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Processing maps for wrinkle free and quality enhanced parts by shear spinning

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Abstract

An experimental investigation was conducted to study the effects of key processing parameters when shear spinning conical part geometries from both aluminium alloy and mild steel disc shaped blanks. It investigated the effects of feed ratio, spindle speed, initial blank thickness, and thickness reduction on the occurrence of the wrinkling failure, effectiveness of thickness reduction, part springback, surface finish, and strain hardening effects resulting from the process. A design of experiments approach was used to conduct the experimental tests and a multi-variate regression analysis method was applied to obtain processing maps of the key parameters which produced wrinkling free and quality enhanced spun parts. The results showed that the feed ratio was the most critical processing parameter, with higher feed ratios led to the onset of wrinkling failure, less effective thickness reduction, more part springback and rougher part surfaces. The process was shown to result in a significant strain hardening effect in the blank material, which was found to be enhanced when the amount of blank thickness reduction was increased.

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Keywords: Shear spinning; Wrinkling; Geometrical conformance; Feed ratio; Strain hardening.

1. Introduction

Metal spinning dates back to the middle ages and was used traditionally for the manufacture of components with low dimensional tolerances such as tea kettles, sauce pans and other domestic implements. In more modern applications, metal spinning has been used for manufacturing components such as nose cones, inlet cowls, and engine components for the aerospace industry [1, 2]. In these applications, the method is effective as near net shape, axis-symmetric, thin

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walled components can be produced with good dimensional precision. The metal spinning process involves only localized deformation of the workpiece, this means that much lower forming forces are involved compared to other forming techniques and therefore only simple tooling is required [3]. Additionally, the strain hardening effects of the spinning process improve the mechanical properties of spun components and often this eliminates the requirement for any additional heat treatment to be carried out on spun components. These potential advantages make the metal spinning process an attractive option for many industrial applications.

The metal spinning process is carried out by clamping a sheet metal blank against a mandrel which is held in the chuck of a rotating machine spindle. The blank is deformed into the desired component geometry by applying forming forces using a dedicated spinning tool. The two classifications given to spinning processes are conventional spinning, in which both compressive and tensile stresses are applied to the blank, and flow forming, in which only compressive stresses are applied. Shear spinning is classified as a flow forming process as the compressive forming stresses applied cause plastic flow of the blank material to occur in the components axial direction, which results in a reduction of the wall thickness of the spun part, described according to the sine law, $t_1 = t_o \sin(\alpha)$. The part thickness is controlled by setting the spacing between the tool and the mandrel to the desired distance. This spacing can be set to follow the sine rule, or alternately, it is possible to achieve either an over or under reduction of the blank thickness by setting this spacing distance to either more or less than that governed by the sine rule. The amount of deviation from the wall thickness given by the sine rule is referred to by the over-roll distance, $t_o \sin(\alpha) - t_1$. Studies have shown that following this sine law is favorable for producing components without the occurrence of manufacturing failure, such as the blank material wrinkling or fracture [4]. The amount of wall thickness reduction achieved by a spinning operation is expressed as the thickness reduction ratio, $[(t_o - t_1)/ t_o] \times 100\%$.

There is a variety of parameters that influence the shear spinning process, these affect both part quality and tooling forces which ultimately affects the machine performance. It is therefore of interest when designing a spinning process to select the optimum parameters for producing a good quality spun part free from manufacturing failure. In spinning, a parameter referred to as the feed ratio is often used, this is defined as the relative movement of the roller tool for a single spindle revolution. Experimental research has determined that, in shear spinning, lower feed ratios are favorable for producing parts with a uniform thickness distribution and low surface roughness, whereas higher feed ratios will result in higher forming forces, which can cause blank failure [4]. Provided a constant feed ratio is maintained, it has been found that altering the spindle speed has little effect on the part quality. Additionally, it is regarded that, for a given feed ratio, an optimal spindle speed exists that gives the lowest tangential tool forces [3]. It is therefore the case, that for the feed ratio and spindle speed, an optimum parameter set exists to achieve an optimized spinning operation in terms of both part quality and machine performance

In this work, the effects of various shear spinning process parameters, including feed ratio, spindle speed, initial blank thickness, and thickness reduction, were investigated by means of an experimental manufacturing trial. A multi-variate regression analysis method was used to analyze the results from the experiment which proved to be capable at determining the significance of the effects of the different parameters investigated. Processing maps for manufacturing wrinkling free and quality enhanced parts were obtained for aluminum alloy and mild steel materials.

