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Technical Paper

Investigation of the effect of roller inclination angle on the forming forces during a splined mandrel flow forming operation

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ABSTRACT

Splined mandrel flow forming (SMFF) process is prone to premature failure of the splined mandrels. Such a failure is thought to be related to the magnitude of the forming forces exerted on the mandrel by the forming rollers. The multi-parametric nature of SMFF processes requires the use of a multi-variable analysis technique (i.e. Taguchi method) in order to assess different process parameters. In the present study, we demonstrated that there is an optimal inclination angle for the rollers that minimizes the forming forces and, therefore, optimizes the service life of the splined mandrel.

1. Introduction

An on-going problem with the SMFF is early, and unexpected, fracture (mainly fatigue fracture) of the protruding mandrel splines. Premature fatigue failure of the mandrel splines may result from either (i) the cyclic impact loading caused by the forming rollers or (ii) the presence of the sharp corners of the mandrel splines which are necessary to form the desired shape of internal ribs on the final part but which acts as stress concentrators [1]. In either case, the overall life expectancy of the splined mandrel is directly related to controllable process parameters that influence the magnitude of the forming force oscillations. The challenge with operating such a multi-variable process (i.e. SMFF) 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 θ, the radius of the forming roller, R_r and the exiting angle, φ, must be properly selected to optimize this process.

Wong et al. [2], experimentally and numerically, studied the effects of roller geometry and feed rate on the forming load and material flow in the flow forming of a simple solid cylindrical component with uniform diameter, using lead as the test material. Jahazi and Ebrahimi [3], using a 3-roller flow forming machine, studied the effects of process parameters such as roller feed rate, roller inclination angle, and work piece thickness reduction ratio on the flow formability of a steel work piece. Ma [4] conducted an experimental analysis to determine the optimal forming roller inclination during a smooth-tube metal spin forming process. Wang and Long [5] 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 radius were used. They reported no obvious effect on the forming force from the mandrel rotational speed. Xia et al. [6] investigated, through both experimentation and numerical simulation, the effect of the forming parameters such as roller offset amount, inclination angle and feed rate on the forming forces incurred in a tube spinning forming operation.

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 during flow forming has not been well reported. Therefore, this paper attempts to assess the effects of the processing parameters (Fig. 1a): Oa (inter-roller offset distance, mm), r_0 (roller nose radius, mm), θ (inclination angle or roller attack angle), R_r (the radius of the forming roller) on the maximum roller forming force, F_{max}, during 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. To this end, several experimental trials were conducted using an instrumented three-roller SMFF machine.

The SMFF machine used in this research can independently control Oa, TR (the work piece thickness reduction), $\dot{X}$ (axial roller feed rate, mm/min), and ω (mandrel rotational speed, rpm). By choosing

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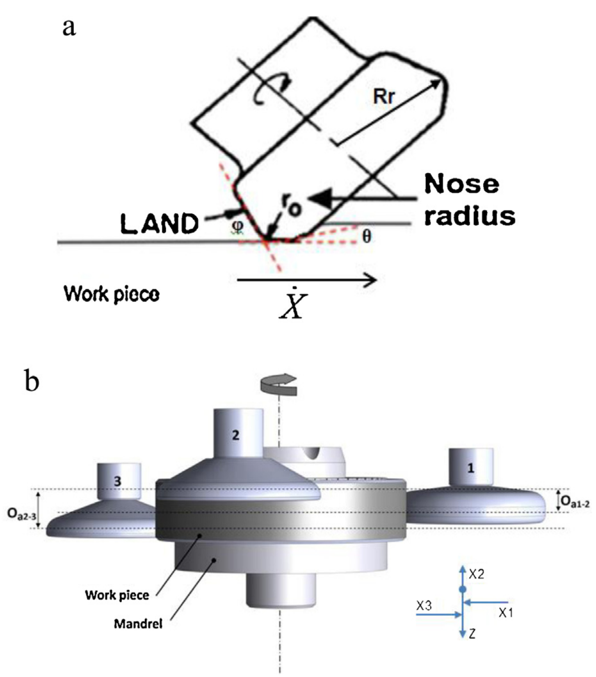

Fig. 1. (a) Key controllable roller parameters during an SMFF operation, (b) illustration of the three-roller flow-forming configuration.

forming rollers with different shapes, the effect of the roller geometry; namely, r_0, θ, ϕ, 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. Experimental procedure

Each of the experiments was conducted on a WF VSTR 400 three-roller splined mandrel flow forming machine. The three forming rollers, identified as $X1$, $X2$ and $X3$, were attached to a movable saddle assembly with an adjustable axial offset between each roller (Fig. 1b). Each forming roller may have a different size, shape, and inclination relative to the mandrel.

