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Comparative Analysis of Thin-walled U-shaped SS 304 Bellows-type Expansion Joint Profiles Formed through Single and Multi-Stage Mandrel Forming Processes

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Abstract

This study investigates the impact of employing single-stage versus multi-stage mandrel cold-forming techniques to fabricate SS 304 U-shaped thin-walled metal bellows-type expansion joint profiles, with a specific focus on post-forming thickness variations and profile precision. The aim is to discern the variations in thickness following the convolution profile formation in single-stage and multistage mandrel forming procedures. There are noteworthy distinctions between the profiles produced using these forming methods, providing valuable insights for manufacturers.

Keywords
Metal Bellows, Mandrel Forming, Thickness, Expansion Joints

1. Introduction
Thin-walled metal bellows-type expansion joints, also referred to as metal bellows or expansion joints, play a vital role in piping systems by accommodating thermal expansion, vibration, and movement. They enable connections between fixed points, allowing axial, lateral, and angular movements in various applications like piping assemblies, vacuum systems, industrial plants, exhaust system assemblies, engines, turbine systems, aerospace applications, nuclear applications, heat exchangers, and pressure vessels (Gawande et al. 2015; Pagar and Patel 2021). A potential malfunction in these components could lead to catastrophic consequences, resulting in the breakdown of the entire system (Gawande et al. 2015).

Expansion joints come in various profiles, each designed to address specific needs in different applications. The U-shaped expansion joint profile is preferred for several reasons. The U-shape allows increased flexibility and axial movement, effectively accommodating a system's thermal expansion, contraction, and other dynamic forces. This profile distributes stress and strain evenly along the bellows, reducing fatigue risk and enhancing overall durability (Mohammad et al. 2015). The U-shaped design also promotes smoother deflection and retraction, minimizing the potential for localized stress concentrations or points of failure. Mohammad et al. (2015) showed that U-shaped bellows have minor internal pressure-induced stress and, in high cycle fatigue (HCF), are more suited for higher internal pressure situations. Figure 1 shows the profile of the stainless steel (SS) bellows that is formed and studied here.

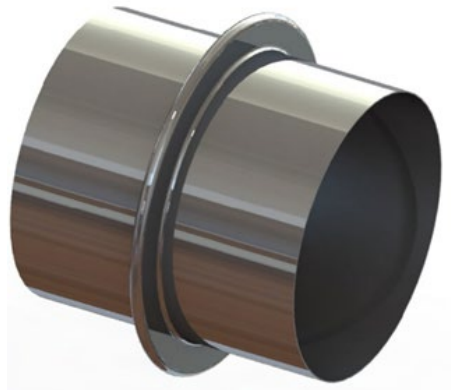

Figure 1. U-shaped single convolution

In the fabrication of thin-walled metal bellows, the conventional process usually entails either rolling and welding a sheet to form a tube or initiating the procedure with an existing tube and then subjecting it to forming. Welded tubes created through sheet rolling and longitudinal welding have improved cyclic durability and corrosion resistance, ultimately extending the fatigue life of single-layer bellows (Petrushin et al. 1977). While metal expansion joints can be formed through various methods, this research concentrates on mandrel forming, a less-explored aspect. Mandrel forming is a specialized manufacturing technique to create these flexible components' characteristic corrugated or convoluted shapes. During mandrel forming, a precisely shaped mandrel, often resembling the internal contour of the desired bellows, is inserted into a metal tube or sheet. As the metal undergoes the forming process, it conforms to the shape of the mandrel, creating the convolutions or corrugations that give the bellow flexibility and resilience (EJMA, 2019). However, it can be difficult to ensure the consistent thickness of the walls in this process. Variations in wall thickness play a crucial role in determining the quality and performance of the bellows, and the convolution shape's precision equally impacts the forming quality and practical performance of these components (Jiang et al. 2019).

