OPTIMIZATION OF CUTTING PARAMETERS AND MACHINING DISTORTION ANALYSIS FOR AA2050

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Abstract

High strength and low density requirement is the fundamental issue in aerospace industry. Many new engineering materials have been focused in recent years. After the 2nd World War, aluminum alloy (AA) 2050, (AA2050), which have low density, high fatigue resistance and excellent corrosion resistance, have become the focus of attention with their lighter weight, although they show high performance based on strength values as other using aluminum alloys in aerospace structural parts such as heavy plate applications, fuselage frames, wing skins and bulkheads. In addition to the strength values of materials used, when they show during machining, the reactions can change the desired strength values and geometrical dimensions.

In this study feed rates, spindle speed, and radial depth of cut which directly affect the machining distortion, were optimized with the usage of the Box-Behnken experimental design method for AA2050. Based on the optimum cutting parameters obtained from the experimental design studies, materials were machined in a milling center with using a carbide end mill which have 20 mm diameter and 0.5 mm tip radius. Depending on the optimum parameters, cutting speed, material removal rate, and spending time are calculated for mass production terminology. Also, with the optimum parameters, on the machined part; geometric dimensioning and tolerance data such as perpendicularity, parallelism and flatness were examined, the distortion values on the workpiece were obtained. Based on the distortion analysis, a significant improvement has been achieved on the workpiece by optimization of cutting parameters.

Keywords: Milling, machining of AA2050, cutting parameter optimization, distortion.

1. INTRODUCTION

The tendency to carry the largest number of passengers and ammunition at once, and accordingly to minimize fuel, wages, and taxes, is one of the main goals of the aerospace industry. Composite materials and aluminum alloys which have low-density and high-strength, are generally preferred in aircraft structures due to their weight on cost through fuel. Because of the high manufacturing cost and machinability difficulties of composite material, aluminum alloys are the best suitable materials which satisfies critical requirements. While AA2014 was used in the first years of the aerospace industry, 7XXX series alloys are used in parallel with the yield strength requirement from 1960 to nowadays [1]. 7XXX aluminum alloys are a type of heat treated material that is frequently used in arches and beams that form aircraft main body structures. The increasing popularity of the lightness feature in the industry has led to the use of aluminum-lithium (Al-Li) alloys instead of the 7XXX series alloys [2]. For instance, AA2050 compared to AA7050, it has become the focus of attention in the aerospace industry, with -4% density reduction, +6% toughness, +46% corrosion resistance, +7% stiffness and +25% fatigue resistance [3]. Despite their advanced strength features, parts manufacturing from AA2050 materials by machining is a serious problem on the basis of machining distortion.

This study focuses on the terminology of AA2050, applications on aircraft structures, studies on optimum cutting parameters, and machining distortion analysis. AA2050 which contains lower-weight lithium-copper metals, is one of the aluminum-lithium series alloys. Lower densities, high strength of materials characterizations are the fundamental causes to use in aerospace industries. It was designed to provide improvements in strength, toughness, elastic modulus, and fatigue crack growth resistance, together with a reduction in density, as compared to conventional non-lithium bearing 2XXX and 7XXX series alloys [2, 3]. First applications of Al-Li alloy were in the 1960s with the advent of the AA2020 (Alcoa,1958, USA) and then VAD23 (1961, USSR) as the first generation Al-Li alloys [4, 5]. Al-Li alloys are divided into three generations and it depends on Li:Cu ratio. AA2050 is the 3rd generation Al-Li alloy. 3rd generation series alloys are created because of to understand the effect of chemical composition and microstructure on mechanical and corrosion performance and to optimize the thermal-mechanical processing. The improvements of 3rd generation aluminum alloys explained the Li and Mg effects which are reducing density, improving strengthening on alloys, Zr and Mn for solid solution strengthening, controlling of recrystallization, and Fe and Si effects the fracture toughness, fatigue, and corrosion [6].

