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Improving hydro-formability of stainless steel tubes by tube channel pressing

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Abstract. Tube channel pressing (TCP), which is one of the severe plastic deformation (SPD) technologies to refine grain size into submicron size for tubular materials, have been applied to ferritic stainless steel tubes for one pass, in order to alleviate ridging and enhance the hydro-formability. It was found that grain-scale shear bands were introduced by one-pass TCP, and texture and microstructure was successfully modified by promoting recrystallization of deformation microstructure, which is otherwise hard-to-recrystallize, in the post-TCP annealing. Elongation to failure, strain-hardening exponent (n-value) and Lankford values of both longitudinal and circumferential directions increased in comparison to with the tube fabricated by conventional process.

Keywords: ridging, formability, recrystallization, randomize, tube channel pressing

1. Introduction

Ferritic stainless steels (FSS) have high corrosion resistance, heat resistance and press workability. Therefore, they have been applied to various industrial applications, mostly as sheets or tubes. For example, tubes of FSS has been applied to exhaust tubes of automobile, which is frequently deformed into complicated shapes by hydro-forming. However, FSS exhibit ridging when they are subjected to tensile plastic strain in the rolling direction leading to reduction of the formability and the early fracture [1]. The ridging is a kind of rumple and it is caused by plastic anisotropy of the so-called colony with similar crystallographic orientations and is a feature of ferritic stainless steel. Therefore, it is important to promote recrystallization and randomize the texture to alleviate ridging.

In our previous study, we demonstrated that the ridging can be alleviated and the formability is enhanced in FSS sheets by equal-channel angular pressing (ECAP) [2], which is one of severe plastic deformation (SPD) methods. It was found that $\langle 100 \rangle_{\text{ND}}$ grains effectively recrystallized and changed into other orientations leading to randomization of texture in the post-ECAP annealing. Dense grain-scale shear bands were introduced by ECAP in large grains of $\langle 100 \rangle_{\text{ND}}$ which is otherwise hard-to-recrystallize, and promote recrystallization. There are some processes of SPD about tube materials, for examples, tube twisting is effective to impart strains [3]. Recently, modified ECAP was invented for tube materials and called tube channel pressing [4] and TCP which have been successfully applied to aluminium alloys tube to obtain ultra-fine grain (UFG) structure [4]. In the present study, we applied one-pass TCP to FSS tube in order to control texture and alleviate ridging and enhance the formability.



2. Experimental Procedure

2.1. Entire Process

Figure 1 shows entire flow of conventional process and TCP process. FSS (AISI409L) tubes of 42.7 mm in diameter and 1.0 mm in thickness, 25 mm in length were deformed by TCP process for one pass. Before and after TCP process, tubes were annealed. For comparison, the tubes were annealed before TCP as conventional process in order to relieve the plastic strain of as-received state. Tensile test was carried out to evaluate r -value, n -value and ridging. An optical microscope was used to see microstructure and a laser microscope was used to measure the surface roughness.

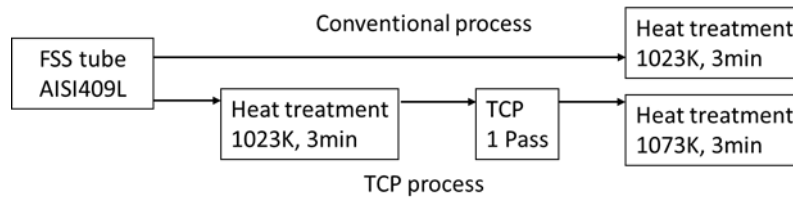


Fig.1 Entire flows of both conventional and TCP process.

2.2. TCP process

TCP is one of SPD process developed by Iranian researchers in order to refine grain size of tube materials [5]. TCP is a modified SPD of ECAP, and intensive shear deformation is given at the bended part of the circular channel. As shown in Figure 2, tube sample is pressed into the die by a tube plunger. In this way, the sample can be pressed for several times until UFG formation. Although, the sample is commonly deformed by simple shear in both ECAP and TCP, there are two important different points. First, there are three to four bended parts where the material is subjected to shear strain in TCP, whereas the typical ECAP has only one, so that billets are subjected to shear strain for several times according to die design in one pass.

