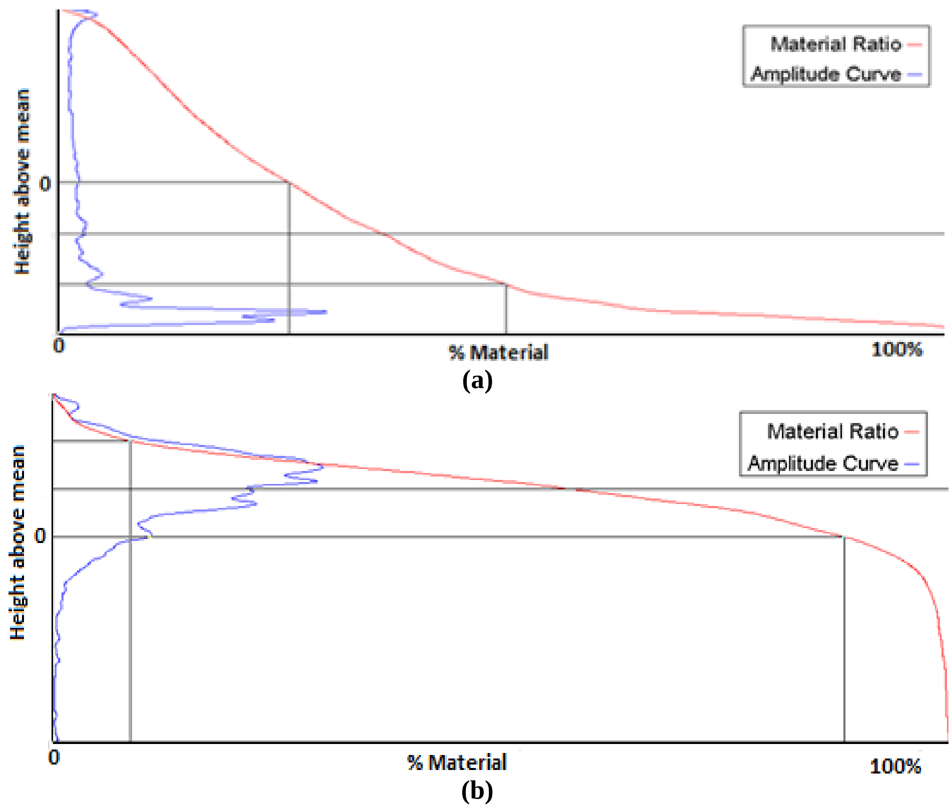


Fig. 6 Sample roughness profile shape with different Skewness: (a): $R_{sk}>0$, (b): $R_{sk}<0$.

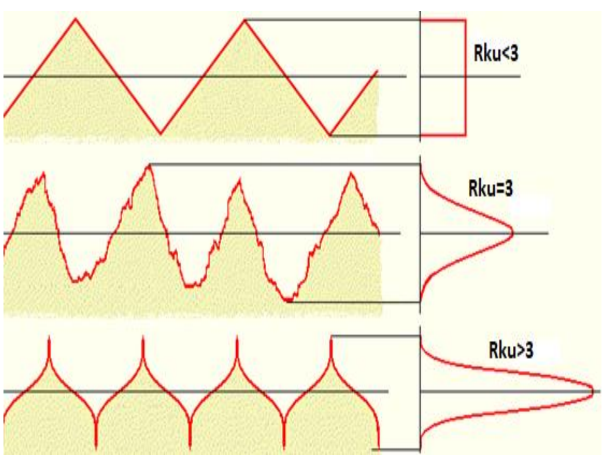


Fig. 7 Surface profiles shape with different Kurtosis.

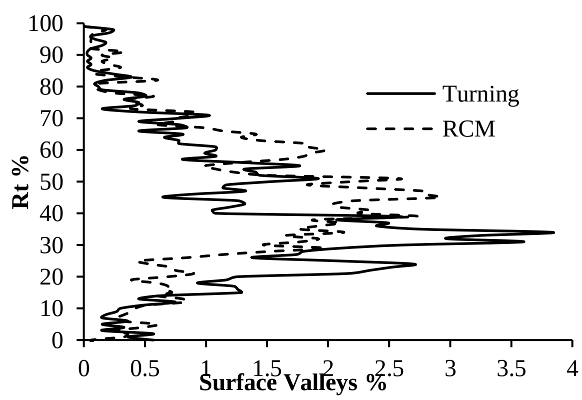


Fig. 8 Amplitude distribution curve (ADC) of the RCM and the turning processes.

