Multiscale Analysis of Surface Topography from Single Point Incremental Forming using an Acetal Tool

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Abstract. Single point incremental forming (SPIF) is a sheet metal manufacturing process that forms a part by incrementally applying point loads to the material to achieve the desired deformations and final part geometry. This paper investigates the differences in surface topography between a carbide tool and an acetal-tipped tool. Area-scale analysis is performed on the confocal areal surface measurements per ASME B46. The objective of this paper is to determine at which scales surfaces formed by two different tool materials can be differentiated. It is found that the surfaces in contact with the acetal forming tool have greater relative areas at all scales greater than 5 x 10⁴ µm² than the surfaces in contact with the carbide tools. The surfaces not in contact with the tools during forming, also referred to as the free surface, are unaffected by the tool material.

1. Introduction

This paper presents information on a new forming tool that has a forming tip made from an acetal resin. Parts are formed with this new tool and a more commonly used carbide tool. The surfaces of the parts are then measured and analyzed using area-scale analysis. This paper compares the scales at which the surfaces produced by the acetal tool are different from the surfaces created by the carbide tool.

Single point incremental forming (SPIF) uses a forming tool that is in contact with one side of a material, the forming tool moves relative to the sheet metal in order to form the part [1]. A die is not required on the other side of the material; this surface is referred to as the free surface. SPIF has the potential to bring complex sheet metal parts to market, without the need for forming dies. An important step in the advancement of SPIF to a stage where the process can be widely used in industry is the development of good surface quality during manufacturing. The main shortcoming of surface quality in SPIF is the greater roughness. The mean values of average roughness (Ra) reported have typically been in the range of 4-12µm [2], while more traditional forming processes have produced surfaces with mean Ra 0.8-3µm [3].

Much of the previous study on surface topography in SPIF has discussed the topography that is easy to visually observe [4-9]. Previous work has focused on ridges created in the part from the toolpath and tool geometry as the tool steps down into the part (step down ridges). These ridges provide discernible surface topography. Generally, the toolpath is described in terms of step down and forming angle. The most common tool geometry is a hemispherically tipped cylinder. The literature on SPIF toolpaths refers to the amount the tool “steps” into the material during each spiral of the toolpath;
commonly described as the step down [10]. The step down is the most frequently studied SPIF process variable in relation to surface topography.

The side of the sheet metal that does not contact the tool during forming is referred to as the free surface [11]. The surface topography of the free surface has seldom been studied in SPIF. The roughening of the free surface during forming is referred to as “orange peel”. This roughness is generally described as occurring on the scale of grain size and occurs with movement of grains relative to the surface [12]. Although other work has found the mean length of the roughness to be ten times as long as the grain size [11], high-speed compression testing with the tool contacting one side of the sheet metal, found that roughness increases with increasing strain when the grain size is constant [11]. The mode of deformation and the grain size have also been shown to affect this roughness [11]. In SPIF, it was found that the tool’s feed direction (or toolpath) can sometimes be seen on the back side of the part [6]; implying that the tool diameter and step down might influence the surface topography of the free surface.

Area-scale fractal analysis can be used to calculate fractal parameters described in ASME B46.1 [13] or to search for differences [14] or correlations [15] between surfaces as a function of scale. Area-scale fractal analysis first virtually tiles the surface with triangular tiles. The area of each tile is the scale. Then relative area is calculated by taking the sum of the area of all of the tiles and dividing that sum by the nominal area. The relative area is calculated at a series of scales and can be plotted and analyzed at each scale.

F-tests have previously been used as a function of scale to determine at which scales the relative area of two surfaces are significantly different [14]. Area-scale analysis has also been used to find the scale with the greatest correlation [15]. Scale-base correlation has also been established by filtering with a shifting band-passed filter before calculating roughness parameters to test for correlation [16]. A Mann-Whitney U-test has been previously employed to determine if the relative length of groups of surfaces are significantly different as a function of scale [17]. The advantage of this approach was that it did not assume that the relative length at each scale was normally distributed. The Mann-Whitney U-Test is more robust due to not having a required distribution of data, such as a normal distribution.