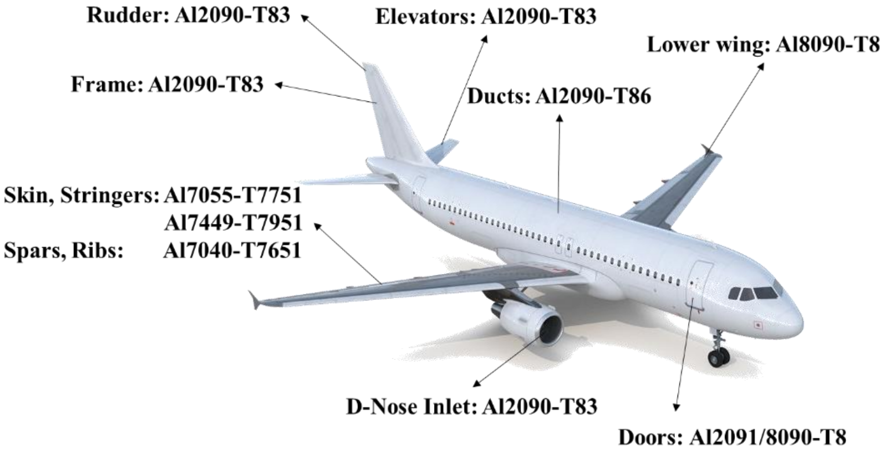

Figure 1 Applications of Al-Li and 7XXX alloys and potentials of Al-Li alloys on the aircraft structure [5]

Al-Li alloys are usually used in aircraft frame, spars, and stringers, for high specific stiffness, high toughness, excellent processing, and welding performance with 7XXX series. Today, Al-Li alloys have started to be more popular in the aerospace industry than 7XXX series alloys due to advantages such as weight reduction and thus high speed and low fuel consumption [7]. For instance; AA7050 which is used in aircraft structural parts, are getting ready to be replaced by AA2050 due to their weight. Also; young modulus and tensile yield strength of AA2050 are higher than AA7050. However, production, chemical composition **(**see **Table 1)** and parts manufacturing from AA2050 are more expensive than 7XXX series alloys. **Figure 1** shows potentials of Al-Li alloys on the aircraft structure [5].

Table 1 Mechanical and thermal properties of AA2050 [3].

AA 2050	**Chemical composition** (wt%)							
	Aluminum	Copper	Magnesium	Zinc	Lithium	Silver	Titanium	Zirconium
	95	3.2-3.9	0.2-0.6	0.25	0.7-1.3	0.2-0.7	0.1	0.06-0.10
	Mechanical Properties					**Thermal Properties**		
	Density (g.cm^{-3})	Tensile strength (MPa)	Yield strength (MPa)	Shear strength (MPa)	*E* (GPa)	Melting point (°C)	Thermal conductivity (W.m^{-1}.K^{-1})	
	2.7	496	462	290	76.5	600-655	93.5	

2. MACHINING OF AA2050

Based on both the soft material type and the resistance it shows against the cutting tool, the machining of aluminum alloys is faster and easier than high-strength metals such as titanium and stainless steel. Along with high cutting speeds and low cutting forces, aluminum alloys are undeniably important materials for the aerospace industry. AA2050 is among the aluminum-lithium alloys, which is the most popular alloy type in the aerospace industry because of the ability of high surface finish in machining [8]. However, the ductility and adhesion of the aluminum alloys are the main problem for both, machining distortion criteria occurs when the optimum cutting parameters are not used in machining.

In this research, effective cutting parameters were carefully identified to use in experimental setup. Cutting speed due to spindle speed, feed rates, and radial depth of cut due to axial depth of cut are fundamental parameters to effect distortion on workpiece in milling process. In the aerospace industry, the distortion is the most important problem, and the cutting speed directly affects the distortion of the machined parts. In machining, when the cutting speed increases in cutting processes, four main regions emerge as distortion such as surface roughness quality. The lowest level of cutting speed, accumulated edge formation and deteriorated surface roughness occur. When the cutting speed is increased, surface quality improvement is defined. When the cutting speed is further increased, vibration may occur there. Fastest cutting speed created a poor surface quality on aluminum alloys. All zones are defined with using milling machine. Another cutting parameter; feed rate directly affects the surface quality of the machined parts. For this reason, it is very important to determine the optimum values of the feed rates in machining. Optimum feed rate values are affected by some other parameters such as chip removal, material type, fixturing, toolpath type etc. In industry, final cuts or finish operations require a slight feed of 0.05 to 0.2 rpm [8]. Cutting action that provides the required depth of material to be cut is defined as the depth of cut. It should be as large as possible for speed and mass production, minimizing the number of cuts required and optimizing strength, chucking equipment, machine tool strength, and amount of stock to be removed. Changing of depth of cut effects cutting forces. The depth of cut should be limited to a value that will not deform or cause the workpiece to slip or overload the machine. In roughing operations, the depth of cut is changes 6 mm to 38 mm. In finishing operations, it goes up to 0-3 mm for small workpieces and up to 10 mm for medium and large workpieces [9].

