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# Minimization of Warpage on Slender Prismatic Parts while Milling of Aluminum 2014-T651 by Inducing Thermal stress

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**Abstract. Minimization of warpage on slender prismatic parts while milling of Aluminum alloy 2014-T651 by inducing thermal stress is new approach. In the present work, warpage is studied on different thickness samples by sizing, carrying out heat treatment at different temperatures, and then milling operations. Thermal stress is induced due to restricted thermal expansion through heat treatment using fixture. In this experiment, Taguchi L16 ($4_4$) orthogonal array and Analysis of Variance (ANOVA) method are used for experiment selection and result analysis. Each experiment contains four control parameters i.e., raw material thickness, temperature, duration & final thickness. Sixteen experiments are performed by taking four levels for each control parameter and values of response parameters namely warpage, hardness and surface roughness are measured. In this approach, optimum values for main parameters are found which have influence on warpage, hardness and surface roughness. The confirmation of experimental results under optimal parametric conditions is provided to ensure improvement in quality characteristics of the process for maximum deviated thickness.**

***Keywords —Warpage, redistribution of stresses, residual stresses, Slender Prismatic parts, Taguchi, Thermal stress, Milling***

## I. INTRODUCTION

In the avionics industry, slender prismatic parts like heat sinks, supports, covers, chassis, etc., are made with wrought aluminum alloy 2014-T651 due to good machinability and conductivity. Slender parts or thin wall parts minimize the weight and thus increase the fuel efficiency of aircraft.

Warpage is bending or curving distortion from flatness of part characteristics by a roughly cylindrical or spherical curvature. Aluminum wrought blocks are quenched after the solution treatment, drastic cooling cause thermal gradient develops which results in residual stresses, these stresses are balanced by induce compressive stresses on sub surface and induce tensile stresses in surfaces [13], these initial residual stresses are redistribute and results in distort the slender prismatic parts [2], [7], [31], [28], [24], [15], while lot of material removing by machining, this distortion do not depend on the volume of material removed [4]. Warpage causes great economic loss in aeronautical industry, due to wastage of lead time and rejection of parts. Stresses redistributed after removal of half of the material removal [3], [21], lateral residual stresses effect is lesser than the longitudinal stress if the length is more than width [25], deformation is stable after 60% of material removal [21], 90% deformation is due to the initial residual stress and 10% of the deformation is due to induced machining stresses [38], thermal induced deformation is more than cutting force deflection [39], if the thickness 5-6 mm machining distortion is more and if the thickness above 10 mm initial residual stresses distortion [14]. Residual stresses are higher in feed direction compared with cutting direction [18], feed rate affects maximum residual stresses than cutting speed and depth of cut [20], [27], [36], and also residual stresses increases with flank wear [29], distortion increases with increase in machining asymmetry [10], distortion is more effect below 1.25 mm thickness parts [5] and also distortion increases with increase in cutter size [8].

Residual stresses can be reduced in the wrought products by polymer quench while solution treatment [16], stretching [6], [34], [26]. Residual stresses can be reduced at machining phase by reducing of depth of cut [22], [33], diamond coated tools using [9], [40], higher helix angle cutter selection [41] or 40-45° helix angle cutter selection [37], minimum number of flutes selection [42], using quasi symmetric machining [11] and using optimum cutter diameter [35]. Vibration stress relief improves the dimensional stability of Aluminum thin wall parts [23].

Heat treatment can be carried out at 260-440°C for aluminum alloys and stress relief & ageing can be carried out 175-205°C for 1-2 hours, and annealing at temperature of 345°C removes strain hardening [45]. Reheating process can carried out to reduce distortion upto 60% at 290°C for

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one hour on AA6061 [12]. Residual stresses can be minimized by uphill quenching on Aluminum alloys to produce high accuracy products [19], [43], [44]. Operators frequently flip the workpiece and hit & trial the cutting parameters in order to balance the warpage and stresses evenly on the two sides [30], this trial and error method causes wastage of production time and loss to the manufacturer.