This research recorded and compared pre-formed sheet thickness and post-formed thickness for a single U-shaped convolution-formed profile using single- and multi-stage forming. Single-stage forming is a mandrel forming process that employs a one-step procedure in which the entire convolution (100%) is shaped in a single stage utilizing a mandrel tool that expands to the maximum required depth of the convolution. In contrast, multi-stage forming involves the same tool and process as single-stage forming but unfolds across several stages. In this method, a single convolution is shaped progressively in increments, such as the first stage completing 60% and subsequent stages forming in 10% increments until reaching 100% (e.g., 5 stages). In each stage, the mandrel expands and then reverts to its original position, allowing for incremental shaping of the convolution.

In the specific context of this research, SS 304, commonly employed in bellows fabrication, is chosen as the material (EJMA, 2019). Austenitic stainless steel is routinely chosen for manufacturing metal bellows due to its exceptional mechanical properties, corrosion resistance, and high-temperature performance (Jha 2006).

1.1 Objectives

This study aims to evaluate and record the thickness variations evident in U-shaped SS 304 profiles following forming, employing both single-stage (completing 100% of the convolution in one step) and multi-stage (specifically, a 5-stage process initiating with 60% formation and involving repeated forming and retraction until the desired profile is attained) mandrel forming methods. The emphasis is on comprehending the impact of these mandrel forming techniques, executed with identical tools, machinery, room temperature, pressure, operating conditions, and materials, on the resulting wall thickness variations in the metal bellows.

2. Literature Review

Selecting the appropriate geometric configuration is instrumental in attaining the desired resonant frequencies, ultimately leading to an extended fatigue life (Thak et al. 2013). The wall thickness of the metal bellows is designed so that the spring force due to the wall stiffness has a minimal influence against medium-induced expansion while limiting radial expansion due to thermal creep (Hamada and Tsuda 1997). According to Jang and Kim (2015), with an increase in the thickness of metal bellows, there is a corresponding increase in spring rate, thrust force, and stress levels. The fatigue life is also affected due to this change in thickness. Therefore, the wall thickness is a crucial aspect affecting the fatigue life of metal expansion joints. The thinning observed as an after-effect of single-stage or multi-stage forming can help manufacturers optimize the profile during forming. New methods, such as Zhang et al. (2023)'s buckling-induced forming method, result in a uniform shape with no noticeable reduction of wall thickness, which is optimal. However, these new techniques are expensive and not explored for all sizes and shapes. Mandrel forming is regularly used in the industry, but its influence on the variation of wall thickness has not been explored before.

3. Methods

Following the experimental design principles proposed by Montgomery (2023), this study systematically categorizes parameters into controlled and variable groups. The controlled parameters encompass consistent material selection (SS 304) with uniform thickness, maintaining an operating environment at room temperature (32℃) and atmospheric pressure, and the absence of additional loads. The circular U-shaped profile design maintains a uniform size while the machinery specifications, including tool sizes, force, and speed, remain constant. The primary distinguishing factor is the expansion rate, delineating between single- and multi-stage formation.

The process commences with rolling and longitudinally seam welding the SS sheet. Following the recommendations of Da Silva et al. (2016), prior to rolling and welding, the sheet metal undergoes thorough cleaning and conditioning to eliminate pre-existing defects, as their presence could lead to crack propagation during forming, negatively impacting the lifespan of the metal bellows. Furthermore, the removal of residual substances, such as sodium, is essential to prevent corrosion and unexpected failure, aligning with findings from Kaishu et al. (2005), who attributed SS 304 bellows failure to stress corrosion cracking induced by exposure to wet hydrogen sulfide. Therefore, a quality check of the selected material is imperative before the forming process. The welding must also undergo a quality check. After ensuring welding integrity and a clean surface of the welded tube, given the component's symmetry about its axis, four specific cross-sections were chosen for detailed thickness analysis at 0, 90, 180, and 270 degrees. These were marked as shown in Figure 2. The sheet used for forming is 0.8 mm thick with a tolerance of ±0.05 mm.