2. Experimental method

A manufacturing trial was carried out to determine the influence of various process parameters on the quality and geometry of the parts produced and the occurrence of any manufacturing failure during a shear spinning process. The trials have been carried out using a modified CNC turning centre, configured to perform a shear spinning operation. The experimental setup is shown in Figure 1.

Initially parameter screening experiments were carried out to determine a workable parameter range to be used in the subsequent trials. This consisted of 10 experimental runs which were carried out at the parameters given in Table 1. Following this, a full factorial experimental design was conducted, consisting of 24 runs (with an additional 10 centre point experiments) for the AA5251 material and 16 runs (with an additional 6 centre point experiments) for the DC01 material. Regression analysis of the results employed 90% confidence intervals to identify factors of statistical significance. To interpret the effects of the different processing parameters the results from all the trials carried out have been analyzed using multi-variate regression modeling. The experimental factors, and their corresponding upper and lower limits and intermediate settings, used in the full factorial experimental design are shown in Table 2 and 3 for the mild steel (DC01) and aluminium alloy (AA5251) blank materials used. The mandrel and roller geometry remained the same during the trials. The mandrel featured a 45° inclination angle and the roller a 5.0 mm nose radius. The blank diameter was maintained at 140 mm.

Table 1. Factors used for the preliminary screening experiments carried out with both the AA5251 and DC01 blank material.

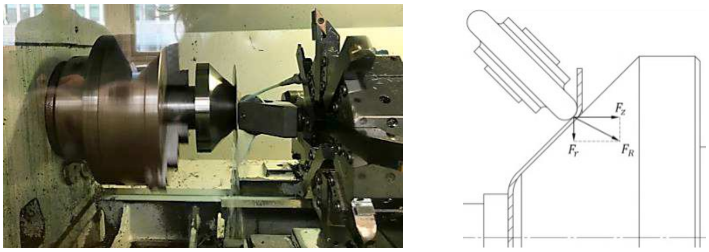
Factor Name	Units	Parameter Range
Blank Thickness, t_o	mm	1.00
Spindle Speed, N	RPM	100 - 2000
Feed Ratio, f	mm/rev	0.10 - 1.50
Thickness Reduction Ratio, t_R	%	30 (True)

Table 2. Factors used for the experiments carried out with the DC01 blank material.

Factor Name	Units	Lower Limit	Upper Limit
Blank Thickness, t_o	mm	1.00	1.10
Spindle Speed, N	RPM	100	2000
Feed Ratio, f	mm/rev	0.20	0.50
Thickness Reduction Ratio, t_R	%	30 (True)	40

Table 3. Factors used for the experiments carried out with the AA5251 blank material.

Factor Name	Units	Lower Limit	Intermediate Value	Upper Limit
Blank Thickness, t_o	mm	1.00	1.15	1.50
Spindle Speed, N	RPM	100	-	2000
Feed Ratio, f	mm/rev	0.20	-	0.70
Thickness Reduction Ratio, t_R	%	30 (True)	-	65



(a) Tool set up on CNC turning center (b) Forces exerted by the roller

Fig. 1. Setup of shear spinning experiment.

(a) AA5251 blank material. (b) DC01 blank material.

Fig. 2. Wrinkling occurrence at feed ratio of 1.5mm/rev.

3. Results and discussion

3.1. Wrinkling failure limits

During the trials, processing failure of the blank material occurred by the formation of wrinkles in the un-spun flange of the blank, as shown in Figure 2. Fracture of the blank material was not evident during the experiments. Observations showed that wrinkling would initiate in the un-spun flange of the blank and then become more severe as the tool pass continued. For this study wrinkling occurrence and severity was assessed on a visual basis and was scored from 0-4. A score of 0 indicated a trial run in which no wrinkling was observed and a score of 4 indicating severe wrinkling of the part. A score of 1 was given when wrinkling was only just visible in the spun part.

