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Research Article

Development of a Novel Tool for Single-Pass Tube Flaring and Forming with Microstructural and Mechanical Analysis of AISI 304 Stainless Steel

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Abstract –In this study, a novel tool design was developed to integrate tu and forming processes into a single operation, without tearing. The tool was employed to shape thin-walled AISI 304 stainless steel tubes, and its influence on the material's microstructural characteristics and mechanical properties was systematically examined. Manufactured from AISI 4140 steel, the tool underwent heat treatment to achieve a hardness of 52 HRC. The flaring and forming operations were performed at a controlled speed under dry conditions, without lubrication. Changes in the material's structure and mechanical properties, including thickness variations, hardness distribution, and deformation-induced martensitic transformation, were investigated. Metallographic analyses revealed notable microstructural transformations, such as grain alignment, increased dislocation density, and the formation of martensitic phases due to deformation.

Keywords – Tube Flaring, Tube Forming, Martensitic Transformation, Deformation-Induced Martensite, AISI 304 Stainless Steel.

I. INTRODUCTION

Tube flaring processes are widely applied to flare the ends of rotating vessels or tubes. Tube flaring is a plastic deformation method, typically performed as a cold deformation process. In tube diameter flaring, the tube end is expanded by shaping the material using a conical die or a die with an arc profile. A conical tool with the same diameter as the tube is pressed along the axial direction of the tube to expand the diameter of the tube end hole.

The tube flaring process involves very complex metal flows. In the axisymmetric tube flaring process with a conical tool, factors such as the friction resistance of the flaring tool, its temperature, and the semi-cone angle play critical roles. Small changes in friction, temperature, or the semi-cone angle can cause variations in metal flow, resulting in significant differences in the shape of the tube end [1]. Generally, the success of the process depends on parameters such as the expansion ratio, the tube-end down-depth ratio, and the tube-end strain ratio [2].

In 1983, Manabe, Nishimura, and Mori [3, 4, 5] conducted a series of theoretical and experimental studies on the expansion of tubes with a conical tool and the formation of tube ends [1]. In the 2000s, research on the expansion of thin-walled tubes gained prominence [6, 7, 8, 9]. During this period, the use of a conical tool at the ends of thin-walled tubes remained widespread [1, 10, 11]. Due to the nature of cold deformation, the risk of tearing is quite high because of the high stresses occurring at the tube end during single-pass flaring operations. Chumadin and Ershove [12] performed an approximate analysis of the stress and strain distribution during the expansion of tubes using a conical tool. Consequently, Kitazawa [13] proposed a pre-shaping process to improve the expansion limit of thin-walled tubes based on his studies to determine the criteria for outward flaring during the tube flaring process.

Today, to prevent tearing during the flaring or forming processes of tube ends, a pre-shaping process is applied in the majority of studies in the literature. However, this leads to a significant increase in production complexity and costs, especially in industrial applications. To address this, the present study developed a tool design capable of performing tube flaring and forming processes in a single pass.

Furthermore, studies examining the effects of tube flaring and forming processes on the microstructure and mechanical properties of the material are very limited in the literature, and no research has been conducted on stainless steel materials. Therefore, this study not only investigates the flaring and forming of thin-walled tube ends in a single pass but also examines the changes in the metallurgical and mechanical properties of stainless steel tubes resulting from these processes.

II. MATERIALS AND METHOD

The tool with the arc profile to be used in tube flaring operations is manufactured from AISI 4140 material (Figure 1). The produced tool was then heat treated with a quenching process to reach 52 HRC hardness.