All cutting parameters directly effect to the cutting forces. To remove constant chips from workpiece, optimum and stable forces are required. The magnitude of the tangential force F_t depends on axial depth of cut, and normal force F_n is proportional to the radial depth of cut which is the effective reason of residual stress depends on radial depth of cut. Cutting force is one of the main reasons of residual stresses in machining. So; in this study, optimum cutting parameters were investigated to obtain minimum distortion on workpiece.

3. APPLICATION OF TAP TEST TO OPTIMIZE CUTTING PARAMETERS WITH USING BOX-BEHNKEN DESIGN OF EXPERIMENTS

Design of experiment methods have been used in the machining industry in the last two decades. Experiments in machining industry are more expensive than the increased number of experiments. Each of variables such as cutting tool types, feed rates, spindle speeds, and values of depth of cut can be changeable at the same time, and the costs are very high if each variable is integrated to the experiments. Thus, design of experiments methods was used for each variable and optimum results were obtained according to cost and energy consumption. Many numerical techniques have been investigated and applied to the machining optimization processes. In this study, Box-Behnken method, which is one of the fastest design of experimental methods, was generated to optimize the processing parameters. The method was used to optimize the feed rate, spindle speed and radial depth of cut. To define range values of parameters, stability diagram which identified by tap test, was generated. It calculates natural and forced frequencies of machining task center. The resulting values are called as frequency transfer function. According to the modal analysis of frequency transfer functions, stability lobes of machining center is drawn in **Figure 2**.