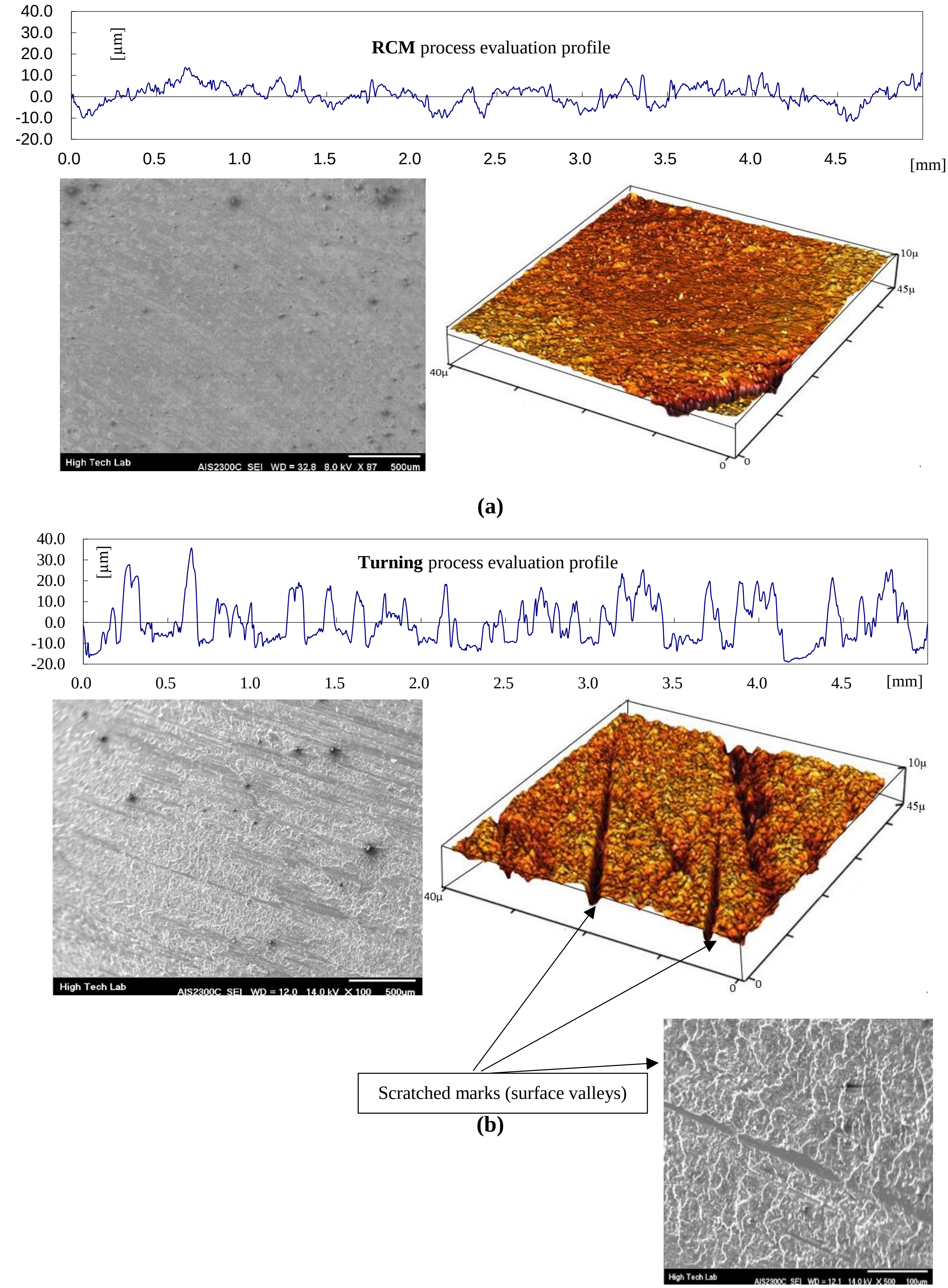


Fig. 9 Surface profiles, SEM topography images and AFM 3D surface of RCM and turning processes.

3.2. Fatigue Life and Residual Stress

The results of the fatigue tests for the two machining processes are compared in “Fig. 10”. From these results, it is evident that these aluminium alloys do not have a distinct fatigue limit. According to S-N diagrams, the specimens shaped by the RCM process have higher fatigue endurance, in comparison to those shaped by the turning process.