Lot of researches have been gone on cutting parameters namely speed, depth of cut and feed, but different residual stresses are present in the wrought products, even if the same composition of raw material is heat treated [1], [17], so that controlling of distortion is difficult, even workshop personnel selected optimum cutting parameters while machining. Hence, initial residual stresses to be minimized before machining. In order to minimize the distortion, uphill quenching and stress relieving procedure can be used, but uphill quenching is required extensive fixtures [43], [44], skilled personnel and it is expensive so it is not suitable for small scale industries. Moreover, stress relieving parameters of AA2014 are not available in literature. Therefore, this research has been performed to minimize of warpage by inducing light compressive force with thermal stress in order to minimize the distortion on AA2014 slender parts.

The objective of the work is to find out the set of optimum values for selected control factors viz. raw material thickness, temperature, duration & final thickness are investigated at four different levels, in order to reduce warpage on AA2014-T651 using Taguchi's robust design methodology and ANOVA.

## II. EXPERIMENTAL SETUP AND DESIGN

In the experiment, following responses namely warpage, hardness and surface roughness are studied on different thickness samples, after sizing of parts, at room temperature and thermal stress applied by restricted thermal expansion with a fixture at different temperatures and final milling operation is carried out on samples to make slender prismatic parts. Taguchi method is used to finalize optimum set of experiments. Four controlling factors viz. raw material thickness, temperature, duration & final thickness are investigated at four different levels. Depth of cut, speed and feed are taken as constant parameters.

### A. Sample Material

The work piece material used is Aluminum alloy AA2014-T651. This alloy is widely used in avionics industry because of good machinability, electrical conductivity & thermal conductivity. Mechanical properties are mentioned in table 1[46].

**Table 1. Properties of Aluminum alloy 2014-T651**

| | |
|---|---|
| Hardness, Rockwell B | 80-86 HRB |
| Tensile Yield strength | 415 MPa |
| Modulus of Elasticity | 73 Gpa |
| Poissons ratio | 0.33 |
| Thermal conductivity | 155 W/m°c |
| Coefficient of thermal Expansion from 20 to 300°C | 24.4x x $10^{-6}$m/°K |

### B. Dimensions for Samples

Different thicknesses are selected (table 8) with 110 mm length and 50 mm width. Dimensional details of the final component are shown in figures 1 & 2.

