An experimental investigation into the relationship between process variables and forming conditions during splined mandrel flow forming operations

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A thesis submitted in partial fulfillment of the requirements for the degree in Master of Engineering Science
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AN EXPERIMENTAL INVESTIGATION INTO THE RELATIONSHIP BETWEEN PROCESS VARIABLES AND FORMING CONDITIONS DURING SPLINED MANDREL FLOW FORMING OPERATIONS

(Spine title: The effect of Process Variables on Forming Conditions during an SMFF Operation)
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by

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Submitted in partial fulfillment
of the degree of
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The University of Western Ontario
London, Ontario, Canada

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The thesis by

**Brandon C. Vriens**

entitled:

**An experimental investigation into the relationship between process variables and forming conditions during splined mandrel flow forming operations**

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Chair of the Thesis Examination Board
Dr. Jim Johnson
Abstract

Splined Mandrel Flow Forming (SMFF) is an effective method for fabricating a variety of internally-ribbed cylindrical parts. The process is, however, prone to premature failure of the splined mandrels and this is thought to be related to the magnitude of the forming forces exerted by the forming rollers on the mandrel splines. In this thesis an experimentation-based approach is used to investigate the effects of critical process parameters; namely, Inter-roller offset of the X1-X2 forming rollers, Oa, roller inclination angle, θ, roller nose radius, r₀, forming roller feed rate, X and mandrel rotational speed, ω, on forming forces exerted on an AISI 1020 steel work piece as it is flow formed over a splined mandrel. The combined effect of these parameters on the maximum forming forces, F_{MAX}, the roller force-oscillation amplitude, ΔF, and the roller/ work piece contact area are examined for an X1 forming roller during the third pass for SMFF tests performed under various process conditions.

The multi-parametric nature of SMFF processes requires the use of a multi-variable analysis technique. The Taguchi method of experimental design ranks the effect of each process parameter on the overall quality of the process in a practical manner consisting of relatively few experiments. The Signal-to-Noise (S/N) ratio is the measure used to perform this evaluation. Analysis of the Signal to Noise (S/N) ratio of F_{MAX} indicated that the most critical process parameter in the SMFF process is Oa. Two optimal forming scenarios were selected: The θ=8° forming roller inclination at an inter-roller offset distance of Oa=-1.25mm from the current production settings was found to be an optimum conditions for minimum ΔF, while
the $\theta=20^\circ$ forming roller inclination at an inter-roller offset distance of $O_a=+1.25\text{mm}$ from the current production settings, was found to be optimal for minimizing $F_{\text{MAX}}$.

Long term, production trials were then carried out to investigate the effect each process parameter on the number of parts manufactured before the occurrence of spline mandrel failure. Using the results obtained from the production trials and the known Hardness of the AISI 1020 steel work piece, a comparison was made between the contact area calculated from the measured forming force and the contact area determined from the semi-analytical technique$^1$.

Premature failure of the mandrel spline was experimentally found to be a direct result of the high number of repetitive load cycles that invoke a stress amplitude, $\Delta\sigma$, upon the mandrel spline region. It is the magnitude of the forming force oscillations, $\Delta F$, which determines $\Delta\sigma$ and thus the rate of fatigue crack growth.

**Keywords:** Splined Mandrel Flow Forming (SMFF), Inter-roller offset, roller inclination angle, fatigue failure, roller/work piece contact area

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Brandon Vriens
December 2012,
London, Ontario, Canada
Notation

$\theta$  Inclination angle, Roller attack angle ($^\circ$)

$\phi$  Land, Exiting angle ($^\circ$)

$Oa$  Inter-roller offset distance (mm)

$r_0$  Roller nose radius (mm)

$R_m$  Mandrel radius (mm)

$R_r$  Roller radius (excluding $r_0$) (mm)

$R$  Percent reduction of starting work piece (%)

$P$  Pitch (ratio of axial roller motion to mandrel revolution)

$\Delta F$  Roller force-oscillation amplitude (kN)

$\dot{x}$  Axial roller feed rate (mm/min)

$\omega$  Mandrel rotational speed (rpm)

$R^*$  Numeric resolution of the contact area solution

$P_1, P_2, P_3, \ldots P_N$  Experimental process design parameters

$\Delta d$  Difference between each S/N ratio for each parameter studied

SMFF  Spline mandrel flow forming

PLC  Programmable logic controller

CNC  Computer numeric control

NC  Numerical control

S/N  Signal-to-noise-Ratio

$F_{\text{MAX}}$  Maximum roller forming force

OFAT  One-Factor-at-A-Time

$S$  Circumferential length

$L$  Axial length

TR  Thickness reduction

OA  Orthogonal Array

DAQ  DataAcQuition
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Chapter 1

Introduction

The flow-forming process is a variant of the traditional metal spinning process in which one or more forming rollers press a metal work piece over a cylindrical metal mandrel. The work piece is initially in the shape of a flat disk that is fixed to the top of the mandrel. Forming rollers press against the work piece as it, and the mandrel, rotate about the mandrel’s axis. This causes the work piece to acquire the shape of the mandrel. When the work piece is formed over a mandrel containing protruding axial splines a cylindrical product containing internal ribs is formed. This is referred to as a Splined Mandrel Flow Forming (SMFF) process. The SMFF process is a very cost effective way to fabricate internally ribbed parts and has found particular application in the automotive industry. An on-going problem with the SMFF technique is early, and unexpected, fracture of the protruding mandrel splines. During the service life of the mandrel, the lower region experiences a significantly high number of repetitive, irregular force-oscillations causing the mandrel to crack. Changes in section size, a sharp corner, or groove in the mandrel geometry all increase the chance of failure.

Attempts to correlate process parameters such as forming roller geometry, roller feed rate, and mandrel speed to the tendency for premature failure of the mandrel splines has not been reported. Forming pressures and forces, tooling
positions, tooling contact areas, and material response during flow forming are the parameters that were investigated. Transform Automotive Ltd (London, ON), a leading user of SMFF for the production of internally-ribbed automobile transmission parts, has supported this research through a collaborative research grant also supported by the Ontario Centres for Excellence (OCE). This thesis is written in the manuscript format and is structured as follows:

Chapter 2 contains a review of the general principles involved in splined mandrel flow forming and describes the highlights of previously reported work. A description is also given of the Taguchi method for studying, and ranking, the effect of individual variables in a multi-variable process such as SMFF.

Chapter 3 describes the experimental methodology that was used to analyse the SMFF process and to assess the influence of the forming roller nose radius, inclination angle and inter-roller offset distance on the maximum forming force during the SMFF process studied.

Chapter 4 presents the results of the experiments described in Chapter 3.

Chapter 5 presents the results from an additional study performed to investigate the effect of optimal processing parameter conditions on the number of parts produced prior to mandrel failure of an industrial SMFF process. A comparison of the experimentally measured forming roller / work piece contact area to the calculated contact area, using a previously developed semi-analytical technique, is also presented. Finally, these data are combined to obtain an assessment of the influence of the specific process variables; namely, the forming roller nose radius, inclination angle, and inter-roller offset distance on the tendency for fatigue failure of the mandrel splines.

Chapter 6 presents a summary of the experimental analyses and suggests additional future work.
Chapter 2
Background information and review of relevant literature

2.1: Principles of metal flow forming

Metal flow forming, also referred to as metal spin forming, is a method for manufacturing thin-walled rotationally-symmetric components. The starting work piece is in the form of a thin circular disk that is clamped to the top of a cylindrical mandrel that has the shape of the desired final product. The work piece and the mandrel are then rotated at a high speed of about 300 rpm and the work piece is pressed against the mandrel by one or more forming rollers that travel down the length of the mandrel. This causes the work piece to acquire the shape of the mandrel. Most industrial flow forming processes incorporate multiple, usually three, hydraulically actuated and CNC controlled forming rollers to incrementally draw the work piece along the length of the mandrel (Figure 2.1).
Figure 2.1: Multi-roller, vertical axis flow forming configuration for a splined mandrel flow forming operation.

Each forming roller may have a different size, shape, and inclination relative to the mandrel. In the case of the common three-roller flow forming operation shown in Figure 2.1, the first forming roller (X3) to contact with the work piece is responsible for cupping the work piece, while the second roller (X2) draws the work piece material tightly against the mandrel, invoking a considerable thickness reduction to the work piece. In the case of SMFF, a third roller (X1) further presses the work piece against the mandrel causing it to flow around the protruding axial splines on the mandrel, thus, creating an internally ribbed part. The position of each roller relative to the central, vertical axis of the cylindrical mandrel is independently controlled by a CNC code. The code is specific to the geometry of the mandrel, the shape and the orientation of each forming roller. Since the position of the roller(s) is hydraulically actuated, it is possible to log the hydraulic pressure versus roller position along the mandrel. This provides a detailed history of the magnitude of the roller forming force. Figure 2.2 shows a typical plot of the X1 roller forming force as a function of the axial roller position.
during a three-pass SMFF process. It is this type of an SMFF process that is studied in the subsequent chapters of this thesis.

Figure 2.2: X1 roller forming force versus total cumulative axial position along the mandrel for a three-pass SMFF process.

2.2: Failure of splined mandrels during SMFF

It has been reported by industrial users that premature failure of mandrel splines is the critical life-limiting factor in many SMFF processes. In the case of fabrication using the splined mandrel geometry studied in this thesis, the location of the premature fatigue failure is in the large splines located near the bottom of the mandrel (Figures 2.1, 2.3). During the second and third passes of such a SMFF operation the roller forming force gradually increases in magnitude as the roller passes across, and the work piece material is forced around, this splined region. This also causes the roller force to oscillate as shown in Figure 2.2. The two forming characteristics that were evaluated for each experimental trial during the third forming pass were the maximum roller forming force, $F_{\text{MAX}}$ and
the roller force oscillation, $\Delta F$. Each were evaluated using the $F$ vs time history measurements along the X1 roller forming force. While minor differences were observed for each set of process conditions, $F_{\text{MAX}}$ and $\Delta F$ were calculated by subtracting the maximum tensile force to the minimum observed as the forming roller passes overtop the mandrel spline (Figure 2.12).

It is this force oscillation that is responsible for the premature fatigue failure of the mandrel splines. Micro-sized fatigue cracks initially nucleate near the edge of the mandrel splines and then propagate circumferentially through the mandrel spline (Figure 2.3).

![Location of fatigue failure](image)

Figure 2.3: Region of high forming forces where expected, premature failure of the lower spline mandrel occurs [10]. The crack first initiates near the inner root of the mandrel spline due to a change in section size.

The resulting fracture surface shows a topography indicative of fatigue failure with the initiation of the fatigue failure occurring at the sharp corner of the mandrel spline (Figure 2.4) [9,10].
Premature fatigue failure of the mandrel splines may result from either of the following factors: (i) The cyclic impact loading caused by the forming rollers or (ii) The presence of the sharp corners of the lower mandrel splines which are necessary to form the desired shape of internal ribs on the final part but which act as stress concentrators [9,10]. In either case, the overall life expectancy of the splined mandrel is directly related to process parameters that influence the magnitude of the forming force oscillations.

2.3: Key controllable process parameters in a flow forming process

The SMFF process is influenced by a number of controllable process parameters. The challenge with operating such a multi-variable process is to determine the effect of each parameter on the overall process. The geometry of each forming roller; namely, the roller nose radius, $r_0$, the roller inclination angle, $\theta$, the radius of the forming roller, $R_r$, and the exiting angle, $\phi$, (Figure 2.5)) must be selected to optimize this process.
Figure 2.5: Key controllable process parameters during an SMFF of an AISI 1020 steel work piece.

