Propagation of surface defects at cold pilger rolling of tubes and pipes

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Abstract
In present study the propagation and transformation of longitudinal as well as transversal surface defects placed on both external and inner surfaces of cold rolled seamless steel tubes (SST) and pipes has been experimentally analyzed. Cold pilger rolling of tubes was carried out through different rolling routes with variable cross section contractions as well as wall thickness and diameter reductions. For characterization of defects transformation during cold rolling the parameter "defect's relative depth" (RdH) was proposed, which is defined as a part of wall thickness occupied by defect. It was determined that reduction of outer tube diameter in rolling route decreases RdH only in case of inclined defects, which are situated on the external surface and oriented transversally to the rolling direction. In all other cases the reduction of outer tube diameter increases RdH. In contrary, RdH of internal longitudinal defects remains constant or increases after cold pilger rolling. Inner longitudinal folds exhibit the maximal intensity of RdH's and probably lead to the propagation of cracks. The change of dimensions of external longitudinal defects depends on both shape of defect`s cross section and such parameter as a part of diameter reduction in contraction of the cross section. Thus, these defects can be partially eliminated at cold pilger rolling. For prediction of defect`s evolution it has been proposed to use the DAP index that considers the relationship between strain parameters of cold pilger rolling and initial defect's shape.

Key words: MANUFACTURING DEFECTS, TUBES AND PIPES, SURFACE, COLD PILGER ROLLING

Introduction

Nowadays, the application of seamless steel tubes (SST) and pipes reduces due to increased attractiveness of both welded steel tubes and seamless tubes from light metals or polymer materials. Thus, the suppliers of SST should to find new ways to remain their market share. One of possible ways is an ensuring of excellent quality of their product, especially of cold rolled. In such conditions, cold rolled seamless tubes made of high quality stainless steels show stability and positive trend of their consumption. One of the main indicators of cold rolled tubes quality is an absence of surface defects [1,2].

The technology of stainless steel tubes and pipes manufacturing usually consist of two stages: hot extrusion with previous piercing and cold pilgering of hot deformed tubes [3]. At cold pilgering the part of hot extruded tube (further - billet) 1 comes into the zone of rolling cage 2 (**Fig. 1**) precipitate motion. The rolling cage is equipped with a couple of dies 3 that have a variable radius. Rolling dies along the stand stroke length form the integrated deformation zone (further - working cone) 4. Consequently, the feeding volume of billet deforms with the low level of partly strains within working cone in tube with finish size 5. The internal surface of tubes formed along the working cone by conical mandrel or mandrel with complex shape 6.

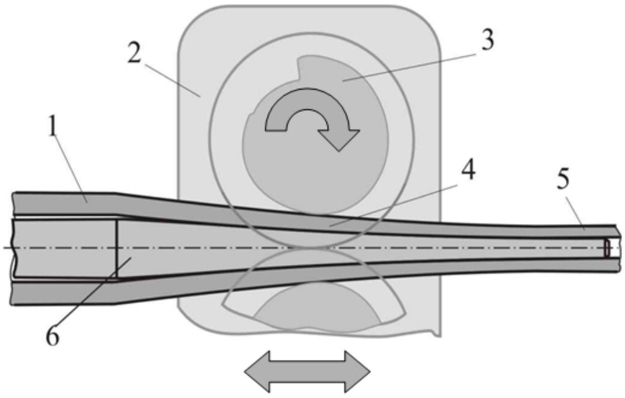

Figure 1. The scheme of cold pilger rolling: 1) hot extruded tube (billet); 2) rolling cage; 3) rolling dies; 4) working cone; 5) tube with finish size; 6) mandrel

It should be noticed that an increase of a part of diameter reduction at contraction of cross section contraction leads to the decreasing of difference between ultimate strength and yield strength of deformed metal. This is valid for all methods and modes of cold deformation as well as after heat treatment. [4]

The intensity of this decreasing depends on strain and technological parameters of cold pilgering. The most important of them are the strain distribution along the deformation zone, the thermal condition of rolling as well as equipment parameters like a length of stroke or feed volume [5]. The main feature of cold pilger rolling is consequent ovalization of cross section inside working cone. It continuously alternates the stress directions and values and thus, provides required ductility of metal even at high level of accumulated strain [6].

However, stress and strain history at cold pilger rolling can be responsible for surface defects. These defects deteriorate the outside view of finished tube and serve as a stress- and corrosion concentrators, especially under tangential load [7].

On the other hand, the quality of surface of cold pilgered tube is limited by quality of previous hot formed billets [8].

Chemical composition of metal, heat treatment as well as deformation mode at hot extrusion determines current metal properties and can provoke surface defects [9].

Previous investigations of formation of surface defects show that there are no consistent opinion concerning the transformation mechanism of these defects at cold pilger rolling of tubes. Schulze et al. have [10] concluded that control operations in technological process chain should prevent a formation of dangerous defects. However, it is well known that even the defects with small depth can be transformed into cracks.