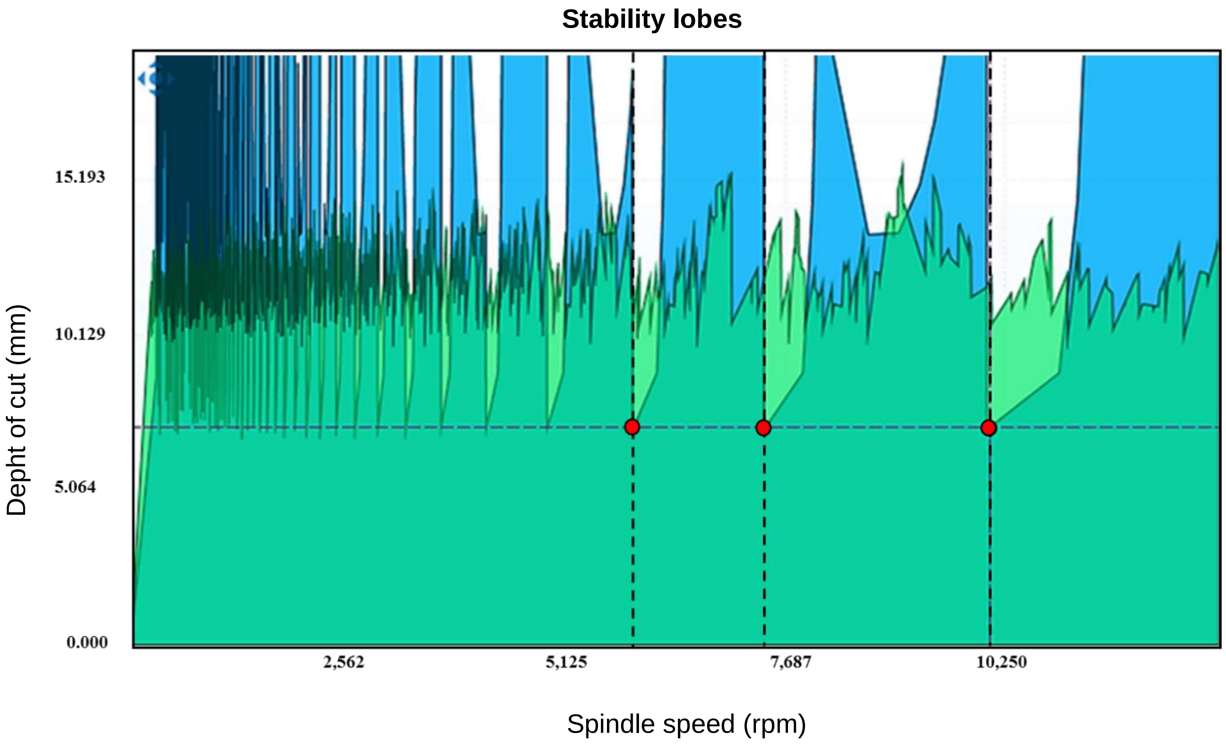

Figure 2 Safety zone due to frequency transfer function and modal analysis

Resulting of analyzing stability lobes gives the optimum spindle speed and axial depth of cut with respect to AA2050 materials and specific machining center. Based on this graphic, **Table 2** gives the optimum results with the calculation of chatter parameters.

Table 2 Chatter analysis at constant axial depth of cut due to maximum spindle speed.

Spindle speed (rpm)	Depth of cut (mm)	Chatter (Hz)
5915	7.1196	1900.2500
7992.5	7.1196	1902.0000
10070	7.1196	1899.9100

Data from **Table 2** were calculated by using Box-Behnken Design technique. Spindle speed is a type of variable factor and selecting of it depends on tap testing results and machine capabilities. Range of axial depth of cut mm is defined by chatter vibrations according to the tap test with depending on the workpiece material and cutting tool properties. However, radial depth of cut selection is changeable to analyze distortion with respect to the workpiece materials. For thin-walled workpieces, one of the most critical aspects of wall milling is to use the full length of the cutting tool effectively. For this reason, 0.5, 1.0 and 1.5 mm radial depth of cut is used. The appropriate feed range for the carbide cutting tool used in aluminum alloys was investigated in the literature review. Specific cutting speed, cutting times and material removal rates were calculated and summarized in **Table 3**.

According to **Figure 2**, maximum axial depth of cut was calculated as 7.1196 mm. However, for improving the cutting parameters, axial depth of cut was selected 5 mm. With respect to Box-Behnken experimental data, un-coded regression equation was obtained. This is a fundamental data to draw response surface graphical charts.

Table 3 Specific calculations of material removal rate, unit spending time and cutting speed by using specific cutting parameters on Box- Behnken design of experimental setup

Feed ($m.min^{-1}$)	Spindle speed (rpm)	Radial depth of cut (mm)	Material removal rate ($mm^3.min^{-1}$)	Cutting speed ($m.s^{-1}$)	Cutting time (s)
0.05	10070	0.5	0.79925	502.1835	0.000993049
0.1	7992.5	1	7.19325	371.65	0.001251173
0.15	10070	1.5	9.063	632.7118	0.000993049
0.1	7992.5	0.5	3.99625	502.1835	0.000625586
0.15	5915	1.5	3.99625	371.65	0.001690617

4. EXPERIMENTAL SETUP AND RESULTS

Experimental setup environment was stabilized. Coolant was soluble oil emulsion, temperature was 25°C, and cutting parameters were generated by Box-Behnken and tap testing. According to the analysis of cutting parameters, the setup of machining details was designed. Based on clamping principle in **Figure 3**, 85x85x110 mm^3 AA2050 stock was clamped. The forces on stock were clearly rigid on both sides and, attachments between clamps and tower were created with pins and screws. Another experimental setup was computer aided manufacturing design. For this purpose, Siemens NX Cad/ Cam software was used to design clamps, stock, and parts and to write toolpath cam program data. After the stabilization and design of the experimental components, computer aided manufacturing was generated by using calculation optimum cutting parameters. In computer aided manufacturing operations; roughing, and finishing operations were used to analyze machining distortions on walls and floor on workpiece. According to the experimental design optimization results, at 10070 rpm spindle speed, 0.15 mm feed and radial depth of cut 1.5 mm were found. The biggest factor in obtaining these optimum parameter values was determined as the material removal rate of 9,063 mm^3 with a cutting speed of 371.65 $m.s^{-1}$ in 0.000993049 seconds. With these values, in the milling process, 230 N as normal force and 210 N as tangential force were found instantaneously on the workpiece. The deformation that will occur on the cutting tool changes depending on the instantaneous change of the cutting forces. It has a deformation range between -0.017 mm and 0.017 mm.