The parameters investigated which were found to have the most significant effect on the onset of wrinkling, were the initial blank thickness and the feed ratio. It was found that higher feed ratios were the predominant cause for wrinkling failure, with thicker blanks showing more resistance to wrinkle formation, particularly at the higher feed ratios at which wrinkles would be present in the thinner material. These findings in shear spinning show agreement with that of the conventional spinning process and that there exists a feed ratio limit, which when exceeded, wrinkling would occur [5]. Consistency with other studies was also shown as it was found that thicker blank materials were able to resist the onset of wrinkling and could therefore be spun at higher feed ratios without the formation of wrinkles; while spindle speed was shown not to have any significant effect on the onset of wrinkling in the part.

The regression equations of the wrinkling response for the AA5251 and DC01 material showing the regression coefficients of the experimental factors found to be of statistical significance when implementing a 90% confidence interval are given by Equations 1 and 2 respectively. Contour plots have been generated showing the parameter limits at which the occurrence of wrinkling failure is onset in each material, these are given in Figure 3. The significant effects of the initial blank thickness and feed ratio on wrinkling occurrence for AA5251 and DC01is shown in Figure 4.

$$Wrinkling\ Severity\ (AA5251) = 0.889 + 1.09f - 0.830t_0 - 1.01ft_0 \quad (1)$$

$$Wrinkling\ Severity\ (DC01) = 2.83 + 3.25f - 1.67t_0 - 1.42ft_0 \quad (2)$$

Wrinkling was onset in the DC01 material at lower feed ratios than the AA5251 material, despite the higher yield strength of the DC01 material. Therefore, contrary to the understanding of the conventional spinning process by Watson et al. [6], the yield strength of the blank material does not appear to be the most significant material property affecting wrinkling when shear spinning. The higher strain hardening coefficient of the DC01 suggests that the strain hardening effect of the process may have a more significant effect on the wrinkling mechanism in the shear spinning specifically. It can therefore be suggested because the strain hardening effect increases the yield strength of the blank material, the stresses required to form the blank increases. Eventually, the compressive circumferential forming stresses in the flange will exceed the bending limit for the material, at which point wrinkles form in the flange [6].

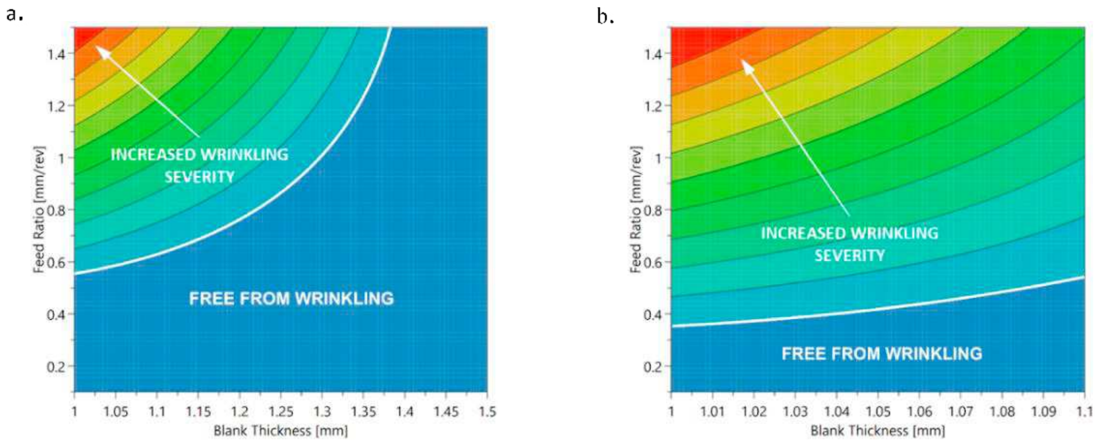


Fig. 3. Process window showing the parameter range for wrinkle fee spinning with (a) AA5251; (b) DC01 blank material.