The SMFF machine used in this thesis can independently control the inter-roller forming offset distance, Oa, the work piece thickness reduction, TR, the roller axial feed rate, \( \dot{X} \), and the mandrel rotational speed, \( \omega \). By choosing forming rollers with different shapes, the effect of the roller geometry; namely, \( r_0, \theta, \phi, R_r \), can also be independently varied. With this ability to control the process variables, key machine parameters can be studied to identify which ones are critical in minimizing the roller forming force magnitude and oscillation and, hence, improve the service life of the splined mandrel.

2.4: Characterizing optimal forming parameters for a single-roller, smooth mandrel, flow forming process

Although the effect of flow forming process parameters on the service life of splined mandrels during an industrial SMFF process has yet to be undertaken, considerable work has been reported on the effect of process variables on single-roller flow forming involving smooth mandrels. Roy et al. [1] measured the
contribution from the forming roller and the smooth mandrel to the total local equivalent plastic strain across the thickness of the work piece and found that the maximum equivalent plastic strain occurred at the roller/work piece interface and was a function of the percentage thickness reduction invoked during flow forming (Figure 2.6).

![Graph showing maximum equivalent plastic strain versus thickness reduction level](image)

Figure 2.6: Maximum equivalent plastic strain incurred at the roller interface from fitted relationships versus thickness reduction level [1].

The presence of large strain gradients when the thickness reduction level exceeded a critical level suggested that there is a maximum thickness reduction level at which the work piece material can be flow formed and still remain defect free [1, 14].

Multiple roller flow forming operations involving large work piece thickness reduction levels and large localized plastic strain around splined mandrel is now used on the industrial scale, however, it is a process which has yet to be fully optimized. It has been recognized that the key approach to optimizing such a process is by simultaneously controlling several key process parameters, among
which the angle of attack of the forming roller is very important [6,17 - 20]. The optimum roller inclination recommended by different authors is somewhat diverse. Gur and Tirosh [2] discovered that one of the major requirements for successful increases in the work piece thickness reduction during a smooth-mandrel flow forming process is to have a large inclination angle for the forming roller relative to the mandrel. Conversely, greater axial roller feed rate and higher levels of friction at the roller/work piece interface results in a decrease in the critical roller inclination angle necessary to achieve an optimal flow formed part.

Ma [3] conducted an experimental analysis to determine the optimal forming roller inclination during a smooth-tube spinning metal forming process. Relevant design parameters such as axial feed rate, work piece thickness reduction ratio, and roller/work piece friction were investigated. The optimal forming roller inclination was found to be 22.0 and 26.3° for work piece thickness reductions of TR = 40% and 60%. As the forming roller inclination angle increased, the spinning forces also increased. Furthermore, the roller inclination angle also affects the build-up of work piece material ahead of the roller. Ma concluded that the optimal roller inclination angle decreases with larger roller diameter and friction factor, but increases with larger roller feed-rate, thickness reduction and initial thickness of the work piece. This increase is presumably related to the onset of pile up of the work piece material ahead of the forming roller causing an increase in the roller/work piece contact area.

Wang et al. [4] carried out an experiment using a single-roller, 3-pass flow forming process over a smooth mandrel and reported that the roller forming forces increased when forming rollers with larger nose radii, \( r_0 \), were used. They reported no obvious effect on the forming force from the mandrel rotational speed, \( \omega \). This is in contrast to a similar experiment performed on a single-pass, conventional spinning operation by Xia et al. [5] who reported the axial and radial components of the roller force increased with the increasing roller feed rate.
Although the literature on the effects of process parameters on the forming forces during smooth and splined-mandrel flow forming is incomplete, and in some instances contradictory, the results suggest that all the process variables studied affect the roller/work piece contact area. Since flow forming is a plastic forming process, the forming force must be related to the yield stress, or the hardness, of the work piece. Any process parameter that increases the roller/work piece contact area must therefore result in increased roller forming forces such that the equivalent stress applied to the work piece must reach the equivalent flow stress of the material.

2.5: Methods to calculate the roller/work piece contact area

The studies described in the previous section have reported the effect of process parameters on the maximum roller forming forces during flow forming operations and it is the magnitude of these roller forming forces that ultimately determines the roller/work piece contact area. The shape of the contact area of course determines the distribution of the forming force to the work piece and this distributed force is transferred to the mandrel. To prevent the onset of premature failure of the mandrel splines, perhaps one should focus on optimizing not one forming parameter but a combination of parameters such that the size and shape of the roller/work piece contact area is optimized to reduce the magnitude of the forces exerted upon the mandrel splines. This of course requires the ability to calculate the size and shape of the roller/work piece contact area. Several attempts have been made to do this, as described below.

The effect of process parameters on the local contact area between the forming roller and the work piece was studied by Gur and Tirosh [2]. They defined the contact area in terms of two characteristic lengths: the circumferential length S and the axial length L. Gur and Tirosh demonstrated that the roller inclination angle, θ, has a very significant effect on the S/L ratio. In their analysis, they used an analytical model that neglects the nose radius of the forming roller. This
treatment renders the roller/work piece contact region as rectangular, of axial length $L$ and circumferential length $S$. This rectangular treatment of the contact area is inaccurate as it does not account for the curved geometry encountered with a standard flow forming roller. Figure 2.7 illustrates $S$ versus $L$ as a function of $\theta$, while holding constant all other key controllable process parameters.

An alternative analytical method for calculating the roller/work piece contact area was proposed by Chen et al. [7]. They recognized that the roller/work piece
contact area was located in three-dimensional space and used an analytic approach to calculate the axial and radial components of the total contact area for a metal spinning application. The effects of blank thickness, roller nose radius, mandrel rotational speed and roller feed rate on the spinning force were then determined using the calculated contact area and were compared to experimentally measured forming forces. The following assumptions were adopted when deriving their analytical expression for the contact area:

1. The work piece material is homogeneous, isotropic rigid-perfectly-plastic with no volumetric change during deformation.
2. Material follows the von Mises yield criteria.
3. The frictional force at the roller/work piece interface is negligible.
4. Strain rate and temperature effects are also neglected.

To better understand the effect of such assumptions, a comparison of the experimentally determined contact area to the analytically calculated contact area was performed. Furthermore, supplementary changes to the semi-analytical contact area calculator to account for changes to the inter-roller offset, Oa, would be necessary to allow for a comparison of process settings, other than current inter-roller offset conditions.

The expressions developed for the roller/ work piece contact area were found to be in agreement with the experimental results [7].

In an industrial flow forming process it is common for the individual forming rollers to have a complex shape. The roller nose region that contacts the work piece can be defined in terms of three parameters: the front inclination angle \( \theta \), the nose radius, \( r_0 \), and the land angle \( \phi \) (Figures 2.5, and 2.8).
Figure 2.8: Images of an X3 forming roller used in a three-roller SMFF process similar to that studied in this thesis research. The three important geometrical parameters are (i) the Front, or inclination angle $\theta$, (ii) the roller nose radius, $r_0$, and (iii) the Land, or exiting angle, $\phi$.

The magnitude of $\theta$ largely dictates the magnitude of plastic strain invoked into the work piece. The magnitude of $r_0$ influences the surface finish and the degree of build up of work piece material ahead of the forming roller. The land angle $\phi$ is responsible for limiting the degree of spring back of the work piece material [15].

The best expression to calculate the roller/work piece contact area was recently reported by Roy et al., [8], who developed a semi-analytical method for calculating the three-dimensional contact area. In this analysis, the contact area was represented as being enclosed by three lines referred to as the (i) tangential exit, (ii) axial entry and (iii) axial exit contours (Figure 2.9).
Roy et al. developed equations that described these lines as a function of the process parameters $r_0$, $\theta$, $\phi$, forming roller radius, mandrel radius, work piece thickness, mandrel rotational speed, axial roller feed rate, and thickness reduction of the work piece. A sectional representation of the roller interacting with the work piece illustrating the three enclosed regions is shown in Figure 2.9.

Due to the complex geometry, Roy et al. were required to make the following assumptions in order arrive at a solution for the contact area:

1. The single roller flow forming process proceeds under steady state conditions. The final and starting thickness, mandrel rotation and feed rate are constant.

2. The deformation response of the work piece is rigid-plastic and, therefore, elastic deformation of the forming roller and the work piece are not considered.

3. Volume of the flow formed work piece is conserved.
4. No material build-up occurs in front of the forming rollers and the work piece conforms completely to the rigid forming roller.

The extents of contour 1, and the starting points of contours 2 and 3 (Figure 2.9) are solved explicitly as they lie exclusively on the xz plane. Once the extents of contour 1, and therefore the starting points of contours 2 and 3, are determined the common end points of contours 2 and 3 are then solved using an implicit technique. The final contact area is defined by six contact roller surfaces: the entry and nosed region of the roller from the previous work piece rotation, the instantaneous roller entry/exit region, the instantaneous roller nosed region and the outer surface of the unformed work piece. Due to the complexity of the roller/work piece interaction, a numerical technique is employed to generate the six boundary surfaces in three dimensions (Figure 2.10).

Figure 2.10: Graphical progression of the algorithm used to solve the starting boundary surfaces at \( i=0, \ R^*=10 \), with the course results shown to the left for \( i=0, \ R^*=10 \) [14].

An iterative analytical technique is then used to calculate total contact area \( A_{xyz} \) included within these lines. In addition to the total contact area, the components of the contact area \( A_{xy}, A_{xz}, \) and \( A_{yz} \) can also be determined. The total surface area as a function of these projections is expressed as:
\[ A_{xyz} = \sqrt{A_{xy}^2 + A_{xz}^2 + A_{yz}^2} \]  \[2.1\]

It was found that changing the material thickness reduction ratio and the forming roller axial feed rate, \( \dot{x} \), had the largest effect on the overall roller/work piece contact area. In order of precedence, the variables, other than thickness reduction and \( \dot{x} \), that had largest effect on the overall contact area were the radius of the mandrel, \( R_m \), the roller inclination angle, \( \theta \), radius of the roller, \( R_r \), and the roller nose radius, \( r_0 \) [8]. Figure 2.11 illustrates the percent change in contact area for a percent change in \( \theta \), the roller radius, \( R_r \), and roller nose radius, \( r_0 \).
While the technique developed by Roy et al. [14] is potentially very useful for the analyses of the roller/work piece contact area for a wide variety of metal flow
forming processes, its accuracy has yet to be verified experimentally. Some of the assumptions that Roy et al. made are clearly inconsistent with what is known to occur during flow forming. For example, it is always observed that the inside diameter of a flow formed part is larger than the outside diameter of the mandrel (i.e. elastic spring back always occurs). Also, if no material build-up occurs ahead of the forming roller, wearing of the forming roller would not occur in the region of the roller above where it contacts the work piece. In reality flow forming rollers show burnish marks in the entry and exit regions above and below the roller nose contact region (Figure 2.9). This indicates that some of the assumptions made by Roy et al will lead to inaccuracy in the calculated roller / work piece contact area however the magnitude of this inaccuracy has yet to be determined. In Chapter 5 of this thesis data are presented to asses the accuracy of Roy et al.’s semi-analytical approach to calculation of the roller / work piece contact area.

2.6: Ranking process parameters with the Taguchi method of multi-variable analysis

One of the primary objectives in optimizing multi-variable processes, such as SMFF, is to rank the sensitivity of the process outcome to the individual variables by conducting a “reasonable” number of tests. For example, in the SMFF process there are at least five parameters defining the geometry of the forming roller alone (Figure 2.5). If one was to study the effect of each of these parameters by evaluating its effect at say 4 levels one would need to perform $5^4 = 625$ tests to completely assess the process. This “factorial” testing approach is clearly not practical.