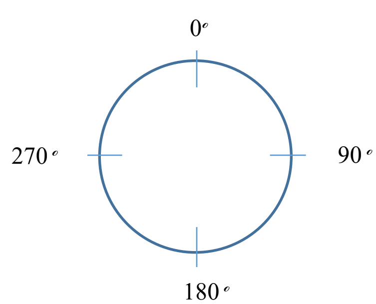

Figure 2. Top view of the expansion joints to depict how it was marked and measured

For forming, the machine and tool (also known as the mandrel) are checked and calibrated. The tool is lubricated as required. The open end of the welded tube is securely clamped or held in place to prevent any movement during the forming process. The mandrel/tool is then expanded or pushed into the tube, causing the metal tube to conform to the shape of the mandrel (EJMA 2019). In a single-stage formation, the complete convolution is formed in one stage. Once the desired bellows configuration is achieved (see Figure 3), the mandrel is retracted. The formed metal bellows is then removed from the machine, and the thickness is observed in the locations as marked in Figure 3.

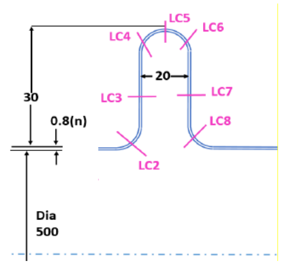

Figure 3. Profile of the thin-walled expansion joint (500 NB diameter)

Utilizing the same material, an identical welded tube undergoes multi-stage forming process using the same machinery, tool force, and speed. However, in this case, there is a variation in the rate of expansion. Initially, 60% of the convolution is formed, after which the tool is retracted. An additional 10% is added at each subsequent stage, followed by retraction until reaching 100% or the completion of the desired profile. Post-forming measurements are taken using a coordinate measuring machine (CMM) 700 series. The specification of the machine used and accuracy that can be expected is given in Table 1.

Table 1. CMM specification

Parameter	Specification
Model	CRYSTA-Apex V 700 Series
Measurement Range (X, Y, Z)	700 mm x 1000 mm x 600 mm
Table Size	880 mm x 1720 mm
Table Material	Granite
Software	Mitutoyo Metrology Software
Accuracy	± 0.002 mm for 100 mm measurement
Resolution	0.0001 mm
Probing System	Touch-Trigger / Scanning
Environmental Conditions	Temperature: 16 to 26 ℃
Power Requirements	0.7 kW
Weight	2063 Kg

Before measurement, fixtures or clamps that hold the object in place during measurement are set up. The CMM is calibrated to ensure accurate measurements. The CMM's software is then programmed with the desired measurement parameters (maximum and minimum points to be measured are inputted) and profile specifications. The touch probe is used for this measurement. The CMM's arm or gantry moves the probe along the surface of the object. The probe makes contact with the object at various points, capturing the X, Y, and Z coordinates of those points. These data points are then used to create a digital representation (or "map") of the profile. The inner profile and outer profile are measured individually and then merged using the software. The same coordinates of the inner and outer profiles are selected and the distance between them is measured as the thickness. The plotted profile shape characteristics and thickness are measured at each angle and recorded at room temperature.

4. Data Collection

In the data collection phase, measurements were systematically taken at specific angular intervals of 0°, 90°, 180°, and 270° (see Figure 2) for both profiles. These measurements were captured immediately following the single-stage and multi-stage forming processes of the profiles. The plotted profile was also observed. Five measurements were acquired at each designated point using the CMM, and the associated data were recorded for analysis. Only a subset of the data is presented here for reference and discussion.

5. Results & Discussions

Thickness measurements were taken at 270° across different locations of the profile for both single-stage and multi-stage forming processes. These are shown in Figure 4.

(a) (b)

Figure 4. Thickness measurements at 270° at various locations of the profile: (a) single-stage, (b) multi-stage

The data for the 270° position are highlighted here since they exhibit identical values for both forming methods. However, it was observed that the multi-stage forming process demonstrated greater consistency compared to the single-stage method for producing metal bellows.