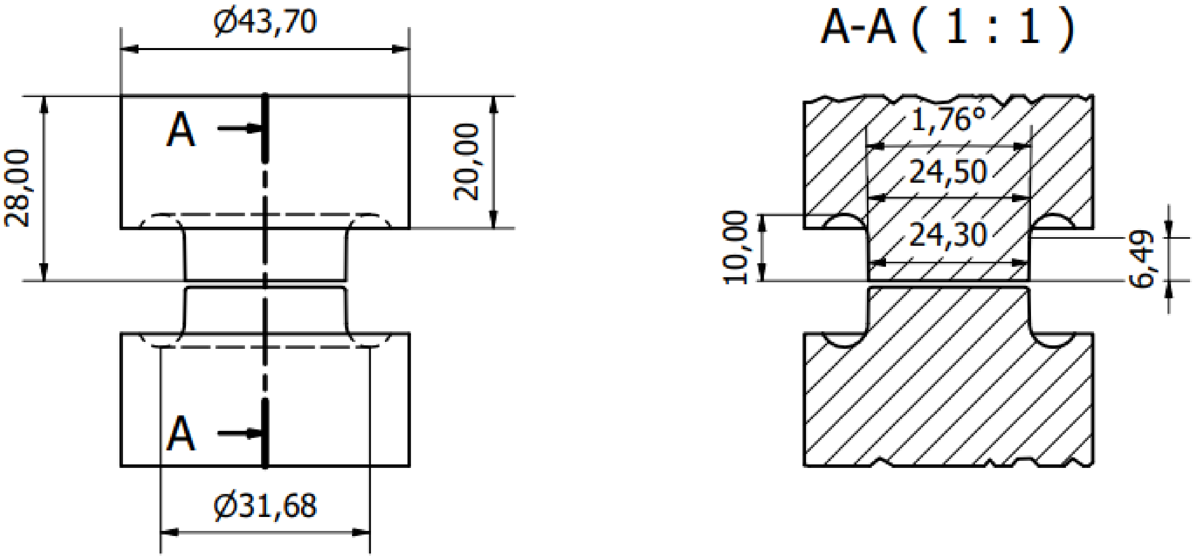

Figure 1. Tool with designed arc profile

In the experimental studies, hot-rolled AISI 304 stainless steel was used as the tube material. The dimensions of the tube before the flaring and forming operations were 29.4 mm in outer diameter and 2.0 mm in wall thickness. To make the thin-walled tube, the end of the tube was machined from the surface, and the outer diameter was reduced to 27.6 mm and the wall thickness was reduced to 0.9 mm. Then, the tube flaring and forming process was carried out with a uniform deformation speed of 4 mm/s until the tool stroke reached 25 mm. The deformation load was applied as 6 tons and no lubricant was used. The schematic representation of the tube flaring and forming process is shown in Figure 2.

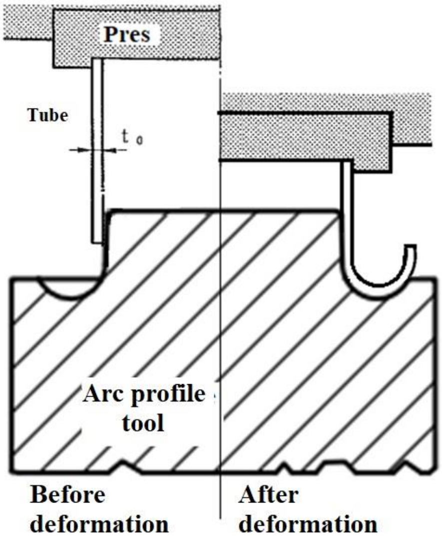

Figure 2. Schematic representation of the tube flaring and forming process

Samples removed from the ends of the deformed AISI 304 stainless steel tube were subjected to grinding and polishing processes and then etched. After this process, the changes in the material were examined by metallographic examination. Metallographic examinations of the obtained samples were performed using Nikon Epiphot 200 Metal Microscope optical microscope. Hardness tests were performed using EmcoTest Durascan 20 G5 Hardness Tester to evaluate the mechanical properties. To determine the hardness distribution of the samples, Vickers test examinations were performed on a line along the thickness starting from the surface. Hardness measurements were made under 200 grams load and 10 s waiting time.

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III. RESULTS AND DISCUSSION

Commercial AISI 304 stainless steel tube is a material produced by hot rolling. As a result of the hot rolling process, grain orientation are formed on the surface of the AISI 304 stainless steel material due to deformation. These grain orientations are especially more intense on the surface and decrease towards the inner parts of the material Figure 3.