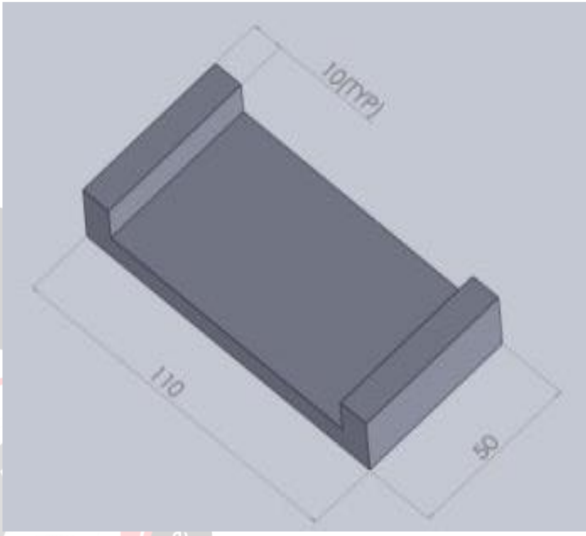


**Figure 1. Model of final component**
All dimensions are in mm

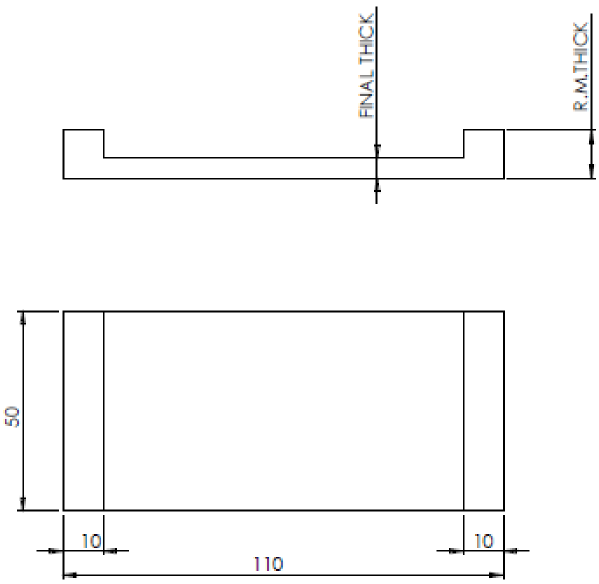


**Figure 2.Dimensions for samples**
All dimensions are in mm

### C. Heat treatment Setup

Sized blocks are kept in the fixture and heat treated in the forced air circulated furnace. Fixture material is Chromium hot work steel AISI H12 which has good resistance to heat


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softening, excellent wear resistance, high strength at elevated temperature, good toughness, low coefficient of thermal expansion and good thermal conductivity [32], [48]. Mechanical properties are mentioned in table 2 [48] and fixture assembly details are shown in figures 3 & 4.

**Table 2. Mechanical properties of Tool steel AISI H12**

| | |
|---|---|
| Hardness at room temp | 54 HRC |
| Hardness at 315°c | 49 HRC |
| Modulus of Elasticity | 207 GPa |
| Coefficient of linear thermal expansion 20-400°C | 12.1 x $10^{-6}$m/°K |
| Thermal conductivity | 18.9W/mK |

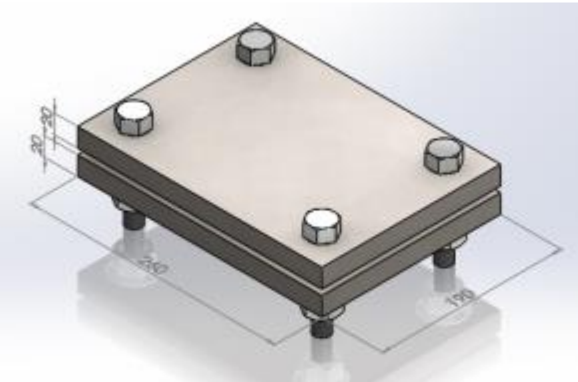

**Figure 3.Model of heat treatment fixture with AA2014-T651 samples**

All dimensions are in mm

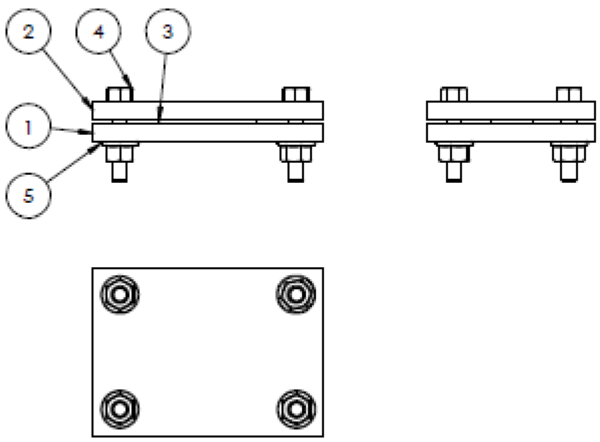


**Figure 4. 2D Drawing for heat treatment fixture**

Item-1 and Item -2: Plates (Material AISI H12)
Item-3: Aluminum sample which is sandwiched between plates by tightening of M16 Bolts and Nuts
Item-4: Bolts - 4 nos
Item-5: Nuts - 4 nos

### D. *Forced Air circulated Electric Furnace*

In the forced air circulated electric furnace, temperature uniformity distribute throughout the work space. Furnace specifications are mentioned in table 3. Samples are kept in forced air circulated electric furnace shown in figure 5, with different durations for various experiments mentioned in table 8.