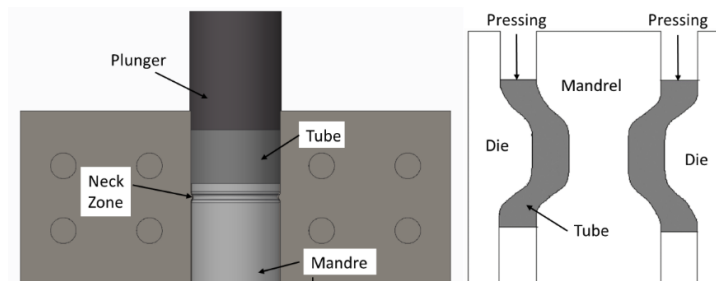


Fig.2 Schematic diagram showing repetitive process of TCP.

3. Results and discussion

3.1. Microstructure

Figure 3 shows optical micrographs before and after TCP. Equiaxial grains before TCP was deformed to elongated shape by shear deformation by one-pass TCP. After TCP, small shear bands are visible inside some grains as shown in Figure 3 (b) and (d). As discussed previous study, such small shear bands are observed in BCC metals such as stainless steels[6], carbon steels[7-10] and IF steels[7,8,11,12], and FCC metals with high stacking fault energy such as aluminum alloys[13-15]. This small shear bands are alternatively called in-grain shear bands [7-9, 11], grain-scale shear bands [13] or micro shear bands [15] by different researchers, and in this paper they are called grain-scale shear bands. It can be confirmed there are shear bands in two directions. This is because there are several shearing points through 1 pass TCP. The tube is squeezed in the radial direction accompanied by thickening of tube

wall. Thus, shear strain is given in not only through-thickness direction as in ECAP, but also circumferential direction as shown in Figure 3 (e). Vickers hardness and microstructures of neck zone after TCP are shown in Figure 4. They have three shear parts. It is confirmed that Vickers hardness increase as much as every shear part and shear bands increase gradually.

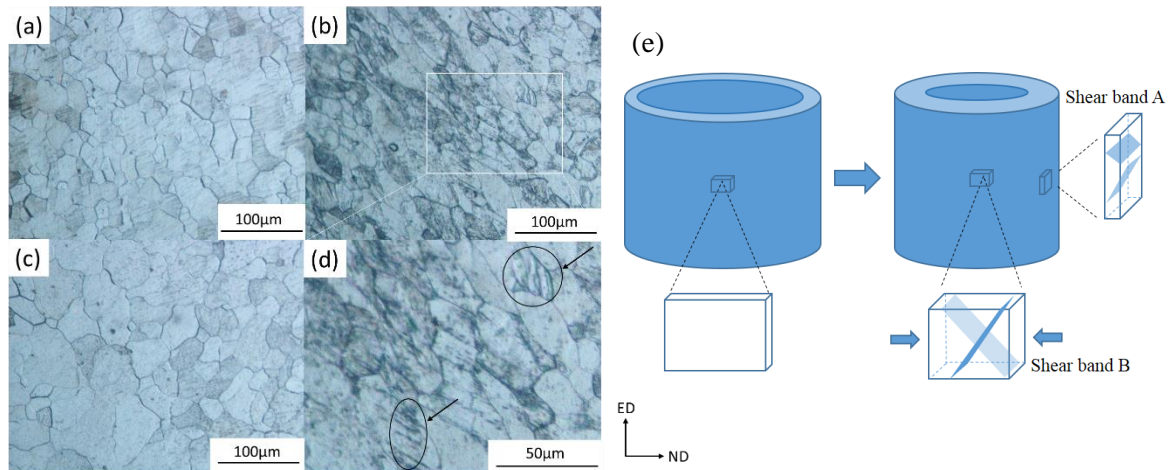


Fig.3 Microstructures of (a) before TCP, (b) after TCP, (c) after final heat treatment and (d) Magnified photo of (b). Arrows in (d) indicate grain scale shear bands and geometry (e) of shear bands A and B formed by shear strain by channel angle and squeezing (reduction of diameter), respectively.