The Taguchi method of multi-variable analysis offers an attractive alternative in that it allows the same ranking of variables to be performed but with a considerably reduced number of tests performed under only certain parametric levels. The Taguchi method ranks the process parameters by assessing their affect on the Signal-to-Noise (S/N) ratio of the process outcome [11, 17, 21]. This can be demonstrated by considering an SMFF process where a set number of
tests are performed for each process condition and, in each test, only one process parameter, say \( \theta \) (Figure 2.5), is changed incrementally from \( \theta = A \) to \( B \). If the square of the maximum roller forming force \( F_{\text{max}}^2 \) (Figure 2.12) is used as the parameter indicating the process outcome, the average S/N ratio resulting from the small changes in \( \theta \) can be expressed as:

\[
S/N = 10\log \left( \frac{\text{Magnitude of process outcome}}{\text{Variance of the process outcome}} \right) = 10\log \left( \sum_{i=1}^{N} \frac{F_{\text{max},i}^2}{(F_{\text{max},i}^2 - \bar{F}_{\text{max}}^2)} \right) \tag{2.2}
\]

where \( F_{\text{max},i}^2 \) represents the process outcome from the \( i^{th} \) test, \( \bar{F}_{\text{max}}^2 \) is the average process outcome over the \( N \) repeatable tests. For each combination of \( Oa \) and \( \theta \), three consecutive roller force traces were taken, measuring the variation or noise. If the average variance between \( F_{\text{max},i}^2 \) and \( \bar{F}_{\text{max}}^2 \) over the \( N \) tests for one particular test combination is large, the resulting S/N ratio will be small and one can conclude that, for a given \( \bar{F}_{\text{max}}^2 \), changes in the parameter \( \theta \) will have small affect on the overall process outcome. For each of the experimental test combinations, i.e. \( Oa \) and \( \theta \), individual S/N ratios were calculated using the above relationship.

The maximum roller forming force, \( F_{\text{MAX}} \), and the roller force-oscillation, \( \Delta F \), were logged using solid-state transducers installed on the piston-side inspection port of the hydraulic piston-cylinder housing. The magnitude of \( F_{\text{MAX}} \) and \( \Delta F \) was evaluated during the third forming pass, where the maximum value of each characteristic was determined using a macro-command in Microsoft excel.
Figure 2.12: Roller force trace measured along the X1 forming axis during the third forming pass. Identifying the magnitude of $F_{\text{MAX}}$ and $\Delta F$ for each experimental trial is necessary when ranking each process parameter.

2.7: Previous works studying the effects of processing parameters on a SMFF operation

In order to investigate the behavior of a number of interacting process parameters on an SMFF process, Klassen and Haghshenas performed a multi-variable assessment using the Taguchi method. A statistical analysis of three process parameters was performed at three different levels for an SMFF process. A series of nine tests were conducted, each parameter was studied at three settings. Test results for the individual S/N ratio determined from Equation 2.2 were ranked to investigate the effects of mandrel speed, axial roller feed rate and roller nose on $F_{\text{MAX}}$.

---

2 The results presented in this section were reported in a series of internal memoranda and presentations prepared by R.J. Klassen and M. Haghshenas for R. Thompson of TransForm Automotive Ltd (2011).
The variation, $\Delta d$, between the maximum and minimum average S/N ratios, as indicated in Table 2.1, over the range of experimental combinations, i.e. columns P1 ($\omega$) and P3 ($r_0$) are nearly identical. This suggests their impact on the process output is small and doesn’t affect $F_{\text{MAX}}$ regardless of the level of $\omega$ or $r_0$. However, the Feed rate, $\dot{F}$, was found to have a large effect on $F_{\text{MAX}}$ as indicated by the large $\Delta d$ values (Table 2.1).

Table 2.1: Average S/N ratios for P1 ($\omega$), P2 ($\dot{X}$), P3 ($r_0$) with respect to the three levels studied. The ranking of each process parameter is based upon the magnitude of $\Delta d$.

<table>
<thead>
<tr>
<th></th>
<th>Average S/N ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P1- $\omega$</td>
</tr>
<tr>
<td>1</td>
<td>24.9</td>
</tr>
<tr>
<td>2</td>
<td>27.9</td>
</tr>
<tr>
<td>3</td>
<td>22.2</td>
</tr>
<tr>
<td>$\Delta d$</td>
<td>5.8</td>
</tr>
<tr>
<td>Rank</td>
<td>2</td>
</tr>
</tbody>
</table>

For an SMFF process characterized by three process parameters, namely, the Mandrel speed, Feed rate, and the Roller radius, when it comes to minimizing the maximum roller forming force for the X2 forming axis during the third and final forming pass, the axial roller feed rate was the most critical forming parameter.

2.8: Summary

In this chapter, the basic operation of a multi-roller splined mandrel flow forming (SMFF) process is described. The critical process parameters are also identified and previous research on the effect of some of these parameters is discussed. The combined effect of these parameters on the roller/work piece contact area has been studied to some extent, and these studies were also reviewed. The equations predicting the roller/work piece contact area have yet to be validated.
experimentally. These experimental validations are performed as part of this thesis research and are described in the subsequent chapters.

The multi-parametric nature of the SMFF processes requires the use of a multi-variable analysis technique. In this chapter the Taguchi technique and the use of S/N equations to rank individual parameters was introduced.

The following chapter presents the experimental procedure that was followed to assess the effects of several key process parameters on the magnitude of the forming forces, roller/work piece contact area and ultimately the mandrel service life during a three-roller SMFF process performed on an AISI 1020 steel work piece.

2.9: References


Chapter 3

Experimental Procedure

This thesis studies the effects of five processing parameters: $O_a$, $\theta$, $r_0$, $\dot{x}$ and $\omega$ (Figure 2.5) on the maximum X1 roller forming force, $F_{\text{MAX}}$, during the third pass of a three-roller SMFF process and links these findings to both the magnitude of the roller/work piece contact area and the ultimate service life of the splined mandrels. Several experimental trials were conducted using an instrumented, three-roller SMFF machine described below.

3.1: The three-roller SMFF Machine

Each of the experiments were conducted at Transform Automotive Ltd. in London, Ontario, on the WF VSTR 400 three-roller, splined mandrel flow forming machine. The three forming rollers, X1, X2 and X3, were attached to a movable saddle assembly with an adjustable axial offset between each roller (Figure 3.1). Computer Numeric Control (CNC) hydraulic actuators connected the forming rollers to the saddle and precisely control the distance between each roller and
the mandrel surface. Three passes of the forming roller / saddle assembly down the mandrel were required to make the final part.

Figure 3.1: Illustration of the three-roller flow-forming configuration. Vertical separation (Oa) of each roller is set manually before the test. The distance of each roller to the mandrel surface is continually adjusted by CNC during the test [1].

For each forming operation, the CNC initiates a command that passes a signal to the Programmable Logic Controller (PLC) performing the required function; namely the opening/closing of a hydraulic servo-valve. Forming roller position encoders are used to verify that the assigned command was satisfied. The servo-valve controls the flow of hydraulic oil to each forming roller actuator. Vertical movement of the saddle assembly was also monitored by a PLC, and controlled by raising or lowering a hydraulic cylinder. The PLCs then report back to the CNC system after a command has been successfully executed. Figures 3.2 – 3.4 show the exterior and the interior components of the WF VSTR 400 flow forming machine.
The SMFF process begins by automatically loading a pre-stamped AISI 1020 steel blank, circular in shape and about “8.5” mm thick, onto the upper surface of the mandrel. The work piece was then secured to the top of the mandrel by a tailstock clamp. The work piece / mandrel assembly was then made to rotate at 300 rpm and the saddle/forming roller assembly, initially located above the mandrel, was then lowered into position. As the assembly was lowered, actuators connected to each forming roller, forced the rollers against the spinning work piece causing it to conform to the shape of the splined mandrel. Water-based coolant was used to reduce the work piece temperature during the flow forming process.
Figure 3.3: First few passes of the forming rollers, displacing the work piece material and forcing it to conform to the shape of the mandrel. Water-based coolant is directed on the work piece to reduce forming temperatures.

Upon completion, the forming rollers retract from the mandrel and the roller/saddle assembly was raised back above the mandrel to allow removal of the formed work piece from the mandrel.

Figure 3.4: Forming rollers in their retracted position after one complete cycle. The finished part, still on the mandrel, is shown in this figure.
Solid-state pressure transducers\(^3\) installed on the piston-side inspection port of the hydraulic actuators of the X1, X2, and X3 forming rollers measured the forming pressure during the flow forming procedure. The output from each transducer ranges from 1 to 5 VDC and represents a linear hydraulic pressure response from 0 to 150 bar. Equation 3.1 was used to convert the hydraulic pressure \(P\) into force \(F\) acting on the forming roller as:

\[
F = P \left( \frac{\pi}{4} \right) \left( d_0^2 - d_i^2 \right) \tag{3.1}
\]

where \(d_0\) is the outer diameter of the hydraulic piston and \(d_i\) is the diameter of the piston shaft.

Real-time capture of the hydraulic pressures applied to each forming roller was achieved at a rate of 100 readings per second by interfacing each pressure transducer to an external Data AcQuisition (DAQ) system\(^4\). The reported accuracy of the transducers is \(< +/-0.5\%\) full scale deflection (\(+/- 25\) mV or \(+/- 0.73\) kN (Eq. 3.1)).

In this experiment we are particularly interested in measuring the maximum roller forming force, \(F_{\text{MAX}}\), during the SMFF process. This global maximum force occurs on the X1 roller during the third pass as the roller forms the work piece over the large splines of the lower part of the mandrel (Figure 2.2).

3.2: Statistical analysis of Results

Although the Taguchi method is not used directly in this study, the results obtained from this “factorial based” study were analyzed using the Signal-to-Noise, S/N, ratio as outlined in Section 2.7 of the previous chapter.

\(^3\) Manufactured by AST Sensor, Model Number AST4100A02500B3D00000

\(^4\) Manufactured by National Instruments, Model Number USB 6009
Two process parameters, $O_a$ and $\theta$, were assessed using a factorial based design of experiments, DOE (i.e. 2 variables studied at 4 levels $= 2^4 = 16$ tests performed (Table 3.1)).

Table 3.1: Breakdown of the factorial based design of experiment for two process parameters ($O_a$, $\theta$), each studied at four levels.

<table>
<thead>
<tr>
<th>Exp. #</th>
<th>P1 - $O_a$ (mm from current industrial setting)</th>
<th>P2 - $\theta$ ($^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>-1.25</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>1.25</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>5.00</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>0.00</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>-1.25</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
<td>1.25</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>5.00</td>
<td>10</td>
</tr>
<tr>
<td>9</td>
<td>0.00</td>
<td>15</td>
</tr>
<tr>
<td>10</td>
<td>-1.25</td>
<td>15</td>
</tr>
<tr>
<td>11</td>
<td>1.25</td>
<td>15</td>
</tr>
<tr>
<td>12</td>
<td>5.00</td>
<td>15</td>
</tr>
<tr>
<td>13</td>
<td>0.00</td>
<td>20</td>
</tr>
<tr>
<td>14</td>
<td>-1.25</td>
<td>20</td>
</tr>
<tr>
<td>15</td>
<td>1.25</td>
<td>20</td>
</tr>
<tr>
<td>16</td>
<td>5.00</td>
<td>20</td>
</tr>
</tbody>
</table>
All tests were performed under the following conditions: \( \omega = 300 \text{rpm}, \dot{X} = 220 \text{mm/min}, r_0 = 15 \text{mm} \) and \( R = 287.28 \text{mm} \). The variation in the maximum roller forming force, \( F_{\text{MAX}} \), was evaluated ranking each combination of \( Oa \) and \( \theta \) based on their effect on the resulting S/N ratio (Equation 2.2).

Roller force data recorded from the X1 forming roller during the third pass was collected for each of the tests presented in Table 3.1. Converting the pressure to a hydraulic force using Equations 3.1, the shape and magnitude of the force-oscillation (Figure 2.12) is a result of the forming roller passing over the splines of the mandrel.