**Table 3. Specifications of Air Circulated electric furnace**

| | |
|---|---|
| Max. temp | 700°C |
| Furnace Dimns | Ø600 x 650 mm |
| Accuracy | ±5°C |
| Power rating | 36 KW |

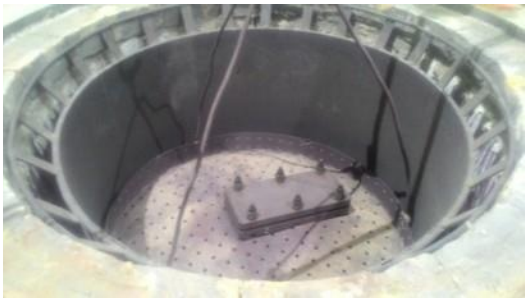

**Figure 5.Air circulated electric furnace with component and fixture at open condition.**

### E. *Vertical CNC milling M/c*

The milling operations are carried out on a CNC vertical milling machine shown in figure 6 and specifications are mentioned in table 4. Samples are hold in vice with supports, shown in figure 7. Milling operation is carried out on samples with constant cutting parameters 3000 RPM, depth of cut 0.25 mm and feed 1000 mm/min using Ø12 mm solid carbide slot drill.


**Figure 6. VR3A CNC Vertical Milling M/C**

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**Figure 7.Work piece in the vice with supports.**

**Table 4. Specification of Vertical CNC Milling M/C**

| Model | VR3A SPEC |
|---|---|
| X Travel | 700 mm |
| Y Travel | 450 mm |
| Z Travel | 450 mm |
| Positional accuracy | ±0.05 |
| Repeatability | ±0.05 |
| Control system | FANUC 6M-B |
| Spindle Motor power | 5.5 KW |

*F. Surface Roughness Tester*

Skid type surface roughness tester is used. A diamond stylus is traversed across the sample and a piezoelectric pickup records all vertical movement. Peaks and valleys are recorded and converted into a known value of a given parameter. Surface roughness (Ra) is measured by MITUTOYO SJ210P surface tester which is shown figure 8, and it cut off length is 0.8mm.

**Figure 8. MITUTOYO SJ210P surface tester measuring**

*G. Hardness Measurement*

Hardness testing is carried on FIE RASNE Hardness tester with HRB scale on samples, shown in figure 9. For HRB scale measurement, 1⁄16-inch-diameter (1.588 mm) steel sphere is used and 100 kgf of load is applied.

**Figure 9. FIE RASNE Hardness tester**

*H. Warpage Measurement*

Warpage is the combination of bow and twist. Bow is measured on the part which is placed on the surface plate with convex facing upwards as shown in figure 10. For each edge, sufficient pressure is applied on both corners of the same sample edge to ensure contact with the surface. Go/No-Go feeler/pin gauge is slide between the sample and the surface plate [47]. Maximum value of bow and twist is taken for measurement.

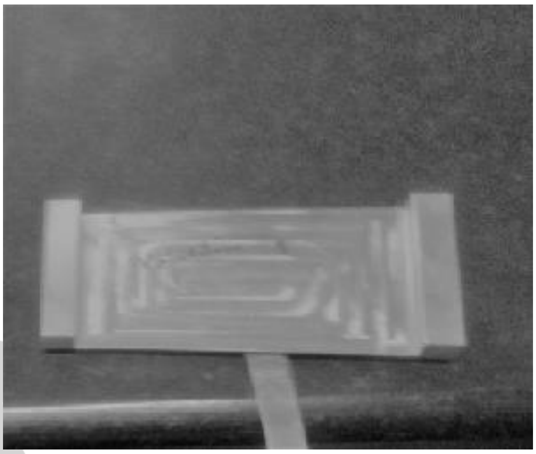

**Figure 10. Bow measuring with feeler gauge**

**Figure 11. Twist measuring with feeler gauge**

Twist is measured with Go/No-Go feeler gauge by sliding under the corner not touching the surface plate and without lifting remaining three corners of the sample from the surface plate [47] as shown figure 11.