Non-parametric statistics are statistical techniques that do not rely on the data belonging to any particular distribution. Non-parametric statistics are typically used when either a data set is shown to be non-normal or the distribution of the data set is not known. Two of the non-parametric tests of interest in this study are the Kruskal-Wallis test, which is similar to a one-way ANOVA, and the Mann-Whitney U-test, which is analogous to a t-test [18]. The Kruskal-Wallis test is used to see if samples originated from the larger sample or population. The Kruskal-Wallis test only determines whether all the samples belong to the population or if at least one does not. It cannot determine which sample does not belong. The Kruskal-Wallis test is a ranked sum test, if the rankings have no order then they all belong to the same large sample. A post-hoc test, after the Kruskal-Wallis test, is needed to determine which samples do not belong. A typical post-hoc test is the Mann-Whitney U-test. The Mann-Whitney U-test compares two samples and determines if they are both part of a larger sample or population. This is done through ranking the sums and determining whether they are lumped or segregated.

The objective of this paper is to determine a) at which scales the contact and free surfaces formed by two different tool materials can be differentiated and b) to gain insight into the mechanisms that form these surface.

2. Methods
The methodology in this work consists of the forming methods used to create the SPIF test pieces, with either the acetal or carbide tool, and the techniques used to characterize the topography of the formed surfaces. SPIF methods are discussed first.

The sheet material used in these experiments is AA 3003-O 1.6 mm thick. AA3003-O has previously been investigated in SPIF studies due to its high formability [1]. The mechanical properties of AA3003-O include: ultimate tensile strength (UTS) = 110MPa, yield strength (YS) = 40MPa, and
Brinell hardness number (BHN) = 28 and n = 0.242 [19]. The mean grain size of the AA3003-O prior to SPIF was previously found to be 25µm; however, not all of the grains are equiaxial [20].

Figure 1 shows the fixture and backing plates utilized to hold the sheet metal during forming. A continuous spiral toolpath is generated using the computer aided manufacturing (CAM) software Esprit®. A step down of 0.13 mm is used, with a spindle speed of 600 RPM and a feed rate of 9 m/min. This toolpath is shown in figure 1.

A Haas VM3 vertical machining center is used to form truncated pyramids of 76 mm by 76 mm, with a depth of 25 mm and a forming angle of 60-degrees. The truncated pyramid is shown in figure 2. The truncated pyramid shape was selected for this study due to the relatively flat sides of the pyramid and because the optical instrument used for measurements has a short working distance. Thus, the relatively flat specimens can be cut from the sides of the pyramids to facilitate measurement.

All of the specimens are created using one of two 12.5 mm diameter tools to form parts. One tool is a conventional carbide tool and the other new acetal-tipped tool. Figure 3 depicts the two different forming tools. The carbide tool is a solid carbide tool with a ground hemispherical tip. The carbide tool requires lubrication, during forming. In these experiments, the lubrication used is petroleum-based wax. The acetal-tipped tool consists of an acetal tip that is press fit into a steel shank. The acetal resin utilized is DuPont™ Delrin® AF 100, consisting of Teflon™ fibers uniformly dispersed throughout the acetal resin. This acetal resin is selected due to its low friction, wear characteristics, and because it is self-lubricating; thus, it doesn’t require additional lubrication.

Optical surfaces [21] are acquired from each side (contact and free surface) of the eight formed parts (four parts formed with the acetal tool, and four parts formed with the carbide tool). A vertical scanning laser confocal microscope with a 408 nm violet laser light is used for the surface measurements, specifically an Olympus LEXT OLS4000. For all specimens, the microscope is used with a 50X objective with a numerical aperture of 0.95 and a 250 nm sampling interval, nine overlapping surface measurements, each with a measurement region of 250 µm x 250 µm, are stitched together to form a single surface optical surface. For each optical surface, relative area is calculated at a series of approximately 2800 scales, based on the standards ASME B46.1 [13], using the Sfrax software. Each surface is grouped according to the tool used to produce the part and the specific side of the part (contact or free surface). The statistical analysis is used to prove whether or not the differences in relative area at each scale are significant.