To calculate the interaction of the parameter \( Oa \) on the overall process output, as indicated by the parameter \( F_{\text{MAX}} \) of the X1 forming roller, the value of \( Oa \) was kept constant and the variation in S/N (Equation 2.2) was measured over the range of \( \theta \) from \( 8^\circ \) to \( 20^\circ \). Similarly, the interaction of \( \theta \) with respect to each level of \( Oa \) was studied by holding \( \theta \) constant and measuring the average S/N ratios over the range of \( Oa \) from -1.25 to 5.00 mm from the current industrial setting.

Each of the experimental combinations of \( Oa \) and \( \theta \) (Table 3.2), characterizes the impact of each processing parameter on the \( F_{\text{MAX}} \) of the X1 roller during the third pass of an SMFF process. The range, \( \Delta d \), is calculated by subtracting the minimum S/N ratio from the maximum S/N ratio for each processing parameter (Table 3.2). The larger the \( \Delta d \) value, the greater the influence the particular processing parameter on the \( F_{\text{MAX}} \) of the X1 forming roller.
Table 3.2: Listing of analyses conducted to assess the sensitivity of the average $F_{MAX}$ of the X1 forming roller to the process parameters $Oa$ and $\theta$; the larger the $\Delta d$, the higher the ranking of importance of the process parameter.

<table>
<thead>
<tr>
<th>Level</th>
<th>$Oa$</th>
<th>$\theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Avg. S/N of exp.’s 1-4</td>
<td>Avg. S/N of exp.’s 1,5,9,13</td>
</tr>
<tr>
<td>2</td>
<td>Avg. S/N of exp.’s 5-8</td>
<td>Avg. S/N of exp.’s 2,6,10,14</td>
</tr>
<tr>
<td>3</td>
<td>Avg. S/N of exp.’s 9-12</td>
<td>Avg. S/N of exp.’s 3,7,11,15</td>
</tr>
<tr>
<td>4</td>
<td>Avg. S/N of exp.’s 13-16</td>
<td>Avg. S/N of exp.’s 4,8,12,16</td>
</tr>
<tr>
<td>$\Delta d$</td>
<td>$S/N_{MAX} - S/N_{MAX}$</td>
<td>$S/N_{MAX} - S/N_{MAX}$</td>
</tr>
</tbody>
</table>

Hence, if $Oa$ were to record the maximum “$\Delta d$”, this analysis will suggest that it is the parameter, of the ones studied, that has the greatest affect on the process output (i.e. $F_{MAX}$ of the X1 roller). Section 4.1 presents the results from the above analysis.

3.3: Description of the experimental trials

3.3.1: Roller inclination angle, $\theta$

The roller inclination angle, $\theta$, also commonly referred to as the Front or attack angle, is the angle located between the tangent of the roller profile and the horizontal work piece surface (Figure 3.5).

SMFF tests were conducted using four X1 forming rollers were fabricated from M6 tool steel. Each forming roller was machined to have a different $\theta$ value. Experimental values of $\theta$ studied were 8, 10, 15, 20, $22^\circ$. 
3.3.2: Vertical offset-inter roller offset

For a vertically-aligned, staggered roller arrangement, the vertical position of each forming roller (Figure 3.1) can be adjusted. With no previous research published on the effects of inter-roller offset, the following offset conditions were selected.

1. Baseline conditions (current production settings)
2. Increased vertical offset from the current production settings (1.25, 5.0mm)
3. Decreased vertical offset from the current production settings (-1.25mm)

By increasing or decreasing the inter-roller offset distance, $O_{a1}$ illustrated previously in Figure 3.1, the vertical offset of one forming roller with respect to the other can be optimized depending on the process requirements (Figure 3.6). Details of these changes will be discussed later in chapter 4.
3.3.3: Roller nose radius, $r_0$

Due to the flexibility and ease of modification, roller nose radius trials were also carried out in an attempt to further improve our understanding of the SMFF process. For a slightly larger or smaller roller nose radius, $r_0$, the roller surface expands or contracts depending on the magnitude of the roller inclination angle. For the purpose of this thesis, experimental trials were carried out on X1 forming rollers machined with roller nose radius of 10, 12 and 15mm.

Two additional processing parameters ($\dot{X}$ and $\omega$) were also studied and the sensitivity of $F_{\text{MAX}}$ to these parameters was assessed. Section 4.2.3 presents these results.
3.4: Additional experimental tests focusing on the third pass

In order to identify the optimal forming conditions, additional tests were carried out to further assess the effect of roller inclination angle, $\theta$, and roller nose radius, $r_0$. The objective of these tests was to identifying the points at which $F_{\text{MAX}}$ converges to optimum forming conditions.

3.4.1: Roller inclination angle, $\theta=22^\circ$, evaluated at each level defined by the Taguchi method

Reviewing the data from each of the trials conducted during the factorial-based analysis of the effect of $Oa$ and $\theta$ showed room for additional tests; namely, $\theta=22^\circ$ for the range of inter-roller offset conditions tested. These tests were designed to confirm that the optimal $F_{\text{MAX}}$ as reached in the study.

3.4.2: Additional tests to assess the effect of $r_0$ evaluated at different levels of $\omega$, $X$, and TR

During flow forming processes it is observed that excessive wear along the roller/work piece contact interface generally results from increased roller forming forces. A comprehensive assessment was made of the effect of mandrel rotational speed, $\omega$, axial feed rate, $X$, and thickness reduction, TR, (Table 3.3) on $F_{\text{MAX}}$ for three forming rollers machined with different roller nose radii ($r_0=10$, 12 and 15mm). The series of 6 tests were conducted for each roller nose radius, to measure and compare the difference of $F_{\text{MAX}}$ relative to current production SMFF settings.
Table 3.3: Roller nose radii trials evaluated at alternative thickness reduction ratios, axial roller feed rate and mandrel rotational speeds. All tests were modified from the current industrial settings.

<table>
<thead>
<tr>
<th></th>
<th>$F_{\text{MAX}}$ at $r_0=10, 12, 15\text{mm (kN)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>Production settings</td>
</tr>
<tr>
<td>Test 1</td>
<td>TR=-0.2mm from prod. setting</td>
</tr>
<tr>
<td>Test 2</td>
<td>TR=+0.2mm from prod. setting</td>
</tr>
<tr>
<td>Test 3</td>
<td>$\dot{X} = 180$ (mm/min)</td>
</tr>
<tr>
<td>Test 4</td>
<td>$\dot{X} = 275$ (mm/min)</td>
</tr>
<tr>
<td>Test 5</td>
<td>$\omega = 310$ (rpm)</td>
</tr>
<tr>
<td>Test 6</td>
<td>$\omega = 290$ (rpm)</td>
</tr>
</tbody>
</table>

It should be noted that for all of the tests described above, small changes to the CNC program were required in order to produce a high quality part of suitable dimensional accuracy.

3.4.3: Extended trials for the observed optimal forming conditions

Upon review of the results from the extensive tests described above, optimal conditions of $Oa$, $\theta$, $r_0$ were selected and were applied to actual industrial SMFF trials to determine if these settings resulted in extended mandrel service life. This assessment was completed by comparing the number of parts made prior to mandrel spline failure for SMFF machines running under optimal conditions to identical flow forming machines performing under the currently accepted process parameter settings. The results of these studies are presented in Chapter 5.2.
3.5: References


Chapter 4
Experimental Results

The aim of this thesis is to investigate effect of certain key process parameters; namely, the inter-roller offset, \( O_a \), roller inclination angle, \( \theta \), mandrel speed, \( \omega \), and the axial feed rate, \( \dot{x} \), on the X1 forming force during the third pass of a SMFF operation in order to come up with the optimal process parameter conditions that will maximize the service life of the splined mandrel.

In this analysis the maximum roller force, \( F_{\text{MAX}} \), and the magnitude of force oscillations, \( \Delta F \), are tracked as a function of the process parameter settings. The results of the tests are therefore presented in the form of figures showing \( F \) versus position along the splined mandrel (Figure 4.1) and tables showing \( F_{\text{MAX}} \) and \( \Delta F \) for the various conditions tested (Table 4.1). A total of 550 SMFF tests were performed measuring the effect of \( O_a, \theta, \omega, \dot{x}, r_0 \) on the roller force trace during the mandrel spline region, which has reported by industrial users that is the critical life-limiting factor in many SMFF processes.
4.1: Results from the Taguchi analysis of the effect of Oa and θ

The effect of Oa, and θ on $F_{\text{MAX}}$ of the X1 forming roller during the third pass was analyzed by performing sixteen SMFF tests at four levels of Oa and θ. Additional tests, carried out at $\theta = 22^\circ$, were also included for a complete comparison of all roller forming angles. A total of twenty tests were performed (Table 4.1). All tests were performed under the following conditions: $\omega = 300 \text{ rpm}$, $\ddot{x} = 220 \text{ mm/min}$, $r_0 = 15 \text{ mm}$ and $R = 287.28 \text{ mm}$.

4.1.1: X1 Roller force vs. axial roller position

Figures 4.1 and 4.2 show the X1 roller force versus axial roller position during the third pass of SMFF tests performed at the various levels of Oa and θ. These results are similar in profile to the results obtained from the 550 SMFF tests performed in this study under the conditions described in sections 3.3 and 3.4. For each of these tests, $F_{\text{MAX}}$ was assessed as shown in Figures 2.2 and 2.12.

For the range of inter-roller offset conditions tested, the nature of the oscillation in the roller force corresponded to the frequency at which the X1 roller crossed over the mandrel splines (Figure 4.1). The frequency was similar for all of the tests since $\omega$, and $\ddot{x}$ were held constant.
Table 4.1: Maximum roller forming forces, $F_{\text{MAX}}$, during the third forming pass for a factorial analysis of the effect of $Oa$ and $\theta$ on the third pass of an AISI 1020 steel work piece.

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>$\theta$ ($^\circ$)</th>
<th>$Oa$ (mm from current industrial setting)</th>
<th>$F_{\text{MAX}}$ (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>-1.25</td>
<td>93.87</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>0.00</td>
<td>92.20</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>1.25</td>
<td>113.67</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>5.0</td>
<td>89.61</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>-1.25</td>
<td>94.19</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>0.00</td>
<td>93.80</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>1.25</td>
<td>112.17</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>5.0</td>
<td>88.99</td>
</tr>
<tr>
<td>9</td>
<td>15</td>
<td>-1.25</td>
<td>88.22</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>0.00</td>
<td>93.17</td>
</tr>
<tr>
<td>11</td>
<td>15</td>
<td>1.25</td>
<td>102.00</td>
</tr>
<tr>
<td>12</td>
<td>15</td>
<td>5.0</td>
<td>93.68</td>
</tr>
<tr>
<td>13</td>
<td>20</td>
<td>-1.25</td>
<td>83.88</td>
</tr>
<tr>
<td>14</td>
<td>20</td>
<td>0.00</td>
<td>90.67</td>
</tr>
<tr>
<td>15</td>
<td>20</td>
<td>1.25</td>
<td>84.12</td>
</tr>
<tr>
<td>16</td>
<td>20</td>
<td>5.0</td>
<td>92.88</td>
</tr>
<tr>
<td>17</td>
<td>22</td>
<td>-1.25</td>
<td>87.47</td>
</tr>
<tr>
<td>18</td>
<td>22</td>
<td>0.00</td>
<td>108.12</td>
</tr>
<tr>
<td>19</td>
<td>22</td>
<td>1.25</td>
<td>114.79</td>
</tr>
<tr>
<td>20</td>
<td>22</td>
<td>5.0</td>
<td>93.52</td>
</tr>
</tbody>
</table>

For all of the tests shown in Figure 4.1, one can see that the magnitude of the force oscillations changed in a systematic way with roller position along the
mandrel. This is very likely due to the geometry of both the mandrel splines and the X1 forming roller. As a result, $F_{\text{MAX}}$ always occurs at a position, $x=1.2-1.4\text{mm}$ from the leading edge of the lower mandrel spline. Comparing the plots in Figure 4.2, one can also see that the variation in $F_{\text{MAX}}$ over the range of Oa tested was reduced when the roller inclination angle, $\theta$, was increased.