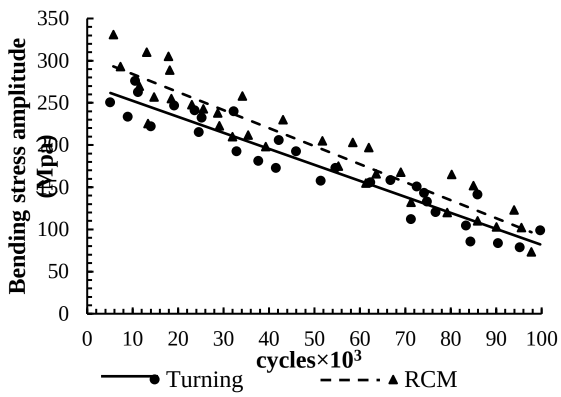


Fig. 10 Rotating Beam Fatigue test (S-N) RCM and Turning process.

The factors affecting this improvement in fatigue strength are surface properties and residual stress [15]. As shown in “Figs. 5 and 9”, by applying the RCM process surface roughness sharply decreases and in comparison with the turning process, smoother surface can be achieved. On the other hand, AFM, SEM images and surface profiles show that in turning process, scratches (valleys) can appear on the surface due to mechanical material removing mechanism. Deep valleys induced during the turning caused cracks initiation that leads to a significant reduction in fatigue strength and specimen failure [16].

Furthermore, during the fatigue test, the associated stress concentrations in the regions of micro-notches induced by mechanical forces will generate a localized plastic strain field [17]. Since machining forces are absent in the RCM process in comparison with the mechanical machining processes such as turning, the residual stress is much lower, therefore it results to higher fatigue strength [17]. Figure 11 shows the residual stress of the machined surface measured by the X-ray diffraction method where the measurements were performed along the axial direction. The conditions for measuring residual stresses are listed in “Table 3” . Residual stress along the axial direction is expected to affect the rotating bending fatigue life of the specimen [18]. It is evident that the residual stress in the RCM process is significantly less in comparison with the turning process. Material Removal Rate (MRR) is another important factor in machining processes which plays significant role in final price of products. In present study, the MMR of RCM process was calculated according to conducted machining conditions. By comparison weight of specimen before and after machining process, it turned out that MRR in RCM process is 8 gr/min.

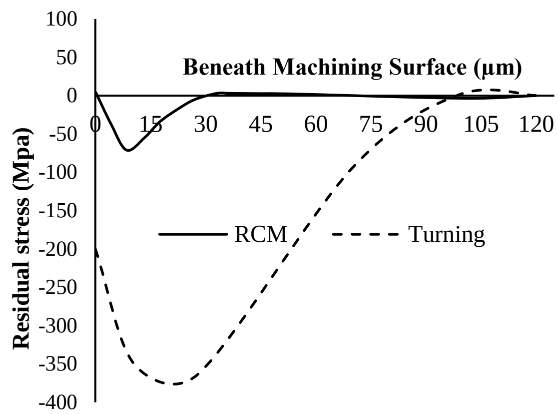


Fig. 11 Residual stress comparison of RCM and Turning process.

Table 3 Residual stress measurement conditions

Model	JSPM-5400 Scanning Probe Microscope
Resolution	Within surface: 0.1 nm, Vertical direction: 0.01 nm
Scan range using standard scanner	XY: 0 to 20 m (resolution: 16 bits 3DAC, equivalent to 21 bits) Z:0 to 3 m (resolution: 22 bits)
Sample size	Up to 50 mm×50 mm×5 mm (T) Standard: 10 mm×10 mm×3 mm (T)

4 CONCLUSIONS

In this study, the novel RCM process is introduced and Al 7075 specimens are examined in terms of surface properties, fatigue life and residual stress. Obtained results of the RCM process are compared with conventional turning process and the outcome of each process is investigated. The results of SEM and AFM images show that the surface integrity of the specimens shaped with the RCM is free from burrs and scratches (micro-notches) in comparison to turning, therefore, it results in higher surface quality so that Ra and Rz reduced from 3.1µm and 32 µm to 1.5 µm and 16.3 µm, respectively. Furthermore, due to the absence of machining forces in RCM process, residual stress is drastically reduced from 365MPa to 71MPa which plays a significant role in fatigue endurance limit. It can be concluded that the RCM process is an efficient method for machining the round parts particularly in cases where high fatigue strength and surface quality are desired.

ACKNOWLEDGMENTS

Authors would like to show their gratitude to Ms. Roza Ghadiri (Macquarie University) for providing language help and writing assistance in this research.

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