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Cutting Forces and Tool Wear Investigation for Face Milling of Bimetallic Composite Parts Made of Aluminum and Cast Iron Alloys

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ABSTRACT

Bimetallic parts are used in many industries for weight and cost reduction of workpieces, working under high loads and wear. One of the application for this type of composite material is in automotive industry. In this work, the tool wear and cutting forces in the face milling of bimetallic parts made of aluminum and cast iron were investigated. A356 and GG25 alloys that are common materials for bimetallic engine cylinder block were selected as material for aluminum and cast iron samples, respectively. Machining length was 3.6 meters in the experiments and the tool wear was calculated on the flank face of tool using image processing method (KNN approach). Results indicated that with the machining parameters selected here, the wear of aluminum sample is not significant but the wear for cast iron and bimetallic materials was considered. It was also discovered that the wear and machining force for bimetallic parts are much higher than samples with cast iron material and the analogy was observed between cutting force and tool wear quantities. From this, it can be concluded that instead of time consuming wear tests, the tool wear trend in face milling of bimetallic parts can be predicted from cutting force measurements. It is also conculded that KNN image processing method is very accurate for calculating the tool wear.

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1. INTRODUCTION

With development of new manufacturing methods like 3D printing, the application of multi material components in many industries is incraesing [1].

Weight reduction is one of the main design trends for advanced internal combustion engine components. This concept is followed by replacing components made of cast iron alloys with Aluminum and magnesium alloys [2]. In some internal combustion engine components like cylinder block and piston, aluminum and cast iron alloys are used in a composite structure to build a bimetallic part [3-5] composed of the light weight material as a base material. Wear resistance and strength of the structure is then improved in some areas by using higher wear resistannt material. One important challenge is realized the wear rate for these bimetallic parts and selection of the appropriate tool. For machining of these bimetallic parts, the tool-workpiece contact will change from soft to hard material for workpiece in one cycle of tool rotation [6-7]. The resulting force difference in hard and soft sections is the main challenge for tool selection for machining of bimetallic parts [8-9].

Uthayakumar et al. [9] investigated deburring and surface finish of bimetallic piston using CBN tool and extracted optimized machining parameters using Taguchi method. They have also investigated the cutting forces in machining of bimetallic parts in another work [10, 11] and proved that dipping time (a process in manufacturing of bimetallic piston) had very vital influence on cutting forces. Wear mechanism of CBN inserts during machining of bimetal aluminum-grey cast iron engine block has been investigated by Malakizadia et al. [4]. Simulation and finding the optimum machining conditions (minimum cutting forces) has been implemented by Manikandan et al. [12]. The obtained optimum conditions were cutting speed of 585 m/min, feed rate of 0.16 mm/rev for and depth of cut of 0.16 mm.

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Characteristics of machining forces that occur when turning three sets of dissimilar metallic specimens made of aluminum–titanium, aluminum–cast iron, and stainless steel–mild steel was described by Sharif Ullah [13]. He found that in machining of bimetallic steel based work pieces, low feed rate and high cutting speeds should be applied. He also concluded that very soft materials should not be used in fabricating the bimetallic parts because it creates machining problems .

Various methods presented for quantification of tool wear [14], among them the image processing based methods have the capability of using in online tool monitoring. Most of the image processing works for tool wear quantification focused on the edge detection techniques [15-16] like Canny [17] and Hough transform [18-19] approaches. Determination of the appropriate threshold value is the main challenge of edge detection methods. This value depends on the image characteristics and the optimum value could be different from one image to another one .

As is found in the literature survey, there are very rare independent researches for analyzing of the tool wear during milling of bimetallic parts. In the current work, cutting forces and wear rate of face milling tool was measured using image processing in the face milling of bimetallic workpieces. For overcoming the mentioned problems of edge finding image processing methods, KNN approach is utilized successfully for tool wear image analysis. KNN is a clustering method for image analysis and the main application is in medical industry [20-21].