![Figure 4.1a: Force-oscillation during the third pass for various conditions of Oa at $\theta=8^\circ$.](image)

Figures 4.1 (a) and (b) indicate that rollers machined with smaller inclination angles, $\theta=8$ and $10^\circ$, resulted in the lowest $F_{\text{MAX}}$ when the inter-offset distance was increased by 5.0 mm relative to the current production offset. Minor differences in the cyclic amplitude (force-oscillation) were observed in Figures 4.2 (a) and (b) for tests conducted with $\theta=8$ and $10^\circ$ forming rollers. This is likely due to the roller nose profile limiting the extent to which the roller surface impacts the leading and trailing edge of the mandrel spline. When $\theta$ was increased to $15^\circ$, the measured variation, $\Delta F$, in the roller force during the third pass was significantly reduced for all Oa conditions tested (Figure 4.1c).
4.1.b: Force-oscillation during the third pass for various conditions of Oa at \( \theta = 10^\circ \).

4.1c: Force-oscillation during the third pass for various conditions of Oa at \( \theta = 15^\circ \).
With an increase to the roller inclination angle, $F_{\text{MAX}}$ was observed to decrease slightly, suggesting that $F_{\text{MAX}}$ is related to both $Oa$ and $\theta$. The magnitude of the force-oscillation for each condition of $Oa$ also increased when $\theta$ was increased beyond 10°. These observations can be explained in terms of the effect of $\theta$ on the shape of the roller nose region, which comes into contact with the work piece. For a larger roller inclination angle, the nose region is much more prominent, resulting in greater impact force as the roller crosses over the mandrel splines.

Setting the X1 roller inclination angle to $\theta=20^\circ$ resulted in optimal forming conditions across the full range of $Oa$ tested (Figure 4.1d). The magnitude of the force-oscillation remained constant for each condition of $Oa$, with little to no variation in $F_{\text{MAX}}$ observed for each test.

4.1d: Force-oscillation during the third pass for various conditions of $Oa$ at $\theta=20^\circ$

4.1.2: Analysis of the S/N ratio: Ranking of process parameters ($Oa, \theta$)

The Signal-to-Noise (S/N) ratio of $F_{\text{MAX}}^2$ (Equation 2.2) was assessed to rank the influence of the two parameters, $Oa$ and $\theta$, on the SMFF process. The S/N ratio
(Equation 2.2) was calculated for the first 16 experimental trials listed in Table 4.1 and these values are shown in Table 4.2.

Table 4.2: Signal-to-Noise analysis of $F_{\text{MAX}}$ results for the array of experimental tests presented in table 4.1.

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>Oa (mm)</th>
<th>$\theta$ (°)</th>
<th>S/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1.25</td>
<td>8</td>
<td>43.96</td>
</tr>
<tr>
<td>2</td>
<td>0.00</td>
<td>8</td>
<td>28.08</td>
</tr>
<tr>
<td>3</td>
<td>1.25</td>
<td>8</td>
<td>31.45</td>
</tr>
<tr>
<td>4</td>
<td>5.00</td>
<td>8</td>
<td>43.02</td>
</tr>
<tr>
<td>5</td>
<td>-1.25</td>
<td>10</td>
<td>41.63</td>
</tr>
<tr>
<td>6</td>
<td>0.00</td>
<td>10</td>
<td>36.46</td>
</tr>
<tr>
<td>7</td>
<td>1.25</td>
<td>10</td>
<td>30.97</td>
</tr>
<tr>
<td>8</td>
<td>5.00</td>
<td>10</td>
<td>21.75</td>
</tr>
<tr>
<td>9</td>
<td>-1.25</td>
<td>15</td>
<td>45.89</td>
</tr>
<tr>
<td>10</td>
<td>0.00</td>
<td>15</td>
<td>43.44</td>
</tr>
<tr>
<td>11</td>
<td>1.25</td>
<td>15</td>
<td>46.30</td>
</tr>
<tr>
<td>12</td>
<td>5.00</td>
<td>15</td>
<td>41.51</td>
</tr>
<tr>
<td>13</td>
<td>-1.25</td>
<td>20</td>
<td>52.46</td>
</tr>
<tr>
<td>14</td>
<td>0.00</td>
<td>20</td>
<td>46.90</td>
</tr>
<tr>
<td>15</td>
<td>1.25</td>
<td>20</td>
<td>48.18</td>
</tr>
<tr>
<td>16</td>
<td>5.00</td>
<td>20</td>
<td>48.97</td>
</tr>
</tbody>
</table>

The following eight average S/N ratios were calculated:

1. **SNp11**: Avg. S/N value of experiments 1-4 (all conditions of Oa at $\theta=8^\circ$)
2. **SNp12**: Avg. S/N value of experiments 5-8 (all conditions of Oa at $\theta=10^\circ$)
3. **SNp13**: Avg. S/N value of experiments 9-12 (all conditions of Oa at $\theta=15^\circ$)
4. **SNp14**: Avg. S/N value of experiments 13-16 (all conditions of Oa at $\theta=20^\circ$)
5. **SNp21**: Avg. S/N value of experiments 1,5,9,13 ($\theta=8^\circ$ for all conditions of Oa)
6. SNp22: Avg. S/N value of experiments 2,6,10,14 (θ=10° for all conditions of Oa)
7. SNp23: Avg. S/N value of experiments 3,7,11,15 (θ=15° for all conditions of Oa)
8. SNp24: Avg. S/N value of experiments 4,8,12,16 (θ=20° for all conditions of Oa)

Before we can determine the ranking of each process parameter, the maximum difference, ∆d, between each of the average S/N ratios for the eight scenarios presented above was calculated. The greater the magnitude of ∆d, the greater the dependence of the process output, i.e. $F_{\text{max}}^2$, is on the particular parameter studied. It is this value that is used to rank the two process variables Oa and θ as shown in Table 4.3.

Table 4.3: Average S/N ratios for Oa and θ at each of the four levels studied.

<table>
<thead>
<tr>
<th>All conditions of Oa at θ=8°</th>
<th>Oa</th>
<th>All conditions of θ at Oa= -1.25mm from current production settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>All conditions of Oa at θ=10°</td>
<td>32.70</td>
<td>All conditions of θ at Oa= current production settings</td>
</tr>
<tr>
<td>- avg. S/N value of exp. 5-8</td>
<td></td>
<td>- avg. S/N value of exp. 2,6,10,14</td>
</tr>
<tr>
<td>All conditions of Oa at θ=15°</td>
<td>44.29</td>
<td>All conditions of θ at Oa= 1.25mm from current production settings</td>
</tr>
<tr>
<td>- avg. S/N value of exp. 9-12</td>
<td></td>
<td>- avg. S/N value of exp. 3,7,11,15</td>
</tr>
<tr>
<td>All conditions of Oa at θ=20°</td>
<td>49.13</td>
<td>All conditions of θ at Oa= 5.00mm from current production settings</td>
</tr>
<tr>
<td>- avg. S/N value of exp. 13-16</td>
<td></td>
<td>- avg. S/N value of exp. 4,8,12,16</td>
</tr>
<tr>
<td>θ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>45.99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>51.63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>39.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>38.81</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4.4 collects the S/N ratios shown in Table 4.3 and groups them in terms of tests where either Oa or \( \theta \) were held constant. For each level illustrated in Table 4.4, one variable, i.e. Oa or \( \theta \), is held constant while the S/N ratio, or the interaction between the range of test conditions are calculated. The maximum difference, \( \Delta d \), between each of the average S/N ratios is shown in Table 4.4. By comparing the magnitude of \( \Delta d \) one can conclude that the inter-roller offset (Oa) has a greater affect than \( \theta \) on \( F_{\text{MAX}} \) during the third pass of the SMFF process.

Table 4.4: The ranking of Oa and \( \theta \) is based upon the parameter with the larger differential, \( \Delta d \).

<table>
<thead>
<tr>
<th>Level</th>
<th>Oa</th>
<th>( \theta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>36.63</td>
<td>45.99</td>
</tr>
<tr>
<td>2</td>
<td>32.70</td>
<td>51.63</td>
</tr>
<tr>
<td>3</td>
<td>44.29</td>
<td>39.23</td>
</tr>
<tr>
<td>4</td>
<td>49.13</td>
<td>38.81</td>
</tr>
<tr>
<td>( \Delta d )</td>
<td>16.43</td>
<td>12.81</td>
</tr>
<tr>
<td>Rank</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Comparing the results of S/N\(_{\text{AVG}}\), the difference or \( \Delta d \) between each level of Oa and \( \theta \) performed during individual SMFF parametric studies identified the optimal forming condition the inter-roller offset distance. The maximum roller forming force, \( F_{\text{MAX}} \), from each of the 16 SMFF tests was found to be minimum when modifications to the inter-roller offset were made.

### 4.2: Results from the additional tests

To confirm that the test results presented in the previous section accurately determined the optimal SMFF processing conditions, additional tests were conducted to verify that the point at which \( F_{\text{MAX}} \) was minimum corresponded to
the predicted optimal forming conditions (Scenarios 1 and 2) additional inter-roller offset/roller inclination angle trials (Tests 17 – 20, Table 4.1) were for \( \theta = 22^\circ \). Additional experimental trials were also conducted to study the effect of roller nose radius on the \( F_{\text{max}} \).

4.2.1: Analysis of the effect of Oa and \( \theta \) upon \( F_{\text{MAX}} \)

Tests were performed at different combinations of Oa and \( \theta \) to investigate their effect of the on the \( F_{\text{MAX}} \) and the force-oscillation, \( \Delta F \), of the X1 forming roller during the third pass of a SMFF process. The results from these tests are shown in the plots of F versus axial distance shown in Figure 4.2. The shape and the magnitude of the X1 roller forming force was very different for each combination of Oa and \( \theta \) tested. The test data tended to fall into two categories: (1) Tests where \( F_{\text{MAX}} \) was large but \( \Delta F \) was small, and (2) Tests where \( F_{\text{MAX}} \) was small but \( \Delta F \) was large.

These data presented in a systematic fashion in the following sub-sections.

4.2.1.1: Effect of \( \theta \) on \( F_{\text{MAX}} \) and \( \Delta F \) when Oa = 0.00 mm

When the X1-X2 inter-roller offset distance was set at zero (i.e. Oa was set at the current production settings) \( F_{\text{MAX}} \) increased by 3kN, or 6.15% from \( \theta = 8 \) to \( 10^\circ \). When the forming roller inclination angle exceeded \( 10^\circ \) \( F_{\text{MAX}} \) decreased (Figure 4.2a). When \( \theta = 20^\circ \) \( F_{\text{MAX}} \) was reduced by 4kN, or 8.25%. Combining the test results from each experimental trial, one can see that the magnitude of \( F_{\text{MAX}} \) increases on either side of the \( \theta = 20^\circ \) (Table 4.5).
The magnitude of the force-oscillation $\Delta F$ for each roller inclination angle tested remained nearly constant with the exception of $\theta=10^\circ$. The $\theta=10^\circ$ forming roller displayed the lowest $\Delta F$ of 11.84kN, while the $\theta=20^\circ$ forming roller generated the largest $\Delta F$ of 17.98kN (Table 4.5).

Table 4.5: Values of $F_{MAX}$, and $\Delta F$ for third pass SMFF tests performed at Oa=0mm from the current production settings.