## III. DESIGN OF EXPERIMENTS

*A. Selection of Control factors and Levels*

A total of four process parameters are chosen as the control factors with four levels for each parameter such that levels are cover parameter range. The process parameter and their ranges are finalized using literature [45] and experience. The four control factors selected are raw material thickness, temperature, duration & final thickness. Aluminum alloy 2014-T651 work pieces are used in experimentation. The machining is performed individually depending upon the heat treatment conditions. The control levels are listed in table 5.


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**Table 5. Control Factors and Levels**

| Factors /Levels | R.M.Thick mm (A) | Temp°C (B) | Duration hr (C) | Final thick mm (D) |
|---|---|---|---|---|
| 1 | 6 | 26 | 1 | 1 |
| 2 | 8 | 260 | 2 | 2 |
| 3 | 13 | 300 | 3 | 3 |
| 4 | 18.5 | 340 | 4 | 4 |

*B. Experimental Designs*

Orthogonal array L16($4_4$) is generated for 4 control factors and 4 levels using Minitab-17 statistical software. Experiment numbers allotted are shown in the figure 12 and finished samples are shown in the figure 13. Experimental design table is shown in table 6.

**Table 6. L16 ($4_4$) Orthogonal Array with control factors**

| Exp. No | Column | | | |
|---|---|---|---|---|
| | A | B | C | D |
| 1 | 6 | 26 | 1 | 1 |
| 2 | 6 | 260 | 2 | 2 |
| 3 | 6 | 300 | 3 | 3 |
| 4 | 6 | 340 | 4 | 4 |
| 5 | 8 | 26 | 2 | 3 |
| 6 | 8 | 260 | 1 | 4 |
| 7 | 8 | 300 | 4 | 1 |
| 8 | 8 | 340 | 3 | 2 |
| 9 | 13 | 26 | 3 | 4 |
| 10 | 13 | 260 | 4 | 3 |
| 11 | 13 | 300 | 1 | 2 |
| 12 | 13 | 340 | 2 | 1 |
| 13 | 18.5 | 26 | 4 | 2 |
| 14 | 18.5 | 260 | 3 | 1 |
| 15 | 18.5 | 300 | 2 | 4 |
| 16 | 18.5 | 340 | 1 | 3 |

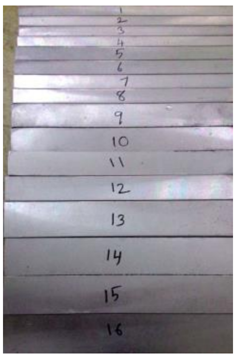


**Figure 12. Alloted experiment nos on the samples.**

**Figure 13. Finished samples.**

*C. Plan of Experiments*

The scope and objective of the present work have already been mentioned in the forgoing cases. Accordingly, the present study has been done through the following plan of experiment.

1) Selected different thickness raw material of AA2014-T651.
2) Sizing operation carried out by Band saw and Conventional Vertical milling machine to maintain dimn. Length and width 50.0 x 110.0 mm.
3) Skin cut operation carried out on the thickness surface 0.25 mm on each side to maintain flatness.
4) Initial load is applied on sample surface area 50 x 110 mm by using fixture and kept in forced air circulated furnace at respective temperature and duration depending on the experimental design.
5) CNC vertical milling machine is selected for performing milling operation.
6) Cutting parameters speed, feed, and depth cut are selected by literature study and preliminary experiments.
7) Selection of appropriate tool depending upon the cutting parameters i.e. speed, feed, depth of cut and cutter diameter and coolant flow are kept constant in the experiment.
8) Performed milling operation, with slot drill, maintaining final thickness depending upon the experimental design.
9) Warpage is measured with feeler guage on the surface table.
10) Hardness is measured using Hardness tester with HRB scale.
11) Surface roughness Ra is measured with the help of a portable stylus-type Profilometer.