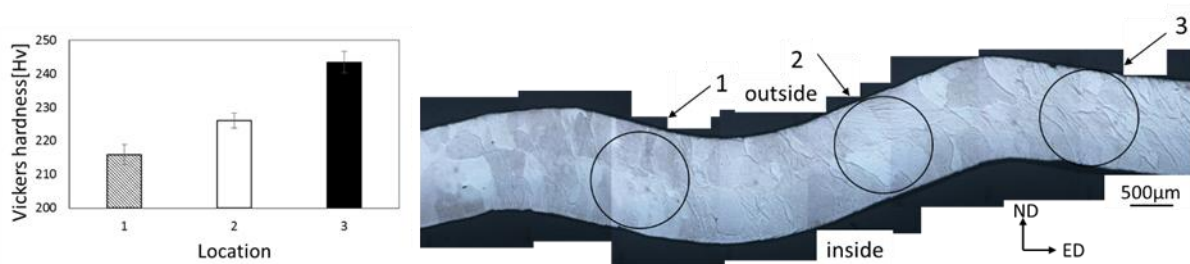


Fig.4 Vickers hardness and microstructures of neck zone after TCP.

3.2. Tensile test

Figure 5 shows the stress-strain curves of axial and circumferential directions. The latter data were obtained by tensile test of ring specimens. Higher elongation to failure in TCP process is evident as shown in stress-strain curve and the photos (Figure 6). Figure 7 shows the relationship between work hardening ratio and true strain of the axial direction, it is evident that the strain hardening rate is higher in TCP process throughout the strain. The strain-hardening exponent (n-value) of conventional and TCP processes are 0.22 and 0.26, respectively. Thus, the tube in TCP process is expected to have higher hydro-formability. Considerable effect is manifest in Lankford value both in axial and circumferential directions as shown in Table 1. Ridging evaluated by tensile test of 15% as shown in Figure 8. Ridging is clearly visible in the conventional process whereas it is mostly alleviated in TCP process. Figure 9 shows $\{100\}$ -pole figures after the final annealing. Since the tubes are fabricated by electric resistance welding (ERW) of cold-rolled sheets, typical cold-rolled and annealed texture can be recognized in the conventional processing with main components of $\{111\}\langle 112 \rangle$ and $\{322\}\langle 236 \rangle$ orientation. It is known that $\{111\}\langle 112 \rangle$ orientations tends to split into these $\{322\}\langle 236 \rangle$ orientations after cold rolling with very high rolling reduction. In contrast, texture is randomly oriented with no clear peak orientations as shown in TCP process. Thus, TCP and the final annealing randomized texture leading to alleviation of ridging and enhanced formability.

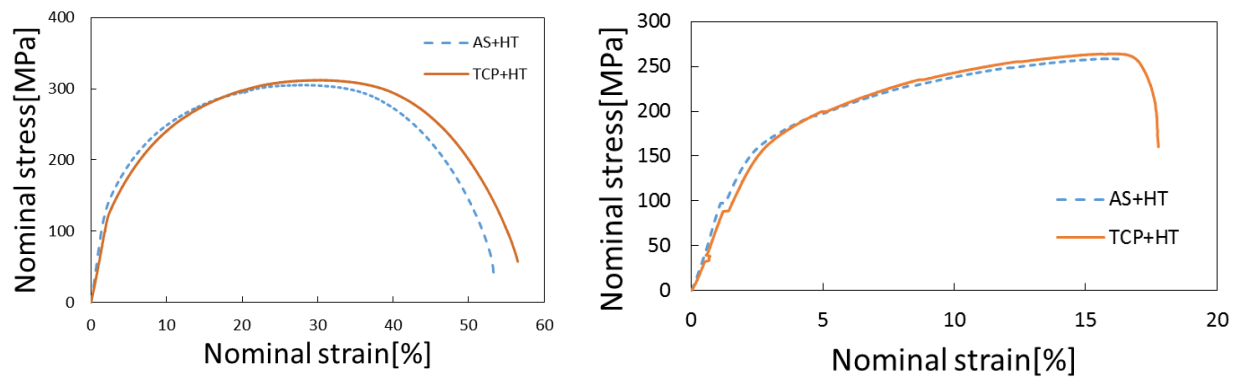


Fig. 5 Stress-strain curves of ring specimens to evaluate tensile behavior of axial (left) and circumferential (right) direction of conventional process and TCP process.