<table>
<thead>
<tr>
<th>$\theta$ ($^\circ$)</th>
<th>$F_{MAX}$ (kN)</th>
<th>$\Delta F$ (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>111.79</td>
<td>16.42</td>
</tr>
<tr>
<td>10</td>
<td>111.51</td>
<td>11.84</td>
</tr>
<tr>
<td>15</td>
<td>109.92</td>
<td>16.33</td>
</tr>
<tr>
<td>20</td>
<td>105.59</td>
<td>17.98</td>
</tr>
<tr>
<td>22</td>
<td>108.12</td>
<td>14.06</td>
</tr>
</tbody>
</table>
4.2.1.2: Effect of $\theta$ on $F_{\text{MAX}}$ and $\Delta F$ when $Oa = +1.25$ mm

For an increase to the inter-roller offset of $+1.25\text{mm}$ from the current production settings considerable differences in $F_{\text{MAX}}$, and $\Delta F$ were observed (Figure 4.2b).

![Graph](image)

4.2b: Roller force-oscillation for $\theta=8, 10, 15, 20,$ and $22^\circ$ at $Oa=+1.25\text{mm}$.

The magnitude of $F_{\text{MAX}}$ decreased by $22\text{kN}$, or $26\%$, for $\theta=20^\circ$ while a lesser effect was observed for $\theta=15^\circ$ (Table 4.6). Otherwise, the magnitude of $F_{\text{MAX}}$ remained nearly constant, and slightly greater than the results from the previous test conditions ($Oa=0.00\text{mm}$).

When $\theta$ was small ($\theta=8$ and $10^\circ$) $\Delta F$ was also small ($\Delta F=7$ to $10\text{kN}$). The $\Delta F$ values were considerably higher, twice in magnitude, when $\theta \geq 15^\circ$ (Table 4.6). It was qualitatively observed during the testing that when $Oa$ was large, as was the case for the tests shown in Figure 4.2b and Table 4.6, the X1 forming rollers with $\theta \leq 10^\circ$ tended to move more smoothly over the mandrel splines, while the rollers with $\theta \geq 15^\circ$ caused audible knocking as they passed over the leading/trailing
edges of the splines. This was the likely reason of the larger $\Delta F$ when $\theta \geq 15^\circ$ (Table 4.6).

Table 4.6: Values of $F_{\text{MAX}}$ and $\Delta F$ for third pass SMFF tests performed at Oa=+1.25mm from the current production settings.

<table>
<thead>
<tr>
<th>$\theta$ ($^\circ$)</th>
<th>$F_{\text{MAX}}$ (kN)</th>
<th>$\Delta F$ (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>113.67</td>
<td>9.45</td>
</tr>
<tr>
<td>10</td>
<td>112.17</td>
<td>7.83</td>
</tr>
<tr>
<td>15</td>
<td>102.00</td>
<td>18.62</td>
</tr>
<tr>
<td>20</td>
<td>84.11</td>
<td>18.38</td>
</tr>
<tr>
<td>22</td>
<td>114.79</td>
<td>19.95</td>
</tr>
</tbody>
</table>

4.2.1.3: Effect of $\theta$ on $F_{\text{MAX}}$ and $\Delta F$ when Oa = +5.00 mm

When the X1-X2 inter-roller offset was set to the maximum allowable distance, i.e. Oa = +5.00mm greater than the current production setting, $F_{\text{MAX}}$ displays the lowest values when $\theta$ was small (Figure 4.2c, Table 4.7).

4.2c: Roller force-oscillation for $\theta=8$, 10, 15, 20, and 22° at Oa=+5.00mm.
F_{MAX} was reduced by roughly 2.77kN, or 5.0%, when θ=8 and 10°. F_{MAX} increased by 0.95% when θ=15° and increased to 8.92 kN (7.2%) when θ=20 and 22°. For this particular Oa, the optimal forming conditions occurred at θ=8° with all other values of θ displaying higher levels of F_{MAX}. When the X1 roller inclination angle was small (θ=8 and 10°) ∆F was slightly smaller compared to equivalent tests performed with Oa=0.00 mm and slightly larger when Oa=+1.25mm from the current production setting (Tables 4.5 - 4.7). For the larger roller inclination angles, θ=20 and 22°, the ∆F was significantly larger, ∆F=19.79 to 21.31 kN, than equivalent tests performed with smaller Oa values.

An axial offset distance of Oa = +5.00 mm from the current production setting indicates a very large spacing between the X1 and X2 forming rollers. Under these conditions excessive noise and vibration was generated during the experimental trials. This is may explain the drastic increase in the roller force oscillations shown in Table 4.7.

Table 4.7: Values of F_{MAX}, and ∆F for third pass SMFF tests performed at Oa=+5.00 mm from the current production settings.

<table>
<thead>
<tr>
<th>θ (°)</th>
<th>F_{MAX} (kN)</th>
<th>∆F (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>89.60</td>
<td>12.20</td>
</tr>
<tr>
<td>10</td>
<td>88.99</td>
<td>13.18</td>
</tr>
<tr>
<td>15</td>
<td>93.68</td>
<td>21.31</td>
</tr>
<tr>
<td>20</td>
<td>92.88</td>
<td>21.18</td>
</tr>
<tr>
<td>22</td>
<td>93.52</td>
<td>19.79</td>
</tr>
</tbody>
</table>

4.2.1.4: Effect of θ on F_{MAX} and ∆F when Oa = -1.25 mm

For a decrease in the inter-roller offset of 1.25mm from the current production settings, the θ=20° forming roller orientation performed best, reducing F_{MAX} by 27.4% when compared to results obtained from the current production settings (Figure 4.2 (a) and (d)). The forming force recorded for θ=22° also performed
very well, reducing $F_{\text{MAX}}$ by nearly 22%. $F_{\text{MAX}}$ was observed to increase when $\theta$ was decreased. For this particular value of $Oa$, $F_{\text{MAX}}$ varied by only 5% across the full range of $\theta$ tested.

4.2d: Roller force-oscillation for $\theta=8, 10, 15, 20, \text{ and } 22^\circ$ at $Oa=-1.25\text{mm}$.

Although slightly above average, the magnitude of $\Delta F$ was also found to minimum when $\theta=20^\circ$ (Table 4.8). This combination of $F_{\text{MAX}}$ and $\Delta F$ presents a unique forming condition where both $F_{\text{MAX}}$ and $\Delta F$ were found to be a minimum at the same value of $\theta$.

Table 4.8: Values of $F_{\text{MAX}}$, and $\Delta F$ for third pass SMFF tests performed at $Oa=-1.25\text{ mm}$ from the current production settings.

<table>
<thead>
<tr>
<th>$\theta$ ($^\circ$)</th>
<th>$F_{\text{MAX}}$ (kN)</th>
<th>$\Delta F$ (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>93.87</td>
<td>15.43</td>
</tr>
<tr>
<td>10</td>
<td>94.19</td>
<td>18.22</td>
</tr>
<tr>
<td>15</td>
<td>88.22</td>
<td>16.12</td>
</tr>
<tr>
<td>20</td>
<td>83.88</td>
<td>14.78</td>
</tr>
<tr>
<td>22</td>
<td>87.47</td>
<td>17.03</td>
</tr>
</tbody>
</table>
Reviewing the results of $F_{\text{MAX}}$ presented in Table 4.1 and the force-oscillations from each of the 16 tests (Figures 4.1 and 4.2), the two optimal forming conditions where $F_{\text{MAX}}$ and $\Delta F$ improved the existing SMFF process with $Oa$ being the dominant process parameter were:

Scenario 1: $Oa=+1.25\text{mm from current production settings, } \theta=20^\circ$

Scenario 2: $Oa=-1.25\text{mm from current production settings, } \theta=8^\circ$

4.2.2: The effect of roller nose radius, $r_0$, on $F_{\text{MAX}}$

Of all the flow forming process parameters studied in the past the effect of roller nose radius, $r_0$, (Figure 2.2) on the roller forming force is studied the most [1 - 3]. In this section results are presented from 21 SMFF tests conducted to assess the effect of $r_0$ on $F_{\text{MAX}}$ under different conditions of $\omega$, $\lambda$, and thickness reduction (Table 3.3, 4.9).

Table 4.9: Breakdown of the additional roller nose radius tests with the corresponding maximum roller forming forces measured during the third pass. The test conditions are presented in Table 3.3.

<table>
<thead>
<tr>
<th>$r_0=10\text{mm}$</th>
<th>$F_{\text{MAX}}$ (kN)</th>
<th>$\Delta F$</th>
<th>$r_0=12\text{mm}$</th>
<th>$F_{\text{MAX}}$ (kN)</th>
<th>$\Delta F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>89.27</td>
<td>15.11</td>
<td>Baseline</td>
<td>89.92</td>
<td>16.29</td>
</tr>
<tr>
<td>Test 1</td>
<td>88.63</td>
<td>18.33</td>
<td>Test 1</td>
<td>90.24</td>
<td>18.21</td>
</tr>
<tr>
<td>Test 2</td>
<td>87.10</td>
<td>19.77</td>
<td>Test 2</td>
<td>88.60</td>
<td>18.39</td>
</tr>
<tr>
<td>Test 3</td>
<td>90.52</td>
<td>18.57</td>
<td>Test 3</td>
<td>90.46</td>
<td>17.49</td>
</tr>
<tr>
<td>Test 4</td>
<td>86.98</td>
<td>18.15</td>
<td>Test 4</td>
<td>88.91</td>
<td>18.99</td>
</tr>
<tr>
<td>Test 5</td>
<td>89.63</td>
<td>22.02</td>
<td>Test 5</td>
<td>89.02</td>
<td>21.07</td>
</tr>
<tr>
<td>Test 6</td>
<td>88.89</td>
<td>16.46</td>
<td>Test 6</td>
<td>87.94</td>
<td>15.52</td>
</tr>
<tr>
<td>$r_0=15\text{mm}$</td>
<td>$F_{\text{MAX}}$ (kN)</td>
<td>$\Delta F$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------</td>
<td>---------------------</td>
<td>--------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>89.80</td>
<td>17.24</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test 1</td>
<td>88.82</td>
<td>18.61</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test 2</td>
<td>87.45</td>
<td>18.64</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test 3</td>
<td>88.84</td>
<td>18.71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test 4</td>
<td>87.74</td>
<td>18.78</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test 5</td>
<td>88.04</td>
<td>21.24</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test 6</td>
<td>88.50</td>
<td>16.44</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For an increase or decrease in the work piece thickness reduction ratio, (tests 1 and 2) slight improvements to the $F_{\text{MAX}}$ were observed for $r_0=10$ and 12mm. For a decrease in the axial roller feed rate, test 4, $r_0=10\text{mm}$ performed the best, lowering the $F_{\text{MAX}}$ by 3kN while the larger roller radius, $r_0=15\text{mm}$, performed best for an increased axial roller feed rate. For the last two tests, where the effect of mandrel rotational speed was studied, rollers with $r_0=12$ and 15mm performed the best, lowering the $F_{\text{MAX}}$ by 2 kN. Regardless of the roller geometry and CNC settings, the maximum decrease in $F_{\text{MAX}}$ was 6%, or 3 kN.

The results presented in Figures 4.3(a) through (c) illustrate the force-oscillation of Roller nose radii trials, $r_0=10,12$ and 15mm, evaluated at alternative work piece TR ratios ($\pm0.3\text{mm from current production settings}$), $\dot{X}$ and $\omega$.  


Figure 4.3a: Roller nose radii trials, $r_0=10\text{mm}$, evaluated at alternative work piece TR ratios ($\pm 0.3\text{mm from current production settings}$), $X$ and $\omega$.