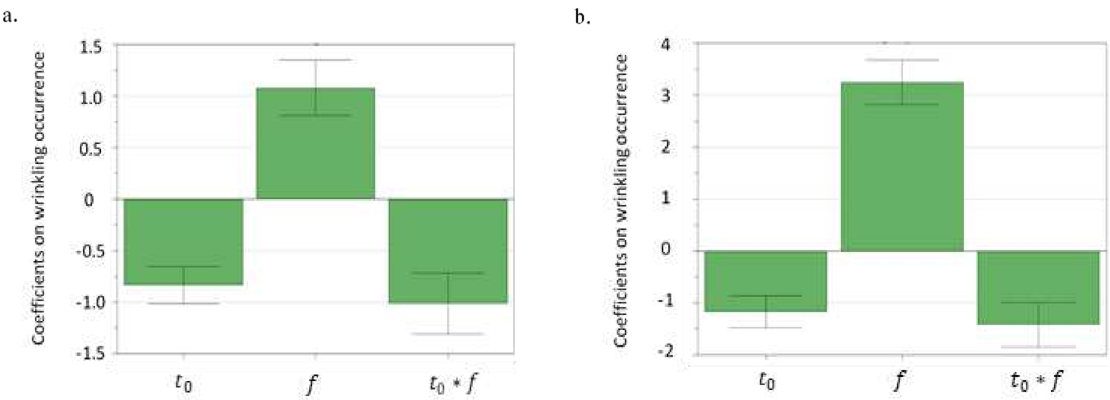


Fig. 4. Regression coefficients of the significant effects on wrinkling occurrence for (a) AA5251; (b) DC01 blank material.

3.2. Wall thickness reduction effectiveness

Wall thickness measurements were taken of the spun parts using a point micrometer at various radial positions along the part. These indicated that the achieved part wall thickness consistently exceeded that of the gap distance set between the mandrel and the roller. To analyze the wall thickness reduction effectiveness of the process, the difference in the achieved wall thickness reduction to that set by the gap distance between the tool and mandrel was modelled. From the regression analysis it was found that higher attempted thickness reduction was the main factor for not achieving the set reduction ratio. Higher feed ratios and initial blank thicknesses were also found to have a similar affect. The parts spun with a wall thickness most similar to that of the set gap distance were found to be the thinner AA5251 blanks and this was achieved when true spinning. The greatest difference was observed when attempting high amounts of over-roll. There are two reasons for being unable to achieve the reduction ratio set by the gap distance between the roller and the mandrel. The first is the material deformation mechanism that occurs in the shear spinning process and the second is due to deflection of the machine and tooling setup used. Considering the deformation of the material itself, the forming stresses applied to the material are not purely plastic shearing. As well as the plastic shear deformation that occurs, the material also deforms by elastic compression. As the roller passes on to an element in the blank, the force generated by the roller on the blank surface will be sufficient to reduce the material thickness enough for it to pass under the gap between the roller and mandrel. However as this force is removed from the blank, as the roller moves over the element, the material is no longer in elastic compression and the material will relax to a thickness more than that of the set gap distance. For this reason, even with a completely rigid tool setup, the achieved thickness reduction of the material will always be less than that of the gap distance set between roller and mandrel.

3.3. Spun part cone angle and springback

Measurements of the cone angle of each of the spun parts were acquired by taking Vernier measurements of the gap at the opening between the cone and mandrel surface and calculating the resulting angle. The mandrel geometry measured showed non-conformance to the 45° mandrel inclination angle. In each case, the part angle exceeded that of the mandrel cone angle, indicating the effects of springback of the part as tool contact was removed at the end of the pass. The regression equations for the part inclination angle are given by Equations 3 and 4 for the AA5251 and DC01 blank material. The regression model showed that a higher feed ratio was the main cause of non-conformance to the 45° mandrel inclination angle. As feed ratios increased, the part inclination angle was found to further exceed 45°. The models also showed that blanks of a greater initial thickness had better conformance to the mandrel geometry than thinner blank materials. The final effect demonstrated to be significant was the effect of the set reduction ratio. Increasing the reduction ratio was shown to improve the conformance of the inclination angle of the blank to that of the mandrel. The effects of the parameters found to be significant in the regression model are shown in Figure 5.

$$\text{Part Inclination Angle } (AA5251) = 48.1 + 1.5f - 1.07t_0 - 0.440t_R - 0.318N - 1.15t_R t_0 \quad (3)$$

$$\text{Part Inclination Angle (DC01)} = 48.5 + 1.56f - 0.0943t_0 - 0.234t_R \quad (4)$$