The tool wear analysis and measurement of cutting forces during face milling of bimetallic parts made of cast iron and aluminum alloys (the common materials for internal combustion engine cylinder block) has not been done before. In the present work, 3 samples with the same geometry of cast iron, aluminum and bimetallic parts, tool wear and cutting forces were investigated. Experimental approach implemented; it was tried to find a relationship between cutting forces and the tool wear. The main novelties of the present work was the cutting forces in milling operation of bimetallic parts. The wear rate measurement in this process was also a new approach of KNN for tool wear calculation via image processing.

2. MATERIALS AND METHODS

For the vpreparationg of bimetallic samples in this work, aluminum and cast iron alloys were selected based on materials that are currently used for bimetallic (cast-in) engine cylinder blocks. A356 that is very common material for passenger car aluminum cylinder blocks and GG25 cast iron that is a common cylinder liner material were selected as a material for samples. Common bimetallic cylinder block is shown in Figure 1.

Figure 1. Bimetallic cylinder block [5]

As shown in this figure, face milling of cylinder block that is a very important manufacturing operation; which is classified in the category of bimetallic machining. The samples are prepared to simulate this type of machining.

The experimental samples are shown in Figure 2. as shown in this figure, length and width of samples were 180 mm and 50 mm respectively. The height of all samples was 50mm. Machining length for all samples was 3.6 meter (20 machining passes). No coolant was used for the experiment and the machining was undertaken in dry condition. The machining parameters like cutting speed, feed rate and depth of cut were selected in their higher range to accelerate tool wear. Selected parameters were in the range that simulate rough machining operation of bimetallic cylinder block.

The milling machine was FP4M-D type from Machine Sazi Tabriz Co. Tool material was made of WC with TiN coating. Tool insert and its holder are shown in Figure 3. There are two important wear parameters for specifying the wear of each tool: flank wear and crater wear. As the flank wear is a very important in case of part surface roughness and dimensional tolerances, this parameter is measured to represent the wear parameter in the current work.

Worn inserts image was captured with optical microscope with magnification of 20 times and the images then analyzed using image processing technique

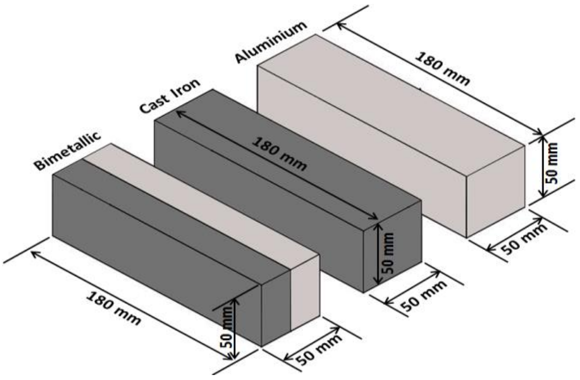


Figure 2. Dimensions of the parts that used in experiments (for aluminum, cast iron and bimetallic samples)

Figure 3. Tool inserts (right) and tool holder (left) for face milling

to convert the binerized black to white image. After that, the area of flank wear was calculated with counting of the white pixels and multiplying the value by the area of each pixel. As noted before, the tool images were analyzed using KNN clustering method. This procedure has been undertaken with a written code of MATLAB software. Magnified and the binerized images derived from image processing are shown in Figure 4.

Experimental test rig that was used for measuring of the cutting forces is shown in Figure 5. Cutting forces were measured with Kistler 9257B dynamometer. As indicated in this figure, the part was clamped from two sides on the dynamometer.

3. RESULTS AND DISCUSSION

With experimental and image processing procedure explained in previous section, the experiments were undertaken under different machining conditions. Machining parameters for three types of materials of aluminum, cast iron and bimetallic are summarized in Table 1. The tool wear were measured for all three cases. Worn tool image and the corresponding binerized image for all cases are shown in Figure 6. As explained in previous section, the KNN image processing method was used to convert tool image to binerized image. Tool wear area that was assigned to the tool wear extent in this work then calculated for each image from binerized image. To evaluate effectiveness of KNN image processing technique the results of the tool worn area acquired from this method was compared with manual counting of pixels and it was found that the KNN method can predict the tool wear with maximum error of 10%