The statistical analysis starts with a Kruskal-Wallis test and, if needed, a post-hoc Mann-Whitney U-test is completed. This is done at each scale. The Kruskal-Wallis compares multiple (more than two) groups of relative areas at a scale to determine if they are not independent. The first step in the test is to rank all of the data from smallest relative area to largest relative area, independent of the scale it is from. The next step in the test is to set the hypothesis that states all ranks from all scales are the same; the alternate hypothesis states not all ranks are the same. The ranks are then tested with the Kruskal-Wallis test statistic, equation 1. A p-value (probability of obtaining a test statistic) is obtained. This is the lowest α value at which a scale is determined to be independent. If the p-value is less than
the selected $\alpha$ (typically $\alpha = 0.05$), then an ad-hoc test is needed to determine which scales are different. As a post-hoc test, the Mann-Whitney U-test is performed multiple times, one time for each pair of scales that needs to be tested or each pair that are to be compared.

$$H = \frac{12}{N(N+1)} \sum_{i=1}^{k} \frac{R_i^2}{n_i} - 3(N + 1)$$  \(1\)

The Mann-Whitney U-test is a rank sum test used to compare two sets of relative areas at one scale. This is done by ranking the data in the two set of relatives areas independently of the set from which it originated. The next step in the test is to create a hypothesis that states that the ranks from the two sets of relative areas are the same; the alternate hypothesis states that the ranks are not the same. The ranks are then tested with the Mann-Whitney test statistic, equation 2. A p-value (probability of obtaining a test statistic) is obtained. This is the lowest $\alpha$ value at which a sample is determined to be different from the larger set of relative areas. If the p-value is less than the selected $\alpha$ (typically $\alpha = 0.05$), then the sample is determined to be different.

$$U = n_1n_2 + \frac{n_1(n_1 + 1)}{2} - \sum R_i$$  \(2\)

3. Results

Figure 4 shows parts formed by a) the acetal tool and b) the carbide tool. Figure 4 shows images of the side that has the forming tool in contact with the material. The acetal tool in contact with the material produces a more matte appearance than that produced by the carbide tool. The direction of the lay is in-line with the original roll marks of the sheet metal for the parts formed with the acetal tool. The roll marks refer to the surface topography created from cold rolling of the sheet. The lay on the parts formed with the carbide tool follows the toolpath.

Two variables (tool material and tool and surface interaction) are changed in order to create four groups of surfaces. The tool material is either acetal or carbide. The tool and surface interaction is “contact” if the tool is in contact with the surface during forming or “free” if the tool is on the other side of the sheet metal during forming. This creates four groups of surfaces referred to the tables and figures as AC for acetal contact, AF for acetal free, CC for carbide contact and CF for carbide free.
Figure 5 shows the height maps of the free surfaces of the parts that are formed by both the carbide and acetal tools. The middle color scale bar is for both the AC and CC height maps and the right color scale bar is for the AF and CF height maps. There is sometimes an apparent texture in the roll mark direction, and the scale bar indicates a much greater roughness than that on the contact surfaces.

Figure 6 is the log-log plot of relative area vs. scale to the relative area for the tool materials and tool-and surface interaction. The four groups resulting from the combinations of the two tool materials and two types of tool-surface contact: carbide tool in contact with surface, carbide tool and free surface (not in contact with tool), acetal tool in contact with surface, acetal tool and free surface (not in contact with tool). Figure 7 is a relative area vs. scale plot for the scales of 0.01 to 1 μm². Since this study is an investigation to understand the surface differences created by: a) the different tool materials and b) whether the tool is in contact with the forming surface, it is important to compare the results of the combinations.

The resulting relative areas for the scale of 0.03125 μm² are provided in table 1(a) for each of the groups. The relative areas of this scale are provided as a detailed example of the analysis done on figure 6 for interpretation of the results of the groups. The hypothesis to test is that all of the median ranks of relative areas for the four combinations of tool materials and contacts are systematically the same, as shown in equation 3. The alternative hypothesis is that there is a tendency for the relative areas to rank systematically higher or lower for at least one of the combinations when compared to the other combinations, as shown in equation 4. The relative areas in table 1(a) are ranked in table 1(b), irrelevant of the group it comes from.

\[
\text{Ho: } \theta_{AC} = \theta_{AF} = \theta_{CC} = \theta_{CF} \quad (3)
\]

\[
\text{Ha: At least one } \theta_j \text{ is different} \quad (4)
\]
Table 1. Relative areas for a scale of 0.03125 μm² (a) all groups, (b) all groups ranked, (c) ranks for acetal groups (AC and AF).