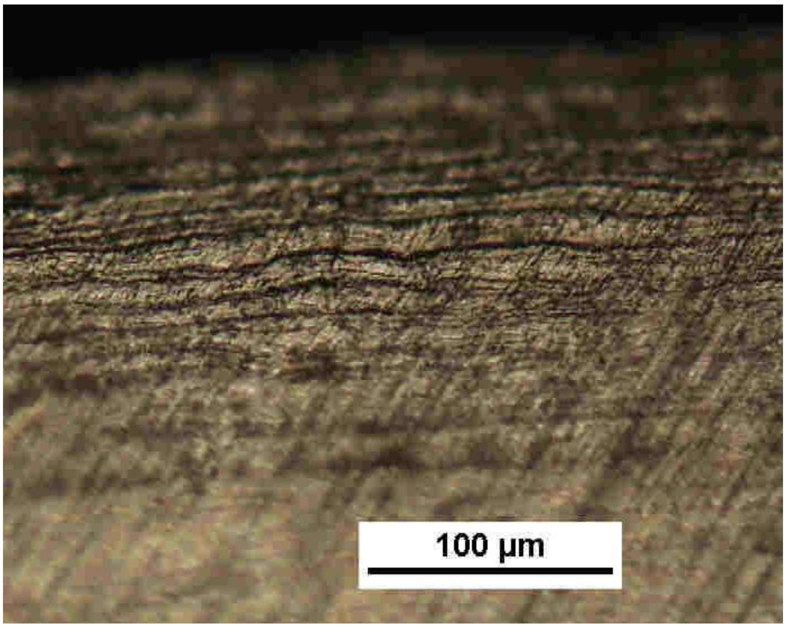

Figure 3. Grain orientation formed on the surface of hot rolled AISI 304 stainless steel tube.

The microstructure of the hot-rolled AISI 304 stainless steel is seen as the austenitic structure with characteristic isotropic, equiaxed grains, and the average grain size was measured as 18 microns Figure 4.

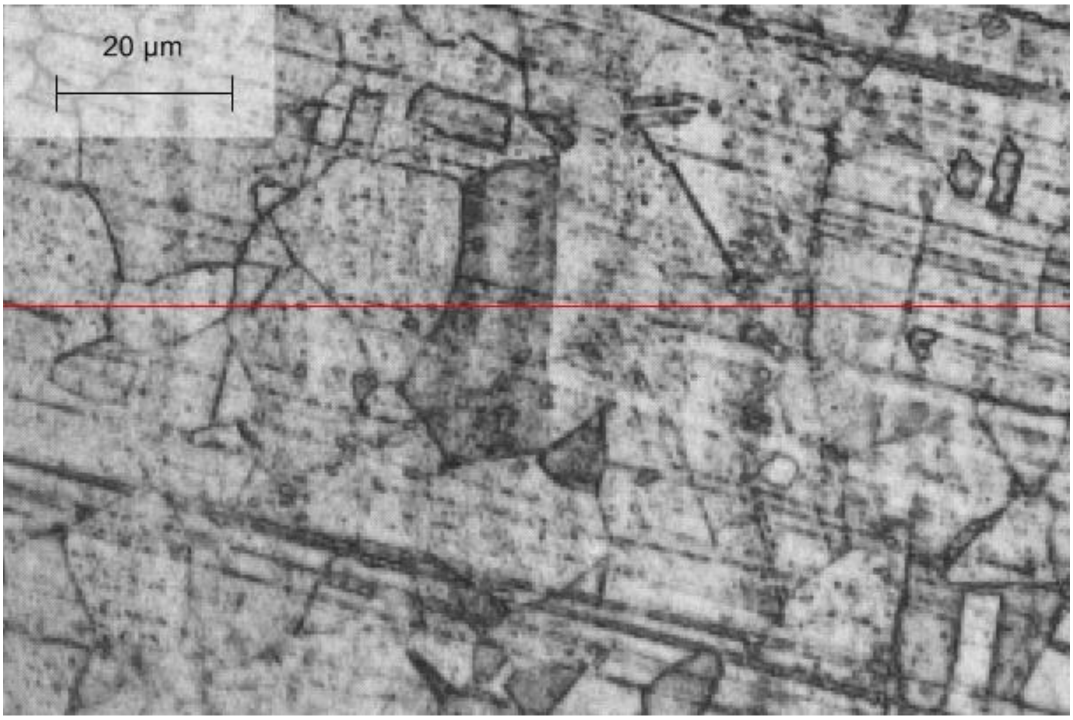

Figure 4. Microstructure of hot rolled AISI 304 stainless steel before tube flaring and forming process

As a result of the operation of flaring and forming the hot rolled AISI 304 stainless steel tube end with the designed tool, the material with a wall thickness of t0 = 0.9 mm was deformed and curled and as a result of the consequent deformation, the wall thickness increased to tk = 1.18 mm. An approximately homogeneous deformation occurred along the entire circumference of the tube and therefore the tube ends were curled uniformly Figure 5.