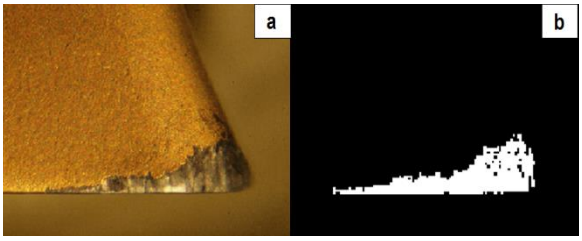


Figure 4. Sample image of worn tool (a) and binerized output image after KNN procedure (b)

TABLE 1. Machining parameters for wear rate investigation

Depth of cut (mm)	Feed rate (mm/min)	Cutting speed (rpm)
2	100	500
2	100	800
1.5	125	1250

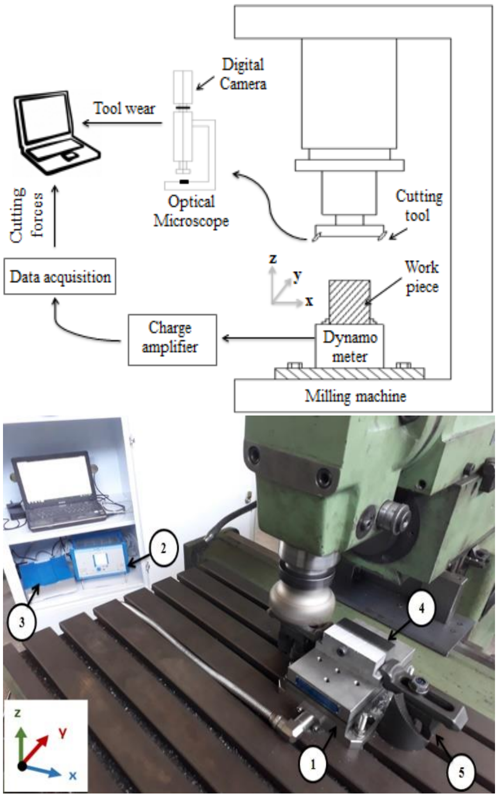


Figure 5. Experimental test rig, schematic (up) and real components (down) (1) dynamometer, (2) Charge amplifier, (3) data acquisition, (4) workpiece, (5) clamping vice

Tool worn area values for cast iron and bimetallic samples with various machining parameters are shown in Figure 7. As shown in this figure, increasing cutting speed and federate will increase tool worn area. For aluminum samples it was observed that with the machining length examined in this work, the wear is near zero which can be neglected. Therefore, comparison study was conducted between cast iron and bimetallic workpieces. For aluminum samples, the buildup edge (BUE) [19] was visualized in the cutting speed and feed rates used in the experiments. The BUE was clearly detectable only when the image was magnified with optical microscope (Figure 8). It should be noted that for all cases, average value of all inserts of one tool wear area is reported. It is apparent from Figure 7 that the wear of bimetallic samples is much higher than the cast iron