(a) | Relative Area |
---|---|
AC | 1.111 | AF | 1.139 | CC | 1.035 | CF | 1.300 |
1.136 | 1.167 | 1.061 | 1.173 |
1.093 | 1.140 | 1.034 | 1.190 |
1.117 | 1.135 | 1.072 | 1.221 |

(b) | Relative Area | Rank | Group |
---|---|---|---|
1.034 | 1 | CC |
1.035 | 2 | CC |
1.061 | 3 | CC |
1.071 | 4 | CC |
1.093 | 5 | AC |
1.111 | 6 | AC |
1.117 | 7 | AC |
1.135 | 8 | AF |
1.136 | 9 | AC |
1.139 | 10 | AF |
1.140 | 11 | AF |
1.167 | 12 | AF |
1.173 | 13 | CF |
1.190 | 14 | CF |
1.221 | 15 | CF |
1.301 | 16 | CF |

Visual inspection of table 1(b), shows that the ranks are not in random order. This needs to be verified by calculating the Kruskal-Wallis H statistic and comparing this to the H critical statistic. The H_test = 13.79 and the H_crit = 7.65, with an α = 0.05 and df = 3. The α value of 0.01 is chosen since a high level of confidence is desired in determining that the relative areas are the same or not. As the H_test > H_crit, the null hypothesis is rejected, which suggests a significant difference in the medians of the relative areas. A post-hoc test is needed to determine which of the groups are different.

The Mann-Whitney U-test is used as the post-hoc test. The Mann-Whitney U-test is another rank sum test, but this time only two groups are compared at once. There are six relevant comparisons to consider: AC-AF, CC-CF, AF-CF, AC-CC, AF+CF-CC, AF+CF-AC. Table 1(c), shows the relative areas for all of the surfaces, using an acetal tool. Table 1(c) is used to demonstrate the Mann-Whitney U-test; the other Mann Whitney U-tests are shown in table 2.

Visual inspection of table 1(c) shows that the ranks are not random order. Calculation of the Mann-Whitney U-test is needed to determine if the absence of randomness is statistically significant, in order to determine that the two groups are different. This is done by calculating the U statistic for each of AC and AF.

\[
U_{AC} = 4(4) + \frac{4(4 + 1)}{2} - \sum 1 + 2 + 3 + 5 = 15
\]
\[
U_{AF} = 4(4) + \frac{4(4 + 1)}{2} - \sum 4 + 6 + 7 + 8 = 1
\]

The result of this calculation is U_test = 1 and U_crit = 0 at α = 0.05 or α/2 = 0.025 for n_1=4 and n_2=4. As the U_test ≥ U_crit, then the null hypothesis is not rejected, this suggests that there is no real difference in the medians of the relative areas. The test statistics can also be evaluated using software and the p-value is calculated. The p-value is the probability of calculating a test statistic that is at least the value of the critical value if the null hypothesis is true. If the p-value is less than your alpha, you reject the null hypothesis. For the above example, the p-value was calculated as 0.06. This p-value is greater than the chosen alpha (α = 0.05), as 0.06 > 0.05 then the null hypothesis is not rejected. Table 2 shows p-values of the Mann Whitney U-tests for all the groups at a scale of 0.03125 μm².
Table 2. Mann-Whitney U-test results at a scale of 0.03125 μm²

| Group | Comparative Groups | p-value |
|-------|--------------------|---------|
| Acetal | AC-AF             | 0.0606  |
| Carbide | CC-CF            | 0.0304  |
| Free   | AF-CF             | 0.0304  |
| Contact| AC-CC             | 0.0304  |
| free-CC|                 | 0.0085  |
| free-AC|                 | 0.0138  |

Comparing the results from the Mann-Whitney U-test to the plot in figure 7, it is noted that one of the AC relative areas is mixed in with the AF relative areas. From the Mann-Whitney U-test, it is known that this test comparison resulted in p-values greater than 0.05, with a chosen α = 0.05 and thus the null hypothesis is rejected. In other words, when the ranks of the relative area of one group is not greater than the other, it is not possible to determine at an α = 0.05 that the comparators are different. For the cases in figure 7, where the ranges of the relative area for each group do not overlap (CC to CF, AF to CF, AC to CC, free surface to CC and free surface to AC), it is found that at an α = 0.05, it is possible to determine that these surfaces are different.

Table 3 shows comparisons of different groups in figure 6 to demonstrate which groups are visually evident as distinct, or to show that there is no overlap of points. The plot of relative area vs. scale (figure 6) is a common method of interpreting area-scale results. The results from table 3 demonstrate that the free surface and the contact surface are always distinguishable from each other.