## IV. RESULTS AND DISCUSSIONS

Aluminum alloy 2014-T651 blocks of dimensions 50 x 110 mm are used for conducting experiment. Using different levels of the parameters the samples have been machined accordingly, depending on the raw material thickness, temperature with restricted thermal expansion, duration and final thickness. Then warpage (bow and twist) is measured with the help of feeler gauge on the surface table, hardness is measured with Hardness tester with HRB scale and then surface roughness is measured precisely with

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the help of a portable stylus-type Profilometer. The results of the experiments are shown in table 7 and its S/N ratios are shown in table 8.

**Table 7.Experimental data responses related to warpage, hardness and surface roughness**

| Exp. no. | Warpage (X) | Hardness (HRB) | Surface Roughness (Ra) |
|---|---|---|---|
| 1 | 2.02 | 85 | 2.227 |
| 2 | 0.45 | 63.2 | 2.2 |
| 3 | 0.15 | 46.2 | 1.938 |
| 4 | 0.2 | 14.9 | 1.681 |
| 5 | 0.06 | 78.9 | 2.212 |
| 6 | 0.2 | 69.6 | 1.355 |
| 7 | 0.1 | 3.9 | 1.664 |
| 8 | 0.35 | 9 | 1.681 |
| 9 | 0.07 | 82 | 2.36 |
| 10 | 0.08 | 47.7 | 2.836 |
| 11 | 0.45 | 64.3 | 4.747 |
| 12 | 0.5 | 10.6 | 4.09 |
| 13 | 0.15 | 82.4 | 4.163 |
| 14 | 0.35 | 50.2 | 2.129 |
| 15 | 0.14 | 29.7 | 4.259 |
| 16 | 0.18 | 31.2 | 3.495 |

**Table 8.Experimental data related S/N ratios of warpage, hardness and surface roughness**

| Exp.no. | S/N X | S/N HRB | S/N Ra |
|---|---|---|---|
| 1 | -6.1070 | 38.5884 | -6.95440 |
| 2 | 6.9357 | 36.0143 | -6.84845 |
| 3 | 16.4782 | 33.2928 | -5.74708 |
| 4 | 13.9794 | 23.4637 | -4.50877 |
| 5 | 24.4370 | 37.9415 | -6.89570 |
| 6 | 13.9794 | 36.8522 | -2.63879 |
| 7 | 20.0000 | 11.8213 | -4.42307 |
| 8 | 9.1186 | 19.0849 | -4.51135 |
| 9 | 23.0980 | 38.2763 | -7.45824 |
| 10 | 21.9382 | 33.5704 | -9.05412 |
| 11 | 6.9357 | 36.1642 | -13.5284 |
| 12 | 6.0206 | 20.5061 | -12.2345 |
| 13 | 16.4782 | 38.3185 | -12.3881 |
| 14 | 9.1186 | 34.0141 | -6.56351 |
| 15 | 17.0774 | 29.4551 | -12.5862 |
| 16 | 14.8945 | 29.8831 | -10.8689 |

S/N ratios are shown in figure 14 (warpage), Figure 15(hardness) & figure 16 (surface roughness). ANOVA are given in table 9 (warpage), table 10 (hardness) & table 11(surface roughness).

In the present study, Design of experiments (DOE), plots and analysis have been carried out using Minitab-17 statistical software.