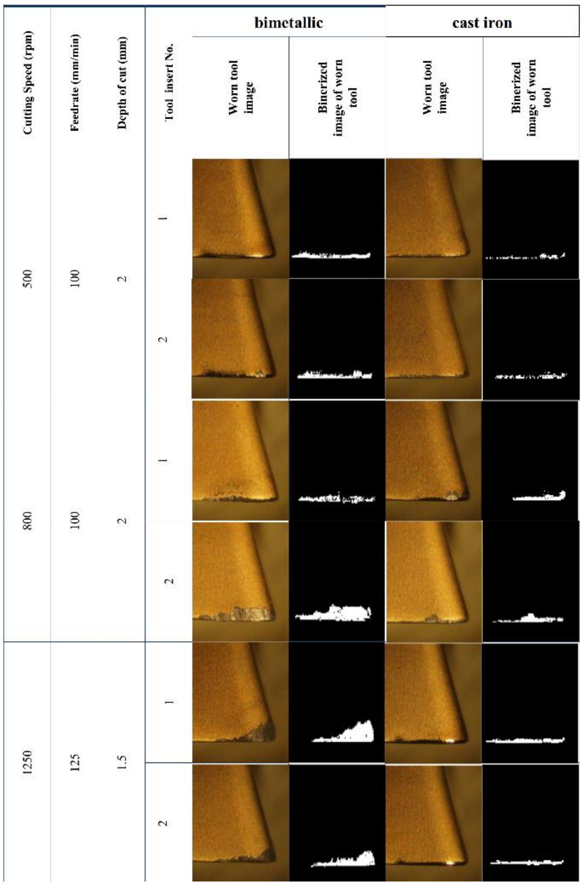


Figure 6. Worn tool images and corresponding binerzied image for various machining conditions

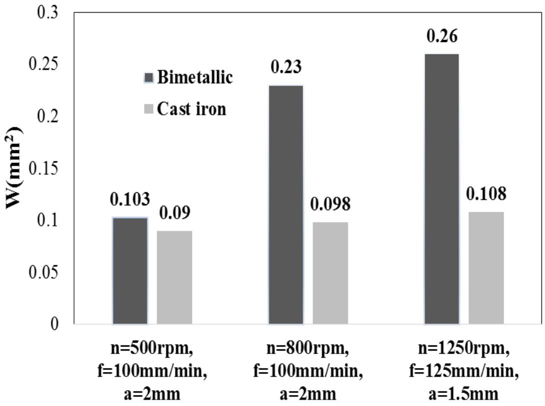


Figure 7. Tool wear area calculated using KNN image processing method for cast iron and bimetallic samples in different machining conditions

samples and for instance, for machining condition of: a=1.5 mm, f=125 mm/min and n=1250 RPM, the wear of bimetallic part is 140% higher than the cast iron sample. The difference between tool wear of bimetallic and cast iron samples is increased by increasing cutting speed and feed rate. For bimetallic part, the effect of BUE could change the tool actual geometry that will affect the cutting forces. The effect of changing from soft to hard material and vice versa for tool workpiece contact exerts high impact loads on the tool that is considerable as well. These two reasons i.e. BUE formation and impact loads on tool could lead to the higher forces and higher wear rate of bimetallic parts compared with cast iron parts.

Wear in the tool flank and crater faces has various mechanisms. In all of them, cutting force magnitude is the most important factor that determines wear quantity. It is a reasonable assumption that in the case examined in this work, wear is dependent on friction and normal force (F_N). From geometry of machining process, it is apparent that Fx and Fy are friction and normal forces, respectively.

For finding a relationship between cutting forces and tool wear, resultant of these two forces were calculated for aluminum, cast iron and bimetallic materials for various machining conditions. The resultant force (Fr') is calculated by the following equation:

$$Fr'(KN) = \sqrt{F_x^2 + F_y^2} \qquad (1)$$

For investigation of influence of cutting forces on the tool wear, experiments were designed with values of cutting forces and feedrates summarized in Table 2. For all tests of this section cutting depth was constant and

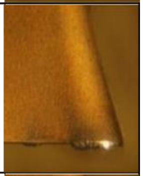
Cutting Speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)	Tool image
800	80	2	
800	125	1	
1250	80	1	
1250	125	2	

Figure 8. BUE formation on tool flank face for aluminum samples under different machining conditions

equal to 1 millimeter. The range of cutting speed and feed rates were selected based on the preliminary tests In order to find the stable machining condition for each material, . the procedure was performing face milling for different conditions for cast iron, aluminum and bimetallic samples. Then the speeds and feeds are selected to cover three different materials. Stable condition was defined the condition with lower vibrations and better surface finish.

Effect of these parameters on the cutting force in directions of X, Y and Z then evaluated for samples with cast iron, aluminium and bimetallic materials.

For all cases shown in Table 2, the average resultant cutting force (Fr') is measured. The average is taken from start of test until its end. Average resultant cutting force for the noted three test conditions are shown in Figures 9-12. As shown in these figures for all machining cases, cutting force increases from zero before tool and workpiece contact. The gradually increases are due to the increase in the contact area of tool inserts and workpiece. After that, it reaches to a constant value and decreases when the tool is leaving the workpiece.