Table 2 shows that the reduced thickness measured in mm in all instances either matches that of the single-stage forming or exceeds, it in the case of multistage forming. This indicates that the percentage variation in thickness is comparatively lower in a profile formed using multi-stage forming than in the single-stage forming processes. Notably, the most pronounced thinning, with a minimum thickness recorded at 0.719 mm, is observed at the LC5 point for a single-stage formed profile. Furthermore, the data reveal that the peak thinning percentage is 11.25% for single-stage forming and 9.6% for multistage forming.

Table 2. Thickness measurements of the convolution at the various marked locations (Figure 3 shows the locations)

Location	**Thickness in mm**							
	0°		90°		180°		270°	
	Single stage	Multi stage	Single stage	Multi stage	Single stage	Multi stage	Single stage	Multi stage
LC2	0.761	0.781	0.771	0.778	0.765	0.779	0.772	0.775
LC3	0.728	0.746	0.732	0.745	0.737	0.746	0.743	0.747
LC4	0.731	0.736	0.726	0.736	0.722	0.734	0.730	0.733
LC5	0.723	0.730	0.725	0.731	0.719	0.733	0.723	0.731
LC6	0.730	0.736	0.723	0.735	0.722	0.735	0.726	0.732
LC7	0.731	0.749	0.741	0.748	0.738	0.751	0.746	0.746
LC8	0.764	0.778	0.754	0.778	0.751	0.779	0.772	0.772

It can be observed that the profile formed is more consistent in multi-stage forming. Based on observations from Figures 5 and 6, the profiles achieved through multi-stage forming appear to exhibit greater consistency compared to those formed through a single-stage process. This enhanced consistency is not only quantitatively evident but is also visually apparent, reinforcing the aesthetic appeal of the multi-stage-formed profiles.

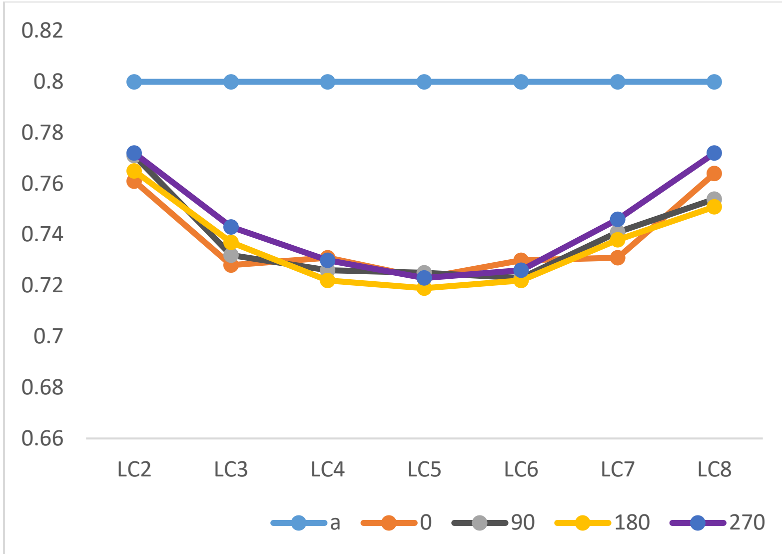

Figure 5. Thickness of SS U-shaped profile formed using single-stage forming vs. 'a' (initial thickness)