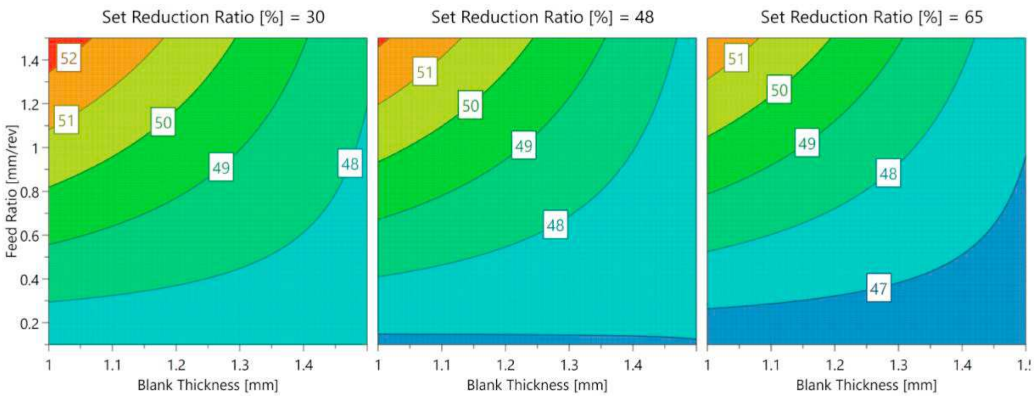


Fig. 5. AA5251 part inclination angle affected by key influencing process parameters (spindle speed 2000RPM).

The main reason for not achieving a part with the same inclination angle as that of the mandrel is due to part springback. This effect is due to the recovery of elastic strain induced in the part during the process as the forming forces are removed when the tool contact is removed [7]. The effect of higher feed ratios contributing to more part springback shows consistency with the conventional spinning process [8]. From the findings in this work, it can be suggested that, when spinning at higher feed ratios, the elastic strain is a larger portion of the total strain induced in the blank material when it is formed. This is due to the larger step over distance the tool makes per blank revolution, which results in a larger radial length of the blank element that requires forming. This effect means that the forming stresses that are applied are less effective at inducing plastic strain in the blank and a greater portion of the blank deformation is achieved elastically. This is supported by the finding that when spinning at higher reduction ratios at lower feed rates, spring back has the least effect and the best part conformance is achieved. For blanks spun at these parameters, the portion of plastic strain to the total strain in the material is the greatest, this is evident as the most effective thickness reduction is achieved. Therefore the portion of elastic strain is lower resulting in less elastic material recovery through spring back.

3.4. Spun part surface roughness

Surface roughness measurements of the outside surface of AA5251 parts produced during the trial were taken using a Mitutoyo SJ 400 surface profileometer. From this data the regression equation, given by Equation 5, highlighting the effects of statistically significant parameters on the resulting surface roughness was obtained. It was found that the feed ratio had the most effect on surface roughness, with higher feed ratios being the cause of rougher surfaces. Following this, blank thickness and spindle speed were also shown to have a statistically significant effect and increasing either of these two factors was shown to result in greater surface roughness. Contour plots of the surface roughness response for the AA5251 blank material, for both true spinning and spinning with over-roll set for a 65% reduction ratio, are shown in Figure 6.

The findings show agreement with the current understanding of the process demonstrated in the work by Chen et al. [9], where increased feed ratio, blank thickness and spindle speed were all shown to result in a rougher surface of the part. The fact that higher feed ratios are shown to result in poorer surface finish can be attributed to the increased step over distance of the roller in contact with the surface of the part. This leads to a greater distance between the peak heights on the parts surface and more pronounced tool contact marks when spinning at higher feed ratios. The findings for the effects of part thickness indicates that, the increased difficulties of reducing the parts wall thickness to that of the set value, due to higher forming forces, not only affects the final part thickness, but also results in a poorer surface finish.

$$\text{Roughness Ra (AA5251)} = 0.815 + 0.390f + 0.0946t_0 - 0.0251N - 0.00197t_R + 0.0886ft_R + 0.0626ft_0 \quad (5)$$