TABLE 2. Machining parameters for cutting force measurement experiments

Test number	Cutting speed (RPM)	Feed rate (mm/min)
1	250	100
2	800	125
3	1250	80

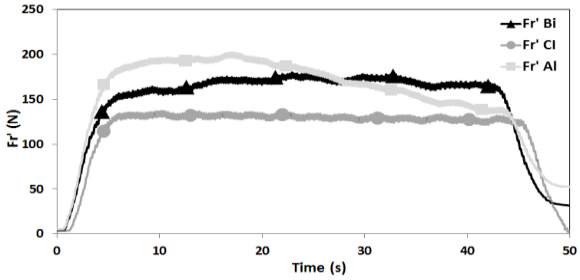


Figure 9. Resultant force versus time for cutting speed of 250 RPM, feed rate of 100 mm/min and cutting depth of 1 mm for cast iron, aluminum and bimetallic parts

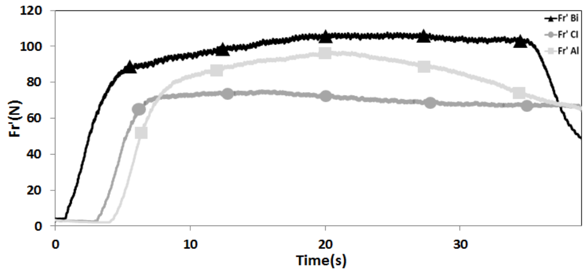


Figure 10. Resultant force versus time for cutting speed of 800 RPM, feed rate of 125 mm/min and cutting depth of 1 mm for cast iron, aluminum and bimetallic parts

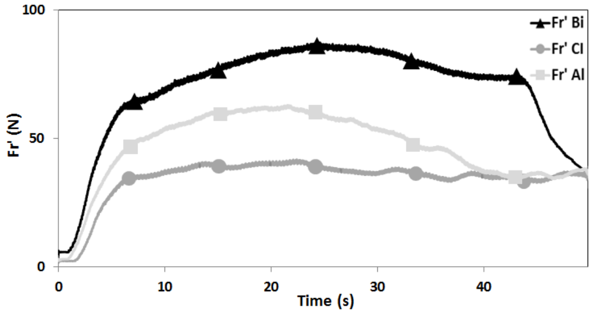


Figure 11. Average resultant force for test cutting speed 1250 RPM, feed rate 80 mm/min and cutting depth 1 mm for cast iron, aluminum and bimetallic parts

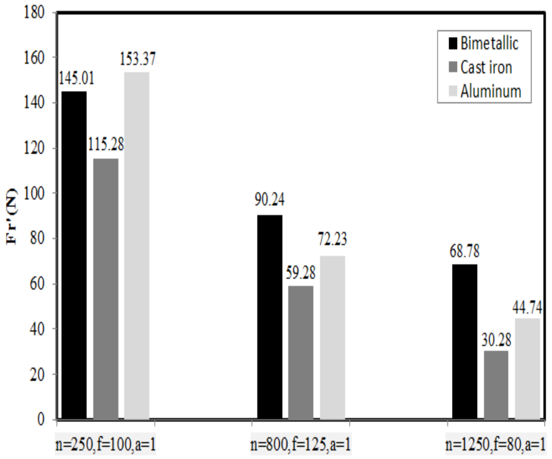


Figure 12. Average resultant force for cast iron, aluminum and bimetallic parts for specific machining conditions