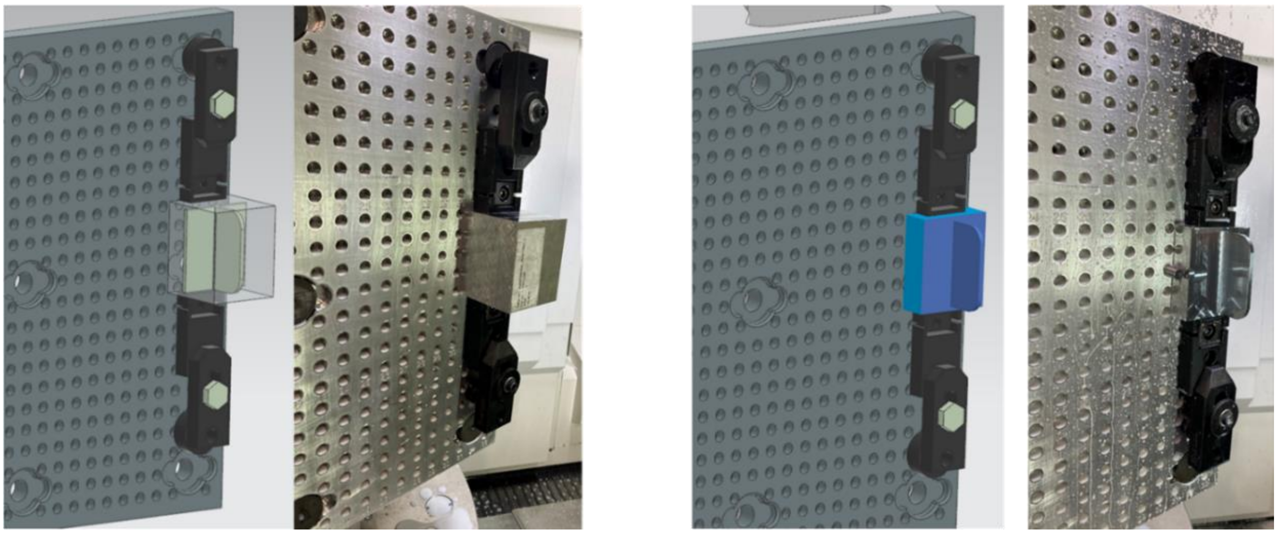

Figure 3 Clamping principle setup and machining view of AA2050

After machining operations of AA2050, distortion which depends on cutting parameters was calculated with coordinate measuring machine. Perpendicularity between thin wall and floor, flatness of wall and floor, parallelism of two sided walls were measured with sensitive probe tool. The maximum range of measuring distortion according to the geometrical criteria was measured in **Table 4**.

Table 4 Machining distortion analysis of AA2050 by using coordinate measuring machine

TYPE	+TOL (mm)	-TOL (mm)	MEASURE (mm)	OUTTOL (mm)
Perpendicularity ⊥	+0.01	-0.01	0.013	0.003
Flatness ▱	+0.01	-0.01	0.011	0.001
Parallelism //	+0.01	-0.01	0.012	0.002

5. CONCLUSION

In this study, the cutting parameters were obtained by tap test and arranged by Box-Behnken design of experimental method. The maximum out of tolerance 0,003 mm was observed in the geometrical dimensioning and tolerance analysis obtained as a result of the machining operations made with the relevant parameters. However, this value was within the tolerance ranges of the aerospace industry and it shows a successful optimization with cutting time. Very low values of distortion were obtained from the general tolerance range values used in the structural parts.

Al-Li-based alloys with high compressive strength and fracture toughness and resistance to torsion have become the center of attraction in aircraft structures. As mentioned, AA2050 will have popular use in the future aerospace industry, and it will require cutting parameters suitable for mass production. Optimization of cutting parameters for AA2050, which are aimed to be widely used in the aerospace industry, will contribute to the machining industry in the future.

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