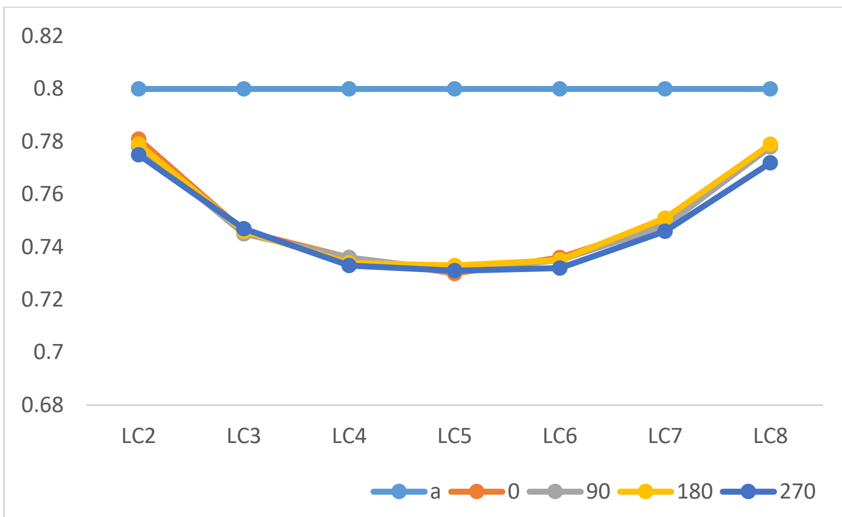

Figure 6. Thickness of SS profile U-shaped formed using multi-stage forming vs. 'a' (initial thickness)

The inconsistency in profile thickness at each coordinate is depicted in Figure 7. The discrepancies may not be discernible to the unaided eye and are quantified in microns.