In order to assess different process parameters, a design of experiments (DOE) technique (Taguchi method) [7,8] was employed. This can be demonstrated by considering an SMFF process where a set number of tests (Table 1) are performed for each

Table 1
Breakdown of the factorial based design of experiment for two process parameters (Oa, θ), each studied at four levels.

Exp. #	$P_1 - Oa$ (mm)	$P_2 - \theta$ (°)
1	0.00	8
2	−1.25	8
3	1.25	8
4	5.00	8
5	0.00	10
6	−1.25	10
7	1.25	10
8	5.00	10
9	0.00	15
10	−1.25	15
11	1.25	15
12	5.00	15
13	0.00	20
14	−1.25	20
15	1.25	20
16	5.00	20

process condition and, in each test, only one process parameter, say θ, is changed incrementally. If the square of the maximum roller forming force $F^2_{\max}$ is used as the parameter indicating the process outcome, the average S/N ratio resulting from the small changes in θ can be expressed as [9]:

$$S/N = 10\log\left(\frac{\text{Magnitude of process outcome}}{\text{Variance of the process outcome}}\right) = 10\log\left(\sum_{i=1}^{N}\frac{\bar{F}^2_{\max}}{\left(F^2_{\max_i} - \bar{F}^2_{\max}\right)}\right) \quad (1)$$

where $F^2_{\max_i}$ represents the process outcome from the ith test, $\bar{F}^2_{\max}$ is the average process outcome over N repeated tests. For each combination of Oa and θ, three consecutive roller force traces were taken, to measure the variation or noise between $F^2_{\max}$ and $\bar{F}^2_{\max}$. If the average variance is large, the resulting S/N ratio will be small and one can conclude that, for a given $\bar{F}^2_{\max}$, changes in the parameter θ will have small effect on the overall process outcome. For each of the experimental test combinations, i.e. Oa and θ, individual S/N ratios were calculated using Eq. (1). Two process parameters, Oa and θ, were assessed using a factorial based DOE.

3. Results

The effect of Oa and θ on $F_{\max}$ of the $X1$ forming roller during the third pass was analyzed by performing sixteen SMFF tests at four levels of Oa and θ (Table 1). Fig. 2 shows the $X1$ roller force versus axial roller position during the third pass of SMFF tests performed at the various levels of Oa and θ. 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. The frequencies were similar for all of the tests since ω and $\dot{X}$ were held constant.

For all of the tests shown in Fig. 2, 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, $F_{\max}$ always occurs at a position, $X = 1.2$–1.4 mm from the leading edge of the mandrel spline. Comparing the plots in Fig. 2, one can also see that the variation in $F_{\max}$ over the range of Oa tested was reduced when the roller inclination angle θ, was increased.

Fig. 2a and b indicate that rollers machined with smaller inclination angles, $\theta = 8°$ and $10°$, resulted in the lowest $F_{\max}$ when the inter-offset distance was increased by 5.0 mm. Minor differences in the cyclic amplitude (force-oscillation) were observed for tests conducted with $\theta = 8°$ and $10°$ 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 θ was increased to $15°$, the measured variation, ΔF, in the roller force during the third pass was significantly reduced for all Oa conditions tested (Fig. 2c).

With an increase to the roller inclination angle, $F_{\max}$ was observed to decrease slightly, suggesting that $F_{\max}$ is related to both Oa and θ. The magnitude of the force-oscillation for each condition of Oa also increased when θ was increased beyond $10°$. These observations can be explained in terms of the effect of θ 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 $\theta = 20°$ resulted in a lower forming force, however larger force oscillations, across the full range of Oa tested (Fig. 2d). The magnitude of the