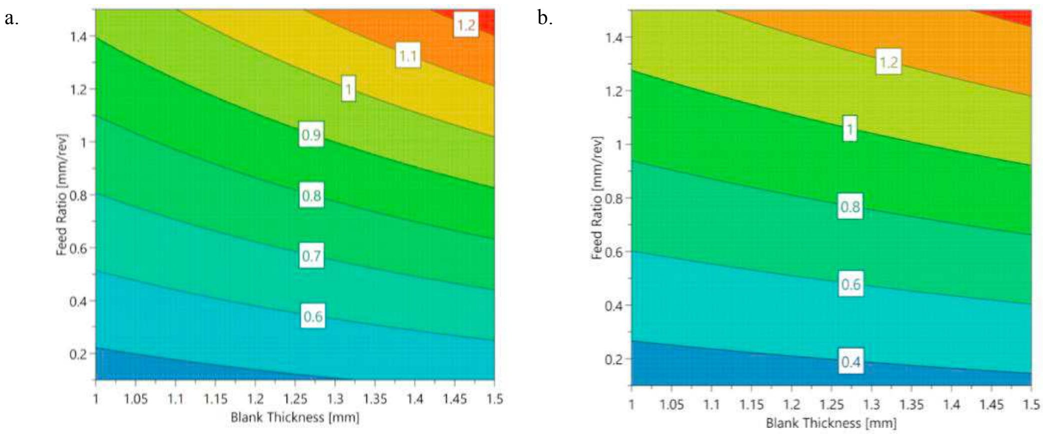


Fig. 6. Surface roughness (Ra, μm) of AA5251 parts when (a) true spinning; (b) using a 65% reduction ratio.

3.5. Strain hardening effects

Comparisons between Vickers indentation hardness measurements taken from samples of the spun parts and un-spun blank material indicated that the shear spinning process resulted in a significant strain hardening effect. For both blank materials, the strain hardening effect of the process resulted in more significant strain hardening of the material at the inside radial position (towards the nose of the part) than at the outside. A suggested reason for this is due to more tool deflection as the tool moves towards the outside of the part and therefore less effective thickness reduction occurring at this position. Increased strain hardening effects of the process was seen in the DC01 material compared to the AA5251 which can be attributed to the higher value of the strain hardening exponent for DC01.

The yield strength increase has been estimated from the hardness measurements using the empirical relationship taken from Paylina [10]. The yield strength is determined by the measured S.I. hardness value using the strain hardening exponent, n. The value for the strain hardening exponent for each material was determined by carrying out tensile and hardness testing of the un-spun blank material. Figure 7 shows the effects of the achieved thickness reduction on the material yield strength increase for each blank material. It is shown that when greater thickness reduction is achieved in practice, the resulting strain hardening effect is increased. This effect is evident at both the inside and outside radial positions of the part. Therefore by adjusting the process parameters to those that give the best results in terms of thickness reduction conformance, such as reducing the feed ratio and blank thickness, the strain hardening effects of the process can be enhanced. These observations are consistent with the findings from Zhan et al. [11], an increased material strain hardening effect when more plastic strain in the blank was achieved due to the effects of more grain elongation occurring in the blank material.

$$\sigma_y = \left(\frac{H_V}{0.3}\right)(0.1)^n$$

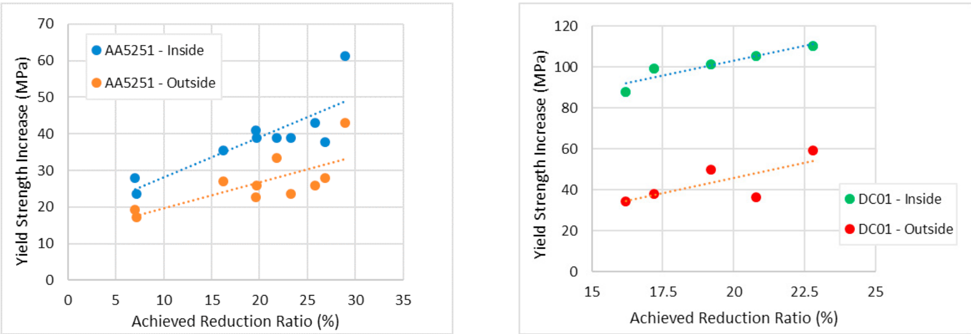


Fig. 7. Material yield strength increase at different achieved thickness reduction ratios with (a) AA5215; (b) DC01 blank material.

3.6. Strength of statistical analysis

To ensure the reliability of the regression analysis used to interpret the results from the experimental trials, an analysis of variance (ANOVA) evaluation was carried out by determining the probability values (p-values) for each model. These values, given in Table 4, are calculated based on the F-test results which compare the modellable and unmodellable variation of the results obtained. Values of $p<0.05$ indicate the test has been satisfied, therefore it is shown from this evaluation that the regression models provided in this work, are capable of indicating the variation for each response, due to the effects of altering each process parameter, to a greater degree than any unexplained variation in the results.

Table 4. P-values highlighting regression model significance.

