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Deep spinning of sheet metals

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ABSTRACT

Spinning of sheet metals into cylindrical cups is an important sheet metal forming process for its advantages of flexible tooling and very small forming loads. The most challenging aspect in this process is its low formability due to wrinkling formation in the free flange. In this work, a new deep spinning process with roller set aided with blank-holder of constant clearance is proposed aiming to suppress the wrinkling formation in the deformation zone. Experimental work on annealed and hard aluminum sheet metals is carried out to assess the new process. The proposed spinning process has shown rapid increase in the formability of the sheet metals as the roller feed increases. On the other hand, significant increase in the roller feed worsens the formability of sheet metals in conventional spinning. The Limiting Spinning Ratios, *LSRs*; or the blank to mandrel diameters ratios, have increased from 1.75 using the conventional spinning to 2.40 using the deep spinning with annealed aluminum sheets in one pass. Also, the *LSRs* have increased from 1.67 using the conventional spinning to 2.24 using the deep spinning with hard aluminum sheets in one pass. New failure modes of flange jamming and wall fracture have been presented and discussed. In addition, the formability limitations, thickness strains, and spun cup form features at different process parameters are experimentally investigated and discussed. Further, a finite element model for the new process is presented and verified showing the limitation of the available shell elements offered by ANSYS Mechanical APDL in modeling the new process.

1. Introduction

Sheet metal spinning of cylindrical cups is a traditional forming process, however, due to the flexibility of the process; it has undergone a renaissance in recent years and has developed into a versatile process for producing lightweight components [1–3]. In this process, a rotating sheet metal disk is deformed over a cylindrical mandrel into a cup by applying incremental small forces using an axially moving roller. Several attempts have been accomplished to study the challenging aspects of this process, particularly, failure modes, geometrical and thickness profiles of the final spun cup, and formability of the spinning process.

Failure of a circular blank to be successfully spun into a cup usually results from either flange wrinkling or wall fracture [1,2]. Studies have reported that blank parameters and working conditions are two main reasons for wrinkling formations in the unsupported part of the blank during conventional spinning of sheet metals. Conventional spinning process has shown increasing tendency to wrinkling formation with small modulus of plastic buckling, large mandrel diameter, and thin original blank sheet metals [4]. In addition, wrinkling formation tendency increases significantly with higher roller feeds and higher roller angles [5–8]. Furthermore, studies have shown that spinning of thicker sheet metals will fail due to wrinkling formation at higher roller feeds [8–11]. Fracture failure in conventional spinning not only occurs with oversized blanks but is also evident with smaller roller feeds, larger roller angles and smaller roller nose radii and this normally increases the tendency of tangential cracks in the partially deformed cup wall [5–11].

The wall thickness of conventionally spun cup is not uniform [6–8]. The cup edge is much thicker than the original blank thickness and the cup wall has two adjacent necks. The first neck is at the cup bottom and the second one is at the cup wall. Cup wall fractures occur due to oversized blanks at the location of the second neck. Conventional spinning process produces thinner cup wall with smaller roller feeds [6–8], smaller roller nose radii [6,7], higher roller angles [7] and smaller radial clearances [6]. The inner profile of the final spun cup is larger than the mandrel profile due to spring back [7]. This difference gets wider with smaller roller nose radii, higher roller feeds, and higher conical roller angles [7].

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The final spun cup by conventional single roller doesn't closely fit to the forming mandrel. The cup is rather shaped with bulged form having a gap between the cup inner diameter and the mandrel. This gap is not uniform and increases with cup height with its minimum at the cup bottom [7]. Also, it is shown that spinning with conical roller produces cups with bulged gap as high as 3.0 mm larger than the mandrel stem diameter [7] and the out of roundness of the spun cup is found to be as high as 0.5 mm [7].

Spinning formability is measured by the Limiting Spinning Ratio, *LSR*, which is the ratio of the maximum original blank diameter that can be successfully spun forming a cup, in a single pass, to the mandrel diameter [5–8]. Based on overcoming the wrinkling and fracture failure modes, many attempts have investigated flat [5,6], conical [7] and D-shape rollers [8] with various working conditions to enhance the spinning formability of conventional spinning. This formability limit is highly dependent on the ratio of mandrel diameter to blank thickness d_m/t_b [5,6]. At high ratios, $d_m/t_b > 30$, failure due to wrinkling formation is generally dominant. On the other hand at small ratios, $d_m/t_b < 30$, failure due to cup wall fracture is generally dominant.

Sieble and Droge [5] have used flat roller in spinning of mild steel cups achieving *LSR* of 1.7 for $d_m/t_b = 40$. However, this formability level decreased rapidly to about 1.5 as d_m/t_b increased to 70.0. On the same hand, Hayama, and Murota (1963) [6] have also used flat roller in spinning of annealed aluminum cups achieving slightly lower *LSR* of 1.67 at $d_m/t_b = 40$ and *LSR* of 1.48 at $d_m/t_b = 70$. They have extended their work to lower values of $d_m/t_b = 20$ achieving *LSR* of 1.86. In these attempts, the maximum *LSR* was achieved by searching for optimum roller feed, which was bounded by the flange wrinkling formation and the cup wall fracture.