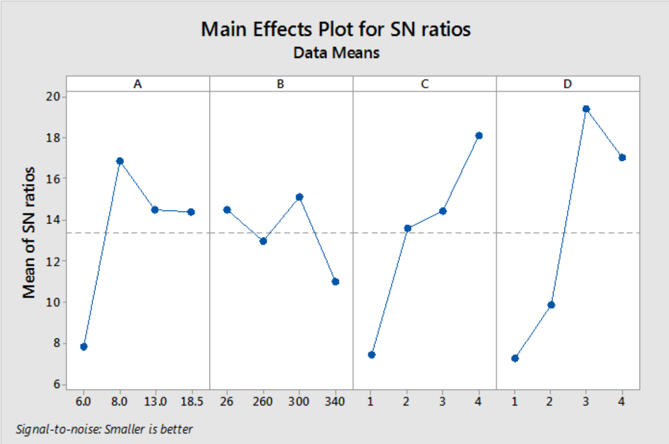


**Figure 14. S/N ratio plot for Warpage vs A, B, C, D**

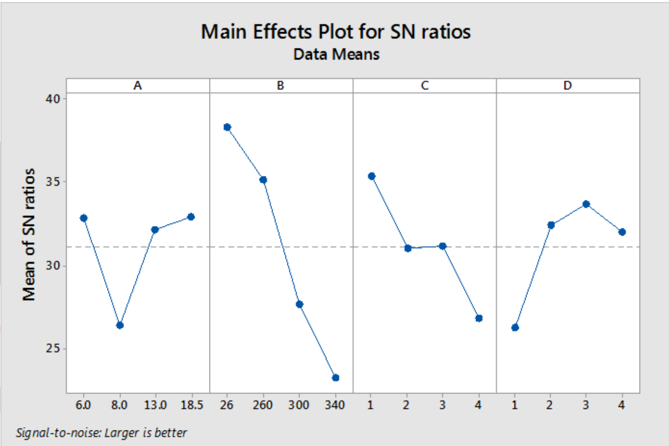


**Figure 15. S/N ratio plot for Hardness vs A, B, C, D**

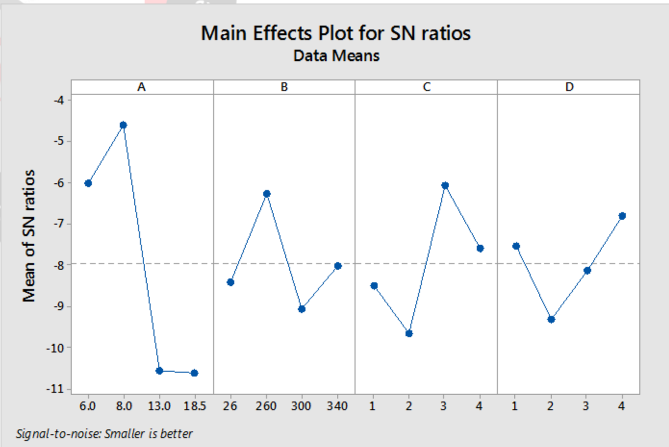


**Figure 16. S/N ratio plot for Roughness vs A, B, C, D**

**Table 9.Analysis of variance for Warpage**

| Factor | DF | ADJ SS | ADJ MS | F-value | Contri-bution% |
|---|---|---|---|---|---|
| A | 3 | 0.7283 | 0.2428 | 1.42 | 25.818 |
| B | 3 | 0.3123 | 0.1041 | 0.61 | 11.09 |
| C | 3 | 0.7867 | 0.2622 | 1.54 | 28.0 |
| D | 3 | 0.9871 | 0.329 | 1.93 | 35.09 |
| Error | 3 | 0.5115 | 0.1705 | | |
| Total | 15 | 3.3259 | | | |


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**Table 10. Analysis of Variance for Hardness**

| Factor | DF | ADJ SS | ADJ MS | F-value | Contri-bution% |
|---|---|---|---|---|---|
| A | 3 | 349.1 | 116.38 | 1.26 | 2.92 |
| B | 3 | 9580.3 | 3193.44 | 34.55 | 80.274 |
| C | 3 | 1336.6 | 445.53 | 4.82 | 11.198 |
| D | 3 | 668.6 | 222.86 | 2.41 | 5.599 |
| Error | 3 | 277.3 | 92.42 | | |
| Total | 15 | 12211.9 | | | |

**Table 11.Analysis of Variance for Roughness**

| Factor | DF | ADJ SS | ADJ MS | F-value | Contri-bution% |
|---|---|---|---|---|---|
| A | 3 | 10.9215 | 3.6405 | 0.013 | 3.475936 |
| B | 3 | 2.1271 | 0.709 | 0.114 | 30.48128 |
| C | 3 | 3.0857 | 1.0286 | 0.072 | 19.25134 |
| D | 3 | 1.4619 | 0.4873 | 0.175 | 46.79144 |
| Error | 3 | 0.4401 | 0.1467 | | |
| Total | 15 | 18.0362 | | | |