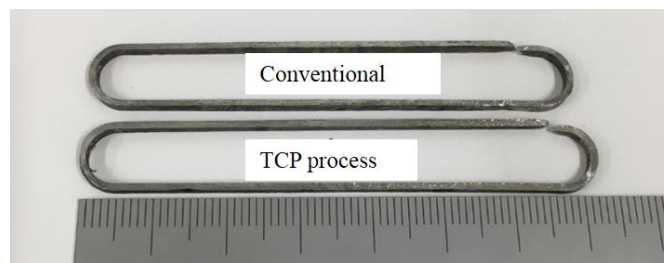


Fig.6 Ring specimen after tensile tests.

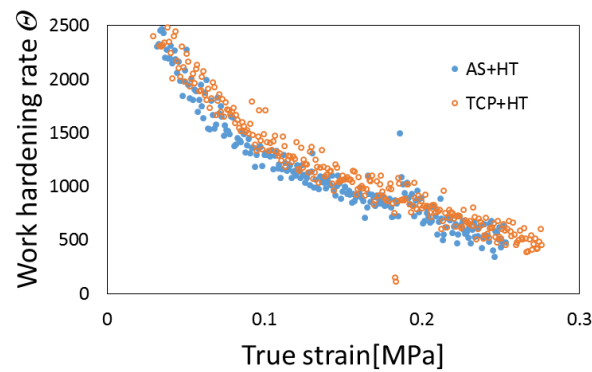


Fig. 7 Relationship between the work hardening rate and true stress of as annealed and 1 Pass of TCP annealed

Table 1 Lankford values of axial and circumferential directions

	axial	circumferential
AS+HT	1.14	0.90
TCP+HT	1.73	1.64

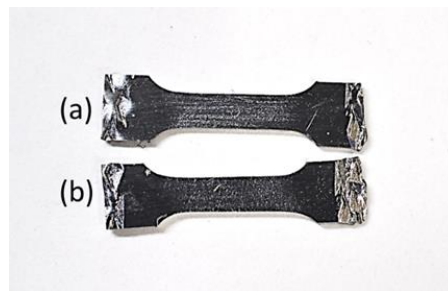


Fig.8 Ridging after 15% tensile elongation of (a) conventional and (b) TCP processing

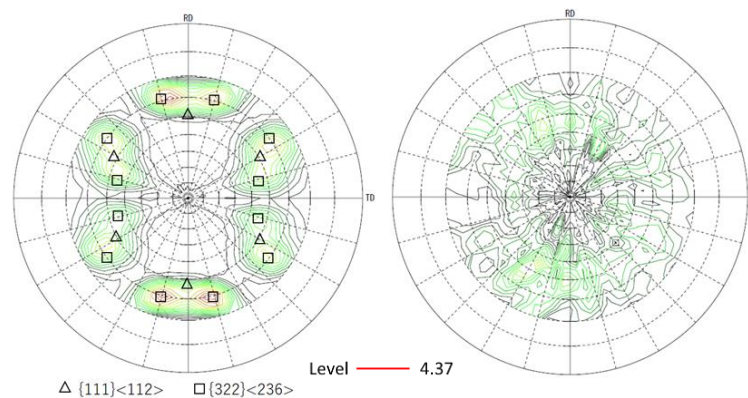


Fig.9 $\{100\}$ pole-figures after the final heat treatment of conventional and TCP process

4. Conclusions

Tube channel pressing was applied to ferritic stainless steel (Fe-10%Cr) tubes for one pass to examine the effect of TCP on recrystallization microstructure and texture and formability. After one pass TCP, grain-scale shear bands were visible in several grains. These shear bands facilitate recrystallization and randomize the texture. Ridging was alleviated, and both strain-hardening capability and r -value was enhanced by one-pass TCP. It can be expected that the hydro-formability is also enhanced.

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