El-Khabeery et al. [7] have used conical rollers achieving *LSR* of 1.9 at $d_m/t_b = 28$ using conical roller with face angle of 45° in spinning of annealed aluminum cups. Xia et al. [8] have used D-shape roller in spinning of steel and aluminum cups achieving *LSR* of 1.68 at $d_m/t_b = 50$. It is worth noting that in these studies [5–8], the roller movement was in the axial direction parallel to the mandrel axis. In earlier work, Terada et al. [12] have presented a numerical study of a convex roller shape moving in radial direction perpendicularly to the mandrel axis instead of the conventional roller axial motion. However, the maximum *LSR* achieved was 1.65 for thick sheet metals with $d_m/t_b = 18.5$.

In a recent attempt, Lossen and Homberg [13] have proposed a new technique to achieve higher formability for complex shapes. In this technique, the blank elements are heated up by friction with roller, and then the roller is moved axially to create the cup wall. This technique has achieved *LSR* of 1.82 at $d_m/t_b = 13.5$, which is lower than that achieved using flat, conical and D-shape rollers.

Currently, high *LSR*s are achievable by multi-pass spinning [15,16]. Furthermore, multi-pass spinning is more favorable than multi-stage deep drawing for its flexibility and significant lower tool cost. Fig. 1 summarizes the maximum achieved *LSR*s of conventional spinning of commercial pure aluminum sheet metals for the previous studies [5–8,12,13] and that for conventional deep drawing [14] at various mandrel diameter to blank thickness ratios d_m/t_b.

The achieved *LSR*s for small values of (d_m/t_b) are lower than those obtained in conventional deep drawing, which is usually higher than 2.0 [14]. Furthermore, for higher values of (d_m/t_b) the difference becomes much wider. It may be noted that the achieved *LSR*s of single pass spinning are banded in a very narrow region implying that the above investigations have not significantly improved the formability limitations of the sheet metal spinning process. Based on the above discussion, the problem persists in the flange wrinkling formation at high roller feeds. The formability of the conventional deep drawing is superior to that in conventional spinning due to the suppression of the flange wrinkling by the aid of a blank-holder.

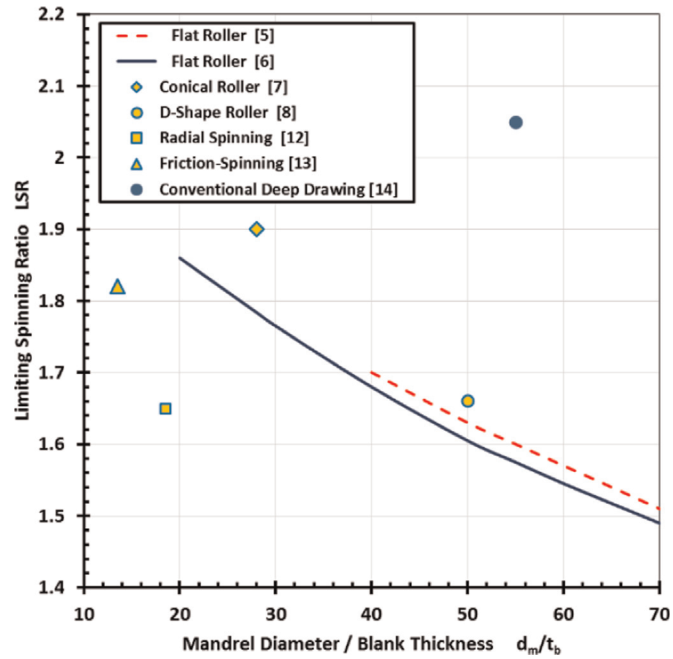

Fig. 1. Limiting spinning ratios at various d_m/t_b ratios with different roller profiles and conventional deep drawing process [adapted from: 5-8,12-14].

The main objective of the current work is to implement a new roller aided with constant clearance blank holder. The new roller is experimentally evaluated to define its ability in suppressing the wrinkling formation to improve the spinning formability. Also, the geometry and thickness distribution of the final produced cups will be measured at different working conditions. Further, the new process will be simulated by finite element method to get more understanding of the process kinematics and deformation mechanism.

2. Experimental setup

The new proposed deep spinning process considers a blank holder to be fixed on the roller shaft as shown in Fig. 2. A hardened spacer with thickness C_h controls the distance between the roller and the blank-holder. The considered process parameters, as shown in Fig. 2, are geometrical and working conditions parameters. The variable geometrical parameters are the radial clearance C_r and the blank diameter D_b. The considered variable working condition is the roller feed S_v. All other parameters are fixed throughout the course of experiments. The full construction of the new proposed deep spinning process with all components is shown in Fig. 3.

The experimental work is carried out on a manually controlled conventional center lathe with a specially designed holder, replaced the tool post, to support the new roller setup. Fine finished flat-headed mandrel with diameter, 48 mm is used. The fillet profile radius of the mandrel is 6 mm, which is one eighth of its external diameter. The tested mandrel is supported on the lathe chuck using a special holder that ensure minimum run out errors. The blank holder and roller have the same diameter $D_r = 180.0$ mm. They are made of hardened alloy tool steel [0.3% C, 0.66% Mn and 0.35% Si], with surface hardness of about 60–62 HRC. The rollers and the blank holder are ground and then polished reaching surface roughness of Ra = 0.19–0.21 μm with minimum Rz = 1.18 μm.