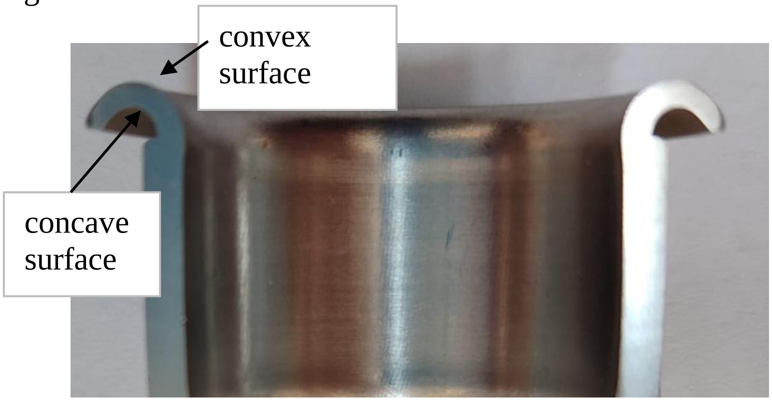

Figure 5. Deformation created at the end of the thin-walled tube using the designed tool

As a result of the deformation during the tube flaring and forming process, a region is created where the martensite phase and dislocation density increases due to the deformation on both the convex and concave surfaces of the material (Figure 6). Especially on the concave surface, the width of this region is greater due to the higher deformation density. These deformation-intensive regions are approximately 450 microns wide on the concave surface and approximately 220 microns wide on the convex surface.

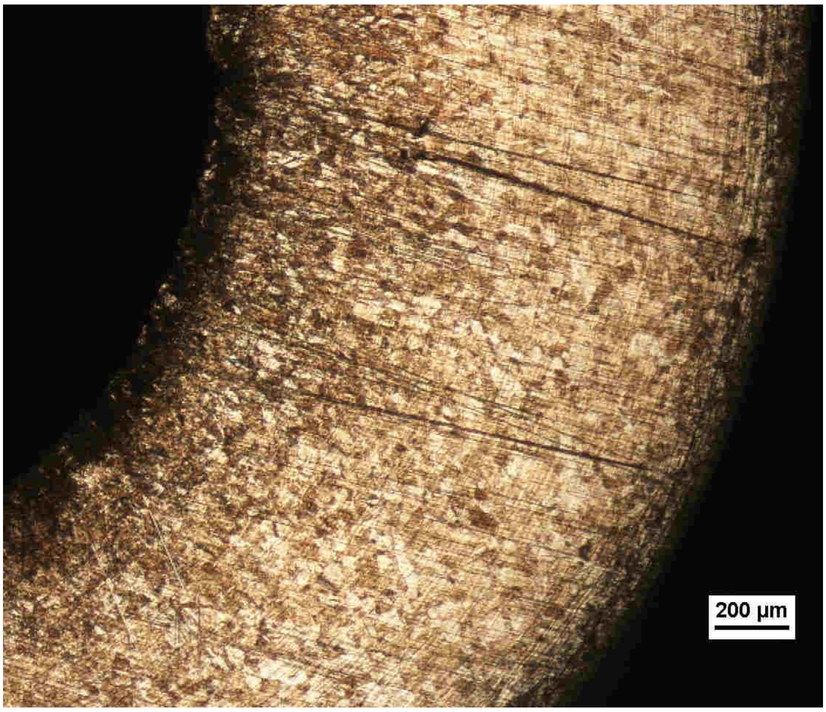

Figure 6. Regions where martensite transformation and dislocation density have increased on the tube end surface due to deformation

As expected, the deformation-induced martensite phase resulting from is more pronounced and dense on the surface of the material (Figure 7). During deformation, a critical stress level was reached, especially in regions close to the surface, causing the austenite structure to lose its stability under high deformation (due to cold deformation at low temperatures) and transform into martensite. Since martensite is a magnetic phase, the magnetic properties in these regions have increased. This magnetic property can be used to detect the presence of martensite through a simple magnet test.