Table 3. Graphical Determination of Comparisons (groups are differentiable - ✓, groups are not differentiable - X)

| Scale  | Individual | Contact vs Free | CF vs. AF | CC vs. AC |
|--------|------------|-----------------|-----------|-----------|
| 10⁻² - 10⁻¹ | X          | ✓               | ✓         | ✓         |
| 10⁻¹ - 10⁰  | ✓*         | ✓               | ✓*        | ✓         |
| 10⁰ - 10¹   | X          | ✓               | X         | ✓         |
| 10¹ - 10²   | X          | ✓               | X         | ✓         |
| 10² - 10³   | X          | ✓               | X         | ✓         |
| 10³ - 10⁴   | X          | ✓               | X         | ✓         |
| 10⁴ - 10⁵   | X          | ✓               | X         | ✓         |
| > 10⁵       | X          | ✓               | X         | X         |

Note: * at all scales within range but 0.781μm².

At most scales, it is not possible to distinguish the acetal tool from the carbide tool, except at the 0.1 – 0.5 μm² scales. On the contact side, the surface formed by the acetal tool has a greater relative area than the surfaces formed by the carbide tool at all scales less than 5 x 10⁴ μm. All of the individual groups could be distinguished from each other only at the 0.1 – 0.5 μm² scales. These are also the only scales at which the relative areas of the free surfaces (AF and CF) can be distinguished.

4. Discussion
The non-parametric statistical methods have been applied to enable significance testing as a function of scale. With only four measurement regions considered for each group, any overlap between relative areas in a group implies that the scale differences in relative area between the two groups is not
significant. While no overlap, implies that the differences between the two groups are significant. The effect of tool material is significant in free surfaces are only different at scales range from 0.1-0.5 µm² but is significant in the contact surfaces at all scales greater than 5 x 10⁴ µm².

This method has shown that the topography of the free surfaces are at minimum, mostly independently of the material of the tool that forms them. That the tool material has no effect on the surface topography of the free surfaces makes sense, as the step down in this work is smaller than the previous study where the bulge of the tool part was evident on the free surface [6]. The surfaces from these two groups are essentially the same in appearance and relative area. When this information is considered collectively, it appears that the surface topography of the free surface is independent of the material of the forming tool.

The carbide tool appears to be burnishing (smearing the surface texture) and creating a pattern of burnished tool marks (consists of ridges and valleys aligned with toolpath). The acetal surface does not form the distinctive pattern of ridges that is typical of most SPIF parts, including the carbide contact surfaces in this study. The result of this apparent absence of burnishing is a greater roughness and an increased relative area at scales greater than 5 x 10⁴ µm². The acetal tool either does not burnish the surface or is only burnishing the surface on some of the peaks. This is likely due to the more conforming nature of the acetal compared with the carbide which reduces the local stresses on the surface due to the increased contact area and thus, lower localized stresses on the surface texture. If burnishing is occurring on the surface when the acetal tool is used, it could be expected to occur on the peaks of the surface texture of the aluminum sheet metal. If this is occurring, than burnishing might be a factor in the surface of the contact side with the acetal tool being smoother than the free surface of the acetal tool.

The surface of the acetal contact surface appears to form in a similar manner to the free surfaces as the appearance of the surface texture is similar although the amplitude of the surface is less. Two possibilities for reduced amplitude are: 1) that either the surface is burnished at the peaks thus reducing the amplitude, or 2) the forces from the tool restrict the out-of-plane displacements of the grains. Thus on the contact side, the acetal tool is forming surface texture with out-of-plane displacements that may be restricted by the forming tool contact or the surface texture may be partially smeared by localized burnishing. The free surfaces are formed in a manner consistent with the "orange peel" effect. That is the mechanism at work in creating these surfaces appears consistent with the slipping of grains in out-of-plane displacements [11].

5. Conclusions
The first objective of this work has been met using non-parametric statistics (Kruskal-Wallis test and Mann-Whitney U-test) to determine at which scales there are significant differences (≥ 95% confidence level) in relative area. It is found that the surfaces in contact with the forming tool have greater relative area when the acetal tool is used than when the carbide tool is used at all scales greater than 5x10⁴ µm². The tool material is not found to have an effect on the surface topography of the free surface.

The second objective of the paper was to gain insight into mechanisms that form these surfaces. The carbide contact surface texture appears to be formed by burnishing. While the acetal contact surface appears to be formed by out-of-plane displacements of grains and possible burnishing, and the free surfaces formed in a manner consistent with "orange peel" effect.

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