Figure 4.3b: Roller nose radii trials, $r_0=12\text{mm}$, evaluated at alternative work piece TR ratios ($\pm 0.3\text{mm from current production settings}$), $X$ and $\omega$. 
Comparing the results of $\Delta F$ for each of the six tests, Figures 4.3a-c, it was found that each of the test rollers lowered the peak value of $\Delta F$, specifically during test 6 (mandrel speed decreased to 290 rpm), below the maximum baseline force-oscillation. On the other hand, test 5 (increase mandrel rotational speed to 310rpm/min), caused the maximum force-oscillation to increase well above the baseline reading. For a TR of $+0.2\text{mm}$, the magnitude of the force-oscillation increased slightly for the range of roller radius trials tested. Similarly, when the axial feed rate is increased above the current production settings, $\Delta F$ also increased, yet on a much smaller scale.
4.3: References


Chapter 5
Discussion of Results

The objective of this thesis is to study the sensitivity to specific process parameters of the $F_{\text{MAX}}$ and $\Delta F$ exerted by the X1 forming roller during a SMFF process. The hypothesis that was followed was that the magnitude of $F_{\text{MAX}}$ and $\Delta F$ both determine how quickly the splines on the mandrel fail by fatigue during service. Therefore, setting the operating parameters; namely, $\theta$ and Oa, to values that minimize $F_{\text{MAX}}$ and/or $\Delta F$ will optimize the SMFF process by extending the life of the mandrel splines. The results of this study were presented in Chapter 4. Some important finding that arose from these tests were:

1) The X1-X2 inter-roller offset spacing, Oa, had the largest affect on $F_{\text{MAX}}$.

2) Two scenarios were identified that resulted in low values of $F_{\text{MAX}}$ and/or $\Delta F$ these were; 1) Oa=+1.25mm from current production settings, $\theta$=20° and 2) Oa=-1.25mm from current production settings, $\theta$=8°.
Section 5.1 presents the results of long term production trials that were then carried out under the above two scenarios to investigate if they actually resulted in prolonged mandrel life relative to current industrial settings.

Since most of the process parameters affect the roller/work piece contact area and, since the hardness of the work piece remains essentially constant, this contact area ultimately determines $F_{\text{MAX}}$ and $\Delta F$. Comparison was made between the contact area calculated from the measured forming force and the contact area determined from the semi-analytical technique presented by Roy et al. [1]. The results obtained from are presented in Section 5.2.

Finally, in Section 5.3, the Paris Law, used to describe fatigue crack growth rate, is applied to understand the combined effect of $F_{\text{MAX}}$, $\Delta F$, and roller/work piece contact area on the fatigue crack growth rate within mandrel splines during this SMFF procedure (Figure 5.1).

Figure 5.1: Roller/work piece illustration, depicting the contact area interface during an SMFF operation.
5.1: Extended production trials performed under optimal SMFF conditions

5.1.1: Rationale for selecting the optimal forming conditions

From the variety of combinations of $\theta$ and $Oa$ studied in Chapter 4, optimal forming conditions were selected on the premise that the inter-roller offset was the most critical design parameter during the third forming pass. Figure 5.2 shows $F_{\text{MAX}}$ versus roller inclination angle $\theta$ for the third pass SMFF test performed with X1-X2 inter-roller offsets set of -1.25, 0.00, 1.25 and 5.00 mm from the current industrial production setting.

![Graph showing $F_{\text{MAX}}$ versus roller inclination angle](image)

Figure 5.2: $F_{\text{MAX}}$ versus roller inclination angles, $\theta=8$ to 20°, for the third pass of an SMFF test performed with the X1-X2 inter-roller offset set at -1.25, 0.00, 1.25, and 5.00 mm from the current industrial production settings.

Figure 5.3 shows the maximum cyclic amplitude, $\Delta F$, versus roller inclination angle for the same tests. The minimum $F_{\text{MAX}}$ was observed to occur when $Oa$ was set either 1.25mm above or below the current production settings and $\theta=20^\circ$, however, of these two conditions, the lowest $\Delta F$ occurred when $Oa=-1.25$mm.
(Figure 5.3). This particular combination of $O_a$ and $\theta$ reduced the magnitude of $F_{\text{MAX}}$ by 26% from the productions settings.

![Graph showing $\Delta F$ versus roller inclination angle for different $O_a$ values.]

A second optimal case was identified where $O_a=+1.25\text{mm}$ and $\theta=8^\circ$. In this case the magnitude of $\Delta F$ was observed to be considerably smaller than any other case studied. This is despite the fact that $F_{\text{MAX}}$ was significantly larger than the scenario discussed above. Although these two optimal selected scenarios are largely dissimilar, they were chosen because they either had the lowest $F_{\text{MAX}}$ or $\Delta F$. Both these parameters are likely to affect the fatigue failure of the mandrel splines.

Based upon the above criteria, the following two production settings were selected and long duration production trials were performed with these settings to investigate if they cause significantly more parts to be manufactured compared to existing settings before mandrel failure.
Scenario 1: Oa: -1.25mm, \( \theta = 20^\circ \)

Scenario 2: Oa: +1.25mm, \( \theta = 8^\circ \)

5.1.2: Results of the extended production trials

For the observed optimal forming conditions, industrial production trials were carried out on the WF flow forming machines at the TransForm Automotive Ltd plant in London Ontario to determine whether the changes made to Oa and \( \theta \) improve the mandrel service life length. During these tests the number of parts manufactured before mandrel failure was recorded and the variation in the X1 maximum roller forming force, \( F_{\text{MAX}} \), and the magnitude of the force-oscillation, \( \Delta F \), during the third pass was periodically measured.

Under normal current production settings (Oa = 0.00, \( \theta = 15^\circ \)) an average of 11,500 \( \pm \) 150 parts\(^5\) are manufactured before fatigue failure of the lower mandrel splines occurs. A total of 15,384 parts were manufactured over the service life of the mandrel subject to Scenario 1. The following observations were drawn from the X1 forming force data results from this test:

- \( F_{\text{MAX}} \) increased by 3.08\%, from 85.18 to 87.89kN, over the duration, from the first to the last part, of the production trial.
- Similarly, \( \Delta F \) increased by 8.60\%, from 21.67 to 23.71kN, over the duration of the production trial. Figure 5.4 shows the Force versus position plots for the first and last parts formed with the Scenario 1 settings.

A total of 11,700 parts were manufactured prior to mandrel failure when q and Oa were set according to Scenario 2. The following observations were drawn from the X1 force data:

\(^5\) Calculated from the mandrel service life records over a total of 32 mandrels (\( \pm \) 1 standard deviation).
• $F_{\text{MAX}}$ increased by 2.79%, from 92.20 to 94.85kN, from the first to the last part made.
• $\Delta F$ increased from 11.13 to 15.71kN, over the duration of the test, a difference of 29.15%.

For the production runs under both Scenario 1 and 2 one can see that the magnitude of $F_{\text{MAX}}$ and $\Delta F$ is larger for the last part made than the first (Figures 5.4 and 5.5). Several reasons for this change are possible including gradual shifting of the roller parameters $q$ and $OA$ over the approximately two-week duration of the production trial, or the fact that the final part, in both scenarios, was formed after the mandrel file has failed. Thus, the cracked mandrel spline may affect the roller force profile of the final parts made. The precise cause for this observed difference in $F_{\text{MAX}}$ and $\Delta F$ between the first and last part was not identified in this study but is certainly an important subject for future work.

Figure 5.4: Roller forming trace at (i) First part, (ii) Last part prior to failure, for $Oa=+1.25\text{mm}$ and $\theta=8^\circ$. 

![Graph showing roller forming force over position of forming roller during third pass](image-url)
In summary, an average of 11,500 ± 150 parts are currently manufactured prior to mandrel spline failure when the SMFF process is performed under the accepted process conditions (Oa=0.00mm, θ=15°). By modifying Oa, and θ the magnitude of $F_{\text{MAX}}$ and $\Delta F$ reduced for each of the two scenarios studied. For Oa=+1.25mm and θ=8°, the resulting low amplitude $\Delta F$ combined with a relatively large $F_{\text{MAX}}$ improved the mandrel service life slightly above the average production count, while the larger roller inclination angle, θ=20°, and Oa=-1.25mm the magnitude of $\Delta F$ was slightly larger but $F_{\text{MAX}}$ was significantly smaller, resulting in a total of 15,384 parts manufactured before mandrel failure. That’s a 33% increase in parts produced compared to what can be produced with currently used settings of Oa and θ.
5.2: Comparison of the experimentally measured roller/work piece contact area with the calculated contact area

To better understand the factors that contribute to the fatigue failure of the mandrel splines it is important to determine the actual roller/work piece contact area. This can be done experimentally by measuring the forming roller force, \( F \), and recognizing that the stress applied by \( F \) to the work piece must be a function of the yield stress of the work piece material. This implies therefore that:

\[
\frac{F}{\text{Contact Area}} = \text{Constant} \quad [5.1]
\]

If we assume that the plastic strain exerted to the work piece during the forming process is constant for all of the SMFF process conditions tested\(^6\) the flow stress and the indentation hardness, \( H \), of the work piece must also be constant. The maximum roller/work piece contact area can then be expressed in terms of \( F_{\text{MAX}} \) and \( H \) as:

\[
\text{Contact Area} = F_{\text{MAX}} H \quad [5.2]
\]

5.2.1: Comparison of the calculated with the experimentally measured contact area

To determine the experimental contact area [Equation 5.2] the Vickers indentation hardness of the AISI 1020 work piece steel was obtained from micro-indentation experiments and was found to be 120 kg.f/mm\(^2\) [5]. The roller/work piece contact area was also calculated by applying the semi-analytical technique proposed by M.J. Roy et al [1,2] and presented in Section 2.5.

---

\(^6\) This assumption is valid since all of the tests were performed under the same work piece thickness reduction ratio (TR).
The measured and the calculated roller/work piece contact areas are shown in Table 5.1. The calculated contact area was much more closely related to the experimentally measured contact area when the roller inclination angle, $\theta$, was large ($\theta=20$ and $22^\circ$). When $\theta \leq 15^\circ$ the percent difference between the experimentally measured and the calculated contact area increases to upwards of 33%.

Table 5.1: Results obtained from the experimentally measured roller/work piece contact area, CA (Exp.) and the semi-analytical model, CA (M.Roy).

<table>
<thead>
<tr>
<th>Oa= Baseline (0mm)</th>
<th>$\theta$</th>
<th>$F_{\text{MAX}}$ (kN)</th>
<th>$\Delta F$</th>
<th>CA (M.Roy)</th>
<th>CA (Exp.)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>111.79</td>
<td>16.42</td>
<td>142.33</td>
<td>94.99</td>
<td>33.26</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>111.51</td>
<td>11.84</td>
<td>128.56</td>
<td>94.76</td>
<td>26.30</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>109.92</td>
<td>16.33</td>
<td>107.26</td>
<td>93.40</td>
<td>12.92</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>105.59</td>
<td>17.98</td>
<td>96.19</td>
<td>89.73</td>
<td>6.73</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>108.12</td>
<td>14.06</td>
<td>92.75</td>
<td>91.88</td>
<td>.94</td>
<td></td>
</tr>
</tbody>
</table>

One possible explanation for the increasing difference could be a result of the start of localized bulging of work piece material ahead of the forming roller. To verify the magnitude and shape of the bulge ahead of the forming roller, a Finite Element Analysis (FEA) may be employed to do so, however, this analysis was not performed in this study. Roy et al. assumed this localized bulging to be minimal, and assumed that the work piece material conformed perfectly to the shape of the forming roller.

Figure 5.6 shows the measured and the calculated ratio of $F_{\text{MAX}}/\text{Contact Area}$ versus roller inclination angle $\theta$. Considering the difference between the experimental and the calculated roller/work piece contact area shown in this figure, the calculated $F_{\text{MAX}}/\text{Contact Area}$ can be approximated to lie on a nearly horizontal line over the full range of $\theta$ tested. This indicated that the semi-analytical approach
to calculating the roller/work piece contact area is relatively accurate. However to accurately represent the process conditions that govern SMFF, the actual multi-axial stress state imposed on the work piece by the forming must be considered. This multi-axial analysis was not performed in this study.