### *A. Effect of Parameters*

Effects of parameters are discussed by studying of figures of S/N ratios & tables of ANOVA

1) From table 9, final thickness, heat treatment duration and raw material thickness contributions in warpage are 35.09%, 28% and 25.8% respectively. Hence final thickness is the major contributor, which is directly proportional to the redistribution of residual stresses.
2) From table 7, Warpage of 2.02 mm is observed for 6.0 mm prismatic slender parts at room temperature (26°C), even after maintaining depth of cut at minimum. Warpage is more due to initial residual stresses in 6.0 mm wrought products.
3) From table 7, maximum warpage is 0.15 mm only for 8.0mm and more than 8.0 mm thick parts at room temperature, because warpage is less due to initial residual stresses are very low in that wrought products.
4) From figure 14, Warpage is minimum at 300°C. Hence, maximum stress relieving is occurred at this temperature.
5) From figure 15, Hardness is decreased with increase in temperature and duration, because material is overaged at higher temperatures and softens the material.
6) From table 10, Temperature has main influence on hardness. Its contribution is 80.27%.
7) From figure 16, Surface roughness is less at a temperature 260°C, because intermetallic alloys are precipitate and minimum stress relieving at this temperature, and also surface roughness indirectly proportional to the final thickness. Surface roughness is increase at lower thickness due to chattering and induced stresses domination.
8) From table 11, Final thickness has significant influence on surface roughness. Its contribution is 46.79%. Because, chattering and induced stresses are less at higher thickness wall parts and vice versa.

### *B. Confirmation test*

The effect of control parameters on warpage, hardness and surface roughness is studied using ANOVA. The control parameters corresponding to combination set “A1B3C1D1” is found to be solution for optimum response parameters.

Confirmation test has been carried out by taking the combination A1B3C1D1 i.e. 6.0 mm thick raw material, temperature of 300°C for one hour duration and 1 mm final thickness. Results are mentioned in the table 12.

**Table 12.Table showing results of Confirmation Test**

| | Initial cutting parameter | Optimal condition | |
|---|---|---|---|
| | | Prediction | Experiment |
| Factor combinations | A1B1C1D1 | A1B3C1D1 | A1B3C1D1 |
| Warpage, mm | 2.02 | 1.348 | 0.31 |
| Hardness,HRB | 85 | 44.15 | 67 |
| Surface roughness, Ra | 2.22 | 2.577 | 0.37 |

Regression equations for responses with respect to the controlling parameters:

$$X = 1.836 - 0.0265\ A - 0.001054\ B - 0.1797\ C - 0.2002\ D$$

$$HRB = 95.6 + 0.197\ A - 0.1792\ B - 7.01\ C + 3.57\ D$$

$$Ra = 1.738 + 0.1503\ A + 0.00017\ B - 0.227\ C - 0.092\ D$$

- Warpage value is reduced by 6.51 times of the initial value by reducing of 1.26 times of hardness. However, hardness values increased to 71HRB after one month due to age hardening.
- Surface roughness value is reduced by 6 times of the initial value.

## V. Conclusion

By the analysis of the experimental results of S/N ratio, ANOVA analysis and confirmation test, the following conclusions can be drawn:

1) Warpage is minimized in slender prismatic parts by subjecting them to thermal stress at the temperature of 300°C for one hour.
2) Warpage of slender prismatic parts is reduced up to 6.51 times by inducing of thermal stress.
3) Surface roughness is reduced up to 6 times by inducing thermal stress.

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4) The proposed method of studying the effect of thermal stresses on warpage for various materials is useful in improving the process sequence and also reducing warpage by inducing the thermal stresses with respect to required final thickness through respective heat treatment and materials.

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