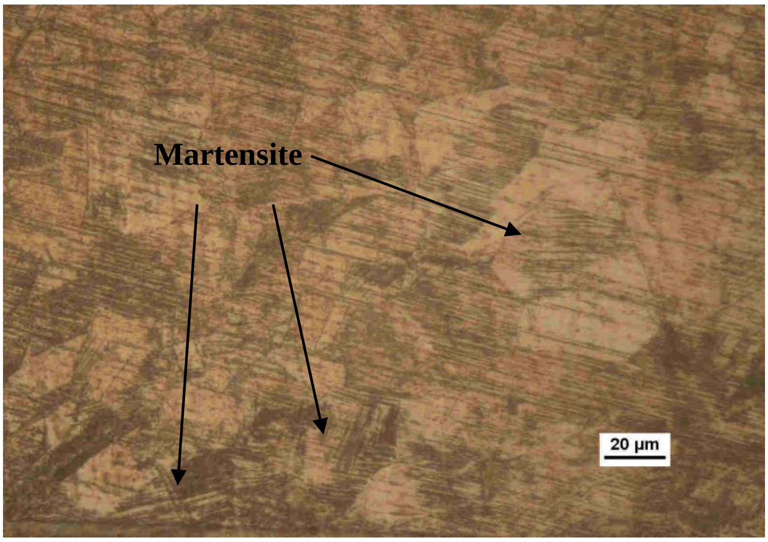

Figure 7. Deformation induced martensite phase

Metallographic examinations have also shown a significant increase in dislocation density on the surface. In Figure 8, the grain boundaries where dislocations accumulate and intense stress regions are formed are seen at dark colors. As dislocations stop at the grain boundaries and accumulate along them, a high-energy state and internal stresses develop within the grains. These high stresses also lead to an increase in hardness.

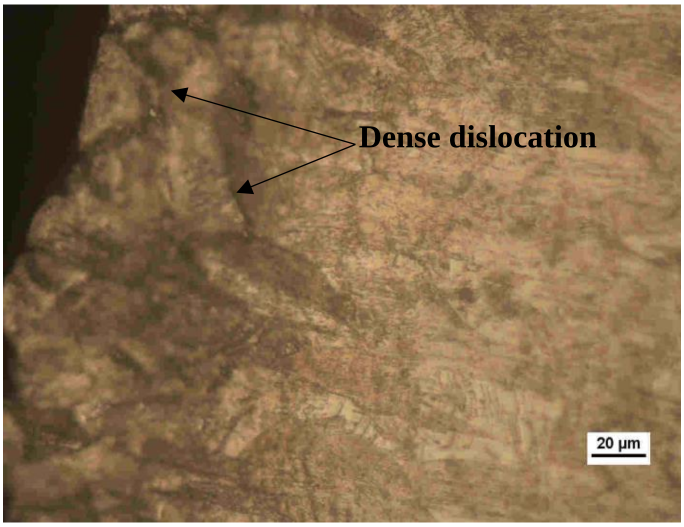

Figure 8. Dense dislocation regions accumulated at the grain boundaries.

In Figure 9, it is seen that the hardness gradually increases towards the surface due to the increase in martensite formation and dislocation density. After the tube flaring and forming operation, the hardness of hot rolled commercial AISI 304 stainless steel increased from 197 HV0.2 to 527 HV0.2. Similar results were reported by some studies [14, 15].

Figure 9. Hardness distribution of the tube-flaring sample

IV. CONCLUSION

In this study, the tube flaring and forming tool developed successfully formed thin-walled AISI 304 stainless steel tubes in a single pass without any tearing, and smooth deformation and thickness increase were achieved. As a result of metallographic examination, significant microstructural changes were detected in the material, including martensitic phase transformation and increased dislocation density due to deformation in the near-surface regions. These changes caused the hardness to increase from 197 HV0.2 to 527 HV0.2. These findings indicate that the designed tool and the single pass manufacturing process can effectively obtain the required material properties for stainless steel components and potentially improve their performance in industrial applications where similar forming and flaring processes are applied.

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