Figure 5.6: Experimentally measured and semi-analytically calculated results of $F_{\text{MAX}}/\text{Contact area}$ versus $\theta$.

Due to the combined effect of mandrel rotation and linear movement of the X1 forming rollers, the forming roller follows a helical path along the mandrel. This causes the roller to contact the work piece in such a way that the total contact area can be resolved into components lying on the XY, XZ, and YZ orthogonal planes (Figure 5.7).
These components can all be calculated using the semi-analytical technique proposed by Roy et al [1,2]. Figures 5.8 and 5.9 show the calculated $A_{XY}$, $A_{XZ}$, and $A_{YZ}$ plotted versus $\theta$. $A_{XY}$ increases as $\theta$ increases, while $A_{XZ}$ remained unaffected by $\theta$ (Figure 5.8). $A_{YZ}$, the largest of the area components decreases linearly with increasing $\theta$ (Figure 5.9).
Figure 5.8: Contact area results for the XY, XZ-plane, obtained from the semi-analytical MATLAB model at zero offset for roller inclination angles (i) 8°, (ii) 10°, (iii) 15°, (iv) 20°, (v) 22°.

Figure 5.9: Contact area results for the YZ-plane, as well as the total combined effect, $A_{XYZ}$. Obtained from the FE model at zero offset for roller inclination angles (i) 8°, (ii) 10°, (iii) 15°, (iv) 20°, (v) 22°.
From these numerical simulations, the following conclusions are made:

- The circumferential component, $A_{YZ}$ of the total contact area is the least sensitive to changes in $\theta$.
- The total contact area, $A_{XYZ}$ is nearly equal to that of the circumferential $A_{YZ}$ component when $\theta$ is small.
- For larger face angles, $A_{XY}$ partially contributes to $A_{XYZ}$

In order of precedence, the process parameters that had the greatest effect on the magnitude of $A_{XYZ}$ was the $R_m$, $\theta$, $R$, and finally $r_0$ [1]. The results presented in Figures 5.8 and 5.9 support the above statement by indicating that the axial component, $A_{XY}$, of the total contact area is the largest, producing a high quality part. If the alternative is true, a bulge will form ahead of the roller, resulting in a defect [3].

The advantage to being able to apply this technique to identify in which plane the majority of the contact area resides allows one to prescribe alternate process parameters that improve the SMFF process by maximizing $A_{YZ}$. Through a series of experimental trials (Table 3.1), it was found that $\theta$ in one case minimizes the circumferential area component the magnitude of $A_{YZ}$, while for other angles of $\theta$ it was maximized. For small angles of $\theta$, the magnitude of $F_{MAX}$ remained unchanged, or even slightly increased, limiting the functionality of the X forming roller during the large spline region. It was only when $\theta$ was combined with a change to the inter-roller offset, $Oa$, that $A_{YZ}$ decreased in magnitude. This also caused a significant reduction in $F_{MAX}$ and $\Delta F$. Forming rollers with larger inclination angles, namely $\theta \geq 15^\circ$, optimize the forming characteristics, $F_{MAX}$ and $\Delta F$, reduce the overall contact area, ultimately improving the process conditions during the third incremental forming pass. Such issues as diametrical growth, porosity (voids in the material), surface defects and most importantly the forming force transferred from the roller/work piece interface onto the mandrel surface arise when both the tangential, and axial contact surface area dominate the total
contact area. All of which stems from the optimization of critical process parameters that affect the overall quality of the finished product.

5.3: Predicting fatigue crack growth rate using $F_{\text{MAX}}$ and $\Delta F$

The data presented in the previous sections of this chapter have shown the effects of critical process parameters on the mandrel service life during an SMFF process. Premature fatigue failure of the mandrel spline is a result of the high number of repetitive load cycles that invoke a stress amplitude, $\Delta \sigma$, upon the mandrel spline every cycle. Three basic factors that are necessary for the onset of fatigue crack growth are: (i) an applied tensile stress of sufficiently high magnitude, (ii) a large enough magnitude of $\Delta \sigma$, and (iii) a sufficiently large number of loading cycles.

Over the course of the SMFF mandrel service life, roughly 3-million irregular force-oscillations result due to the forming roller displacing material in and around the spline region of the rotating mandrel. Over the duration of the third forming pass, the magnitude of X1 forming force trace gradually increases until the work piece material begins to flow in and around the large mandrel splines, resulting in a stress amplitude that is asymmetrical. It is the magnitude of these force oscillations, $\Delta F$, during the third and final forming that affects the rate of fatigue crack growth, $da/dN$. The maximum roller forming force, $F_{\text{MAX}}$, will also have an impact on rate at which the crack grows. It was previously mentioned that for all $\theta$ studied, the difference in the roller/work piece contact area, and therefore the average work piece stress, $\sigma_{\text{max}} = F_{\text{MAX}} / \text{Contact Area}$ was found to be relatively constant when $Oa=0$mm (Figure 5.6). One common method to determine the growth rate, $da/dN$, of cracks during cyclic fatigue is to apply the Paris Law which expresses $da/dN$ in terms of the applied stress amplitude, $\Delta \sigma$, and the instantaneous crack length.
\[
\frac{da}{dN} = C(Y \Delta \sigma \sqrt{\pi a})^m
\]

[5.3]

In this equation \( N \) represents the number of load cycles and \( C, Y \) and \( m \) are all material constants. While the Paris Law implies that \( \frac{da}{dN} \) is dependent upon \( \Delta \sigma \) but not \( \sigma \), many researchers have modified the above expression such that \( m \) was a function of \( \sigma \) and varied from 1 to 6 [4].

In this thesis long term production tests were performed under two scenarios: Scenario 1 consisted of a condition where \( \Delta F \) was large and \( F_{\text{MAX}} \) was small. This is equivalent to saying that the stress amplitude, \( \Delta \sigma \), applied to the mandrel splines was large but the maximum stress, \( \sigma \), was small. Using the same reasoning, Scenario 2 consisted of a condition where \( \Delta \sigma \) was small and \( \sigma \) was large.

Scenario 1 manufactured more parts before mandrel fatigue failure occurred, thus \( \frac{da}{dN} \) was smaller for Scenario 1 compared to Scenario 2. This finding would suggest that \( \frac{da}{dN} \) is more strongly dependent upon the magnitude of \( \sigma \) rather than \( \Delta \sigma \). This is consistent with the Paris Law (Equation 5.3) if \( m \), a parameter in the exponential term, is a function of the applied stress and increases with increasing stress magnitude. This assertion that \( m \) is a function of stress has also been made by others [6-8]. It must, of course, be kept in mind that this conclusion is based upon only two test conditions and therefore, pending more test conditions, must only be considered to be preliminary.

5.4: References


Chapter 6
Conclusions and Future Work

The primary goal of this thesis was to investigate the effect of process variables on the X1 forming roller force, $F_{\text{MAX}}$ and $\Delta F$, during a SMFF process performed on an AISI 1020 steel work piece. Real-time data logging was used to capture $F_{\text{MAX}}$ and $\Delta F$ for a range of X1-X2 inter-roller offset distances (Oa), roller inclination angles ($\theta$) and roller nose radius ($r_0$).

Analysis of the Signal to Noise (S/N) ratio of $F_{\text{MAX}}$ indicated that the most critical process parameter in the SMFF process is Oa. Two optimal forming scenarios were selected: The $\theta=8^\circ$ forming roller inclination at an inter-roller offset distance of Oa=-1.25mm from the current production settings was found to be an optimum conditions for minimum $\Delta F$, while the $\theta=20^\circ$ forming roller inclination at an inter-roller offset distance of Oa=+1.25mm from the current production settings, was found to be optimal for minimizing $F_{\text{MAX}}$. 

The $\theta=8^\circ$, $Oa=-1.25$mm forming roller scenario manufactured a total of 11,700 parts prior to the onset of fatigue failure of the mandrel splines while the $\theta=20^\circ$, $Oa=+1.25$mm forming roller scenario manufactured a total of 15,384 parts. This represents a 33% increase over the average number of 11,500 $\pm$ 150 parts manufactured prior to mandrel fatigue failure under current production conditions ($\theta=15^\circ$, $Oa=0$mm).

In an attempt to validate the semi-analytical contact area model proposed by Roy et al., the experimental results, namely the maximum forming force and the Vickers Hardness of the AISI 1020 tool steel was used to calculate the roller/work piece contact area. For the smaller roller inclination angles, $\theta=8$ and $10^\circ$, the difference between the measured and the calculated contact area was minimal, however, as $\theta$ was decreased in size, the percent difference increased up to about 33% when $\theta=8^\circ$. The differences observed may be due to the bulging of the work piece material in front of the forming roller, elastic springback of the flow formed part and the lack of consideration for the multi-axial stress states.

Premature failure of the mandrel spline was experimentally found to be a direct result of the high number of repetitive load cycles that invoke a stress amplitude, $\Delta \sigma$, upon the mandrel spline region. It is the magnitude of the forming force oscillations, $\Delta F$, which determines $\Delta \sigma$ and thus the rate of fatigue crack growth. When considering the two extended production trials that were performed: Scenario 1 manufactured more parts before mandrel fatigue failure occurred, thus $da/dN$ was smaller for Scenario 1 compared to Scenario 2 despite the fact that $\Delta F$ was larger, but $F_{\text{MAX}}$ was smaller, for Scenario 1. This suggests that $da/dN$ is more strongly dependent upon the magnitude of $\sigma$ rather than $\Delta \sigma$. 
Future Work

While we can reason that $F_{\text{MAX}}$ and $\Delta F$ are the two forming characteristics that contribute to the unexpected premature failure of the mandrel splines; it may be also true that the forming area beneath the upper limit of the hydraulic roller force trace (figure 2.12) has a direct influence on the degree of work the X1 roller is responsible for as the remaining material is displaced in and around the mandrel spline. With a relatively complex, or irregular stress-cycle, integrating over the entire internally-splined region is particularly difficult. Periodic in nature, the stress-cycle increases in magnitude along the length of the mandrel, with no average or baseline position to apply the left, right or middle Riemann sum method. Presumably, a rough estimate of the total forming load, or worked performed by the forming roller on the mandrel, may provide an aid in investigating the differences between each set of conditions. By reducing the overall impact on the mandrel, the surface wear that occurs during the roller/work piece mandrel interface may improve the contact area conditions.

Having performed experimental tests where the inter-roller offset distance was both increased and decreased from the current production settings, it would be
beneficial if the semi-analytical contact area calculator proposed by Roy et al. could account for these modifications. Having found that the parametric study identified \( Oa \) as the process variable that had the greatest effect on \( F_{\text{MAX}} \) and \( \Delta F \) during an SMFF operation, it may be useful when estimating the contact area for alternative forming scenarios. This way, one may better understand the distribution of the forming forces across the mandrel spline region.

While it has been documented by many that the instability of material in between the roller/work piece interface causes many concerns when it comes to the formability of certain processes, it is the instantaneous bulge of material that builds ahead of the leading forming roller that has yet to be fully understood. At some level of thickness reduction, the degree of plastic strain measured through the thickness of the work piece causes the material to bulge, to the point where material defects can be introduced into the bulge of material. If one were to establish the grounds for an FEA analysis, where the material build on the leading edge of the X1 forming roller during the third forming pass can be accurately measured, optimal roller geometry and machine settings can be investigated.

One assumption that many, if not most researchers make when developing numerical simulations is, neglecting the fact that metal deforms plastically in every direction. The multi-axial stress state of the material as the forming roller displaces the work piece along the length of the mandrel was neglected by Roy et al., rendering the results inaccurate. If one were able to measure the multi-axial stress state of the material during plastic deformation, the accuracy of the roller/work piece contact area for the calculated method may better represent the experimentally determined contact area.
# Curriculum Vitae

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