Material Type	Wrinkling Severity	Roughness Ra	Reduction Ratio Difference	Part Inclination Angle
AA5251	2.31e-17	1.19e-12	1.92e-16	8.97e-13
DC01	1.58e-10	-	1.62e-10	7.18e-06

4. Conclusions

By experimentally investigating the effects of various spinning process parameters and employing a multi-variate regression analysis of the results from the experiment, the following conclusions can be drawn:

- Feed ratio was shown to be the most important parameter relating to the onset of wrinkling in the blank. For a given blank thickness a feed ratio limit occurs that should not be exceeded to ensure wrinkle free spinning. Wrinkling occurred in the DC01 blanks at lower feed ratios than the AA5251 blanks, indicating that the work hardening effect of the process affected the occurrence of wrinkling in the two different blank materials.
- The spun part wall thickness exceeded that of the gap distance set between the tool and mandrel. This non-conformance to the set thickness reduction was attributed to the effects of elastic compression of the blank and tool deflection resulted from the forming forces. Increasing the parameters for both the feed ratio and set thickness reduction was shown to have the most effect, resulting in a spinning operation that was less effective at reducing the blank thickness.
- Non-conformance of the spun part geometry to the mandrel inclination angle was observed due to the effect of springback of the part, which was found to be reduced by the effectiveness of the thickness reduction at inducing plastic strain in the blank. Processes involving lower feed ratios and achieving a greater amount of thickness reduction therefore produced parts with better conformance to the mandrel geometry. It was also found that less springback occurred in blanks of a greater initial thickness, due to their increased stiffness.
- Feed ratio was found to have the most effect on the surface roughness of the parts produced; with higher feed ratios producing in parts with a rougher surface. When spinning with over-roll, at a parameter selection which resulted in the most effective wall thickness reduction, it produced the best surface finish.
- Hardness measurements indicated a significant strain hardening effect in both materials as a result of the shear spinning process. The DC01 material exhibited the greater yield strength increase, with an increase of 40% of the yield strength value of the unformed material, compared to 25% for the AA5251 material. The increased strain hardening effect of the process on the DC01 material was attributed to the higher strain hardening exponent of the material. Increasing the effective thickness reduction ratio of the process was shown to enhance the strain hardening effect significantly.

References

[1] Winward Engineering Ltd., “Aerospace Component Fabrication”, (2017).
[2] Metspin Ltd., “Rolls Royce Sabre Certificate Awarded to Metspin Ltd”, (2016).
[3] C. C. Wong, T. A. Dean, and J. Lin, “A review of spinning, shear forming and flow forming processes”, *International Journal of Machine Tools and Manufacture*, vol. 43 (14) (2003) 1419-1435.
[4] O. Music, J. M. Allwood, and K. Kawai, “A review of the mechanics of metal spinning”, *Journal of Materials Processing Technology*, 210 (1) (2010) 3-23.
[5] L. Wang, H. Long, D. Ashley, M. Roberts, and P. White, “Effects of the roller feed ratio on wrinkling failure in conventional spinning of a cylindrical cup”, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*,. 225 (11) (2011) 1991-2006.
[6] M. Watson, H. Long, and B. Lu, “Investigation of wrinkling failure mechanics in metal spinning by Box-Behnken design of experiments using finite element method”, *International Journal of Advanced Manufacturing Technology*, 78 (5-8) (2015) 981-995.
[7] Z. Marciniak, J. Duncan, and S. Hu, *Mechanics of Sheet metal forming*. Butterworth-Heinemann, (2002).
[8] K. Essa and P. Hartley, “Optimization of conventional spinning process parameters by means of numerical simulation and statistical analysis”, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* 224 (11) (2010) 1691-1705.
[9] M. D. Chen, R. Q. Hsu, and K. H. Fuh, “Effects of over-roll thickness on cone surface roughness in shear spinning”, *Journal of Materials Processing Technology*, 159 (1) (2005) 1-8.
[10] E. J. Pavlina and C. J. Van Tyne, “Correlation of Yield strength and Tensile strength with hardness for steels," *Journal of Materials Engineering and Performance*, 17 (6) (2008) 888-893.
[11] M. Zhan, X. Wang, and H. Long, “Mechanism of grain refinement of aluminum alloy in shear spinning under different deviation ratios”, *Materials and Design*, 108 (2016) 207-216.