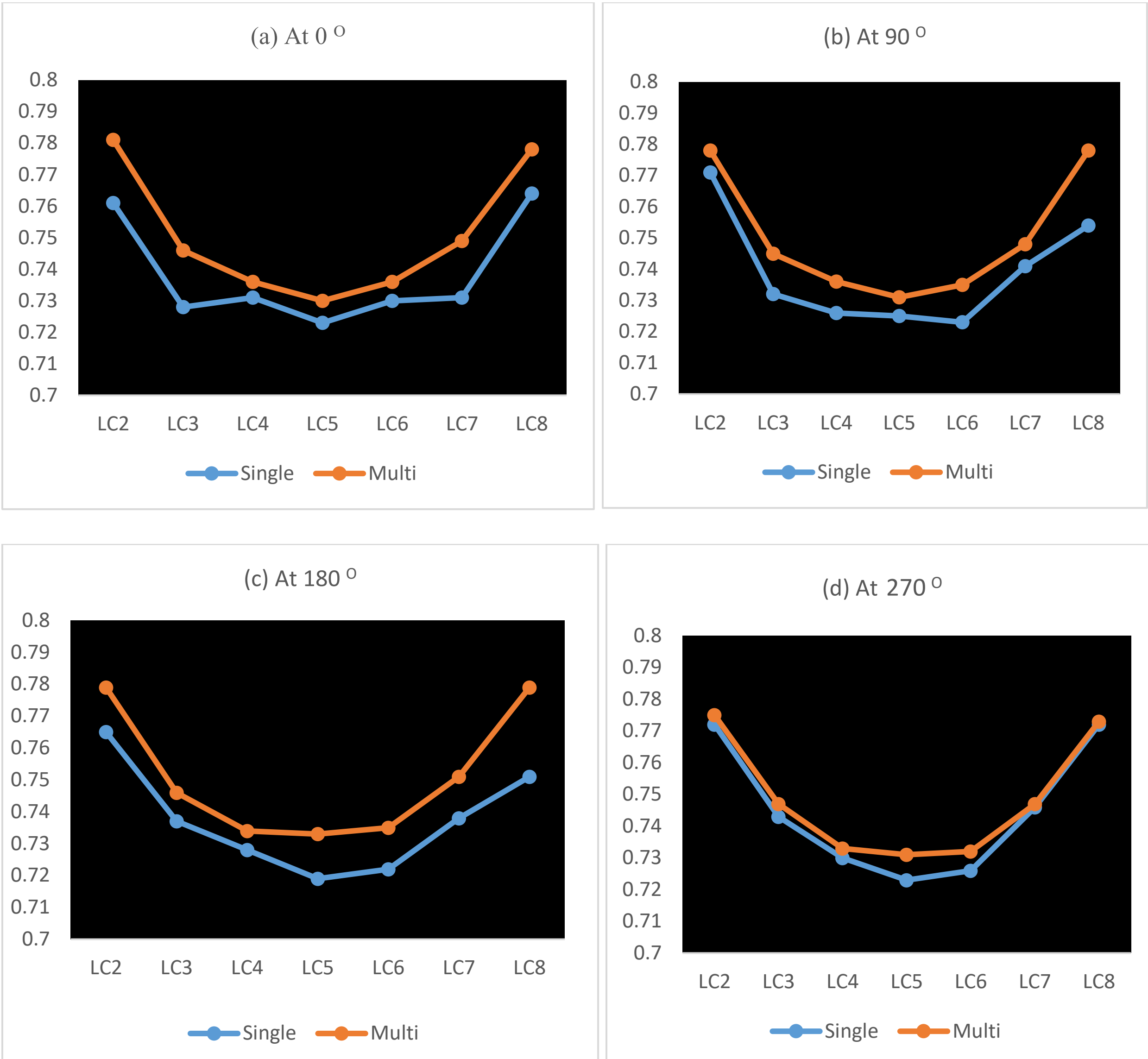

Figure 7. Thickness variations at the various coordinates for metal bellows formed using single- and multi-stage forming

In the fabrication of thin-walled structures, even a slight reduction in material thinning is crucial for ensuring the profile's stability and capacity to withstand intended design conditions. Any improvement in minimizing thinning percentages significantly contributes to enhancing the structural integrity and performance of the profile under operational loads. Maintaining optimal material thickness throughout the forming process is essential to meet design specifications and ensure long-term durability.

6. Conclusion

When considering SS 304 U-shaped mandrel cold forming for metal expansion joint-type bellows, multi-stage forming has superior profile precision and a diminished percentage of variation in thickness. The findings from this study show that multi-stage forming consistently either matches or improves upon the thickness observed in single-stage forming. Notably, pronounced thinning, marked by a minimum thickness of 0.719 mm, is evident in single-stage forming at the convolution curve. In contrast, multi-stage forming exhibits a more moderated thinning, peaking at 9.6%, as opposed to the 11.25% observed in single-stage processes. This observed profile consistency in multistage forming further emphasizes its aesthetic and functional advantages.

7. Future scope

The multi-stage forming technique, given its promising results, could be experimented with across varied sizes, configurations, stages, and materials. Extensive research in these domains would provide a comprehensive understanding and further optimize the multi-stage forming process for broader applications.

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Biographies

Agraja Magesh is currently pursuing her doctoral studies in the School of Engineering Technology at Purdue University. Alongside her academic pursuits, she actively engages in various professional memberships, including being a member of the ASME student body at Purdue and participating in the Indian Society of Non-Destructive Testing (ISNT). With a rich background, Agraja possesses four years of experience in the design and manufacturing sector of the Expansion Joints manufacturing industry. Beyond her academic and professional endeavors, she serves as an Impact Officer in the Global Shapers Community, an international youth-driven initiative established by the World Economic Forum**.**

Umamagesh Ganesan, Director of LSI-MECH Engineers Pvt Ltd, is an expert in the field of welding and thin sheet metal fabrication. He pioneered the expansion of the joint manufacturing industry and was the key to the indigenous development of hydroformed bellow-type expansion joints in India. He has over 37 years of experience in this field. Well-sought out in the manufacturing industry for his unique, customized problem-solving abilities, he was the first bellow manufacturer whose talents are well recognized locally by Engineers Limited India, Indian boiler regulation, and internationally by leading Engineering organizations and process licensors. He is an active member of the ASME Section VIII IWG (India Working Group) and ISNT (Indian Society of Non-Destructive Testing). He was India's first and only MEJ manufacturer to develop jacketed bellows, externally pressurized bellows, many types of uniquely reinforced bellows, etc. He was the first to implement ISO 9001, ISO 140001, and ISO 3834 within his organization. His accolades include successfully supplying products to over 45 countries.

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