It is apparent from force measurements that for all cases average resultant force for cast iron is minimum and except the first case with low cutting speed, the bimetallic sample has maximum cutting force. It should be noted that for low cutting speed (Figure 9) the forces are higher for aluminum compared with bimetallic sample at the beginning of the machining that could be due to the BUE formation in the low cutting speeds. The random behavior of the BUE formation could be another reason of increasing the cutting forces when compared with other machining conditions shown in Figures 10 and 11. As shown in Figure 9 after 30 seconds from start of machining the forces for aluminum workpiece decreases that is possible reason would be disappearing of the BUE due to the heat or other reasons. The high cutting force for aluminum in the first case with low cutting speed could be due to the formation of BUE and changing the mechanics of cutting. Higher cutting forces for bimetallic part can be resulted in from changing the material that is in contact with tool in its each rotation. Impact forces in the interface of aluminum and cast iron also increase the average force for bimetallic parts. Form these results and results of wear tests, the fact that there is a similar trend between cutting force and tool wear which is proved that the cutting forces and wear is evaluated in a similar condition of n=1250 RPM, f=125 mm/min and a=1.5 mm. The obtained results for this test showed that the average resultant cutting force and wear of bimetallic material is 127 and 140 percent higher than cast iron material, respectively. The similarity of the values showed that with cutting force measurement it is possible to predict the wear extent of cutting tool for face milling of bimetallic parts. This can be used in assigning of appropriate tool for machining of these types of composite materials.

Chips produced during machining of the samples are shown in Figure 13. As expected and shown in this figure, the chips of cast iron are segmental and the chips resulted from aluminum milling are continuous types. The chips of bimetallic part are from two types of continuous and segmental.

Figure 13. Cast iron chips (a), Bimetallic parts chips (b) and Aluminum chips (c)

4. CONCLUSIONS

In the present work, wear of bimetallic parts made of cast iron and aluminum in experimental approaches in face milling operation were evaluated. Samples with similar geometry were prepared from aluminum, cast iron and bimetallic materials. After 3.6 meters face milling the wear of the flank face of the tool with image processing technique was investigated. The KNN image processing method was used to calculate the wear area of the flank face. With the range of the machining length used in this work no wear was observed for aluminum samples but the wear for samples made of cast iron and bimetallic materials was considerable and calculated via image processing method. The cutting force measurement also is implemented to investigate the analogy between cutting forces and wear in face milling of the bimetallic parts. Wear investigations results indicated that wear of bimetallic parts is more than workpieces made of cast iron. The cutting force measurement also confirmed the results of wear measurements. The analogy is such that in a similar machining condition (n=1250 RPM, f=125 mm/min and a=1.5 mm) the average resultant cutting force and wear of bimetallic material is 127 and 140 percent higher than cast iron material, respectively. From this similarity it is concluded that instead of high cost wear measurements for the case introduced in this work, the force measurement can be used to predict wear of cutting force. It was also conculded that the KNN method is a very accurate method for measuring the tool worn area. This method can be calculated by the tool worn area with error of maximum 10 percent.

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Persian Abstract

چکیده

قطعات دوجنسی در صنایع مختلف برای کاهش هزینه و وزن برای قطعه کارهای تحت بارهای شدید و سایش مورد استفاده قرار می گیرند. یک کاربرد برای این نوع کامپوزیت، صنایع خودروسازی است.در مقاله حاضر سایش ابزار و نیروهای ماشینکاری در فرآیند فرزکاری روتراشی برای قطعات دوجنسی ساخته شده از آلومینیوم و چدن مورد بررسی قرار گرفته است. آلیاژهای A356 و GG25 که جنس های معمول مورد استفاده برای بدنه موتور هستند به عنوان جنس نمونه های آلومینیومی و چدنی مورد استفاده قرار گرفتند. طول ماشینکاری ۳.٦ متر در آزمون ها بوده و سایش ابزار با استفاده از روش پردازش تصویر KNN محاسبه شد. نتایج نشان داد با استفاده از پارامترهای ماشینکاری در نظر گرفته شده، سایش نمونه آلومینیومی چندان زیاد نبوده ولی سایش ابزار پس از فرزکاری نمونه های چدنی و دوجنسی قابل توجه بود. نتایج همچنین نشان داد، سایش نمونه دوجنسی بیشتر از نمونه چدنی است و تشابه بین نتایج اندازه گیری نیرو و سایش ابزار وجود دارد به نحوی که به جای آزمون های زمان بر سایش ابزار، با استفاده از اندازه گیری نیروهای ماشینکاری می توان به سایش ابزار پی برد. نتایج همچنین نشان داد روش پردازش تصویر KNN روشی بسیار دقیق برای محاسبه سایش ابزار می تواند باشد.