Therefore, present study is devoted to the analysis of defects behavior at cold pilger rolling with variable combinations of cross section contraction as well as wall thickness and diameter reductions. The following three types of defects have been investigated:

- External longitudinal defects;
- Internal longitudinal defects;
- External transversal defects.

Experimental procedure and methods of research

In present study, hot extruded tubes made of steel grade UNS 30400 have been investigated. They have been rejected as defect tubes at quality control due to the surface defects and then prepared to experimental procedure. The initial dimensions of defects were measured and then these tubes were cold pilger rolled according to the specified rolling routes with variable deformation parameters [11].

All surface defects, which were observed on billets, were classified based on their relative width (RdW_0) (equations 1 and 2) as peak (**Fig. 2a**), rectangular (**Fig. 2b**) and round (**Fig. 2c**) defects.

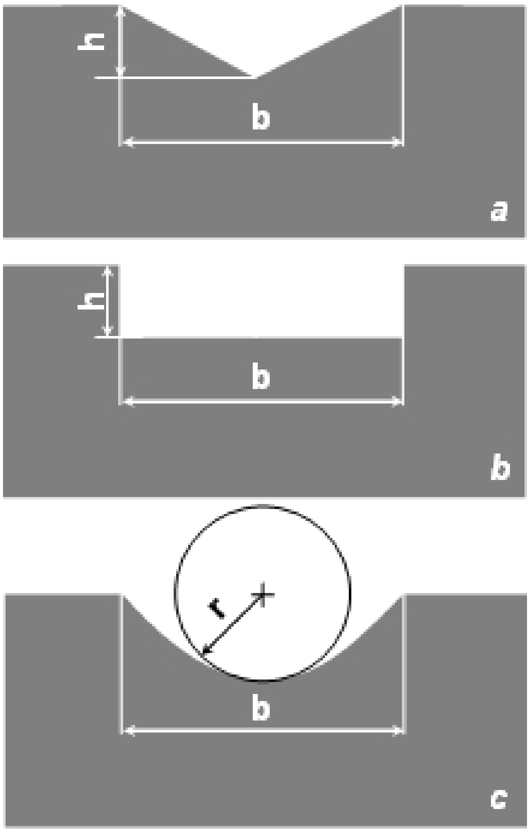

Figure 2. Examples of initial defect`s cross section with destination of their dimensions: **a** – peak defect; **b** – rectangular defect; **c** – round defect; h – depth; b – width; r – radius of defect`s curvature

$$RdW_0 = \frac{b_0}{h_0} \quad (1)$$

for peak and rectangular defects (**Fig. 2a** and **2b**)

$$RdW_{0R} = \frac{r_0}{h_0} \quad (2)$$

for rounded defects (**Fig. 2c**)

where b_0 and h_0 – initial width and depth of defects respectively (mm);

r_0 - radius of curvature of round defect.

Further the defects with $RdW_0 \geq 1$, or $RdW_{0R} \geq 0,5$ are defined as **gentle defects** and defects with $RdW_0 < 1$, or $RdW_{0R} < 0,5$ - as **sharp defects**.

All defects were also classified according to the relationship between their length (a) and width (b):

- a ≤ 3b - surface cavity;
- 3b≤a≤10b - fold;

- a>10b – notch;
- b→0 – crack.

For determination of both strain parameters at cold pilger rolling and propagation of defects, the following parameters were used:

Strain parameters at cold pilger rolling

Tube elongation factor:

$$\mu = \frac{(D_0-t_0)t_0}{(D_1-t_1)t_1}, \tag{3}$$

where, D_0, t_0, D_1 and t_1 are external diameter of billet, wall thickness of billet, external diameter and wall thickness of cold pilgered tube, respectively (mm).

Cross section contraction:

$$\varepsilon_\Sigma = \left(1-\frac{1}{\mu}\right)100\%, \tag{4}$$

External diameter reduction:

$$\varepsilon_D = \frac{D_0-D_1}{D_0}100\%, \tag{5}$$

Wall thickness reduction:

$$\varepsilon_t = \frac{t_0-t_1}{t_0}100\% \tag{6}$$

Part of diameter reduction in cross section contraction:

$$IF = {}^{\varepsilon_D}/_{\varepsilon_\Sigma} \tag{7}$$

If the value of *IF* is less than 0,7, it means that in current rolling route take place substantial wall thickness reduction. If it equals 0,7 or more, this rolling route is characterized by substantial diameter reduction.

Parameters of defects propagation

Relative defect's depth (*RdH*) is defined as a part of wall thickness that is occupied by defect:

Relative defect's depth of billet:

$$RdH_0 = {}^{h_0}/_{t_0}\,100\% \tag{8}$$

Relative defect's depth of cold pilgered tube:

$$RdH_1 = {}^{h_1}/_{t_1}\,100\% \tag{9}$$

Change of *RdH* at cold pilgering:

$$Rd = {}^{RdH_1}/_{RdH_0} \tag{10}$$

Thus, *RdH* of defect after cold pilger rolling increases at Rd>1 and decreases at Rd<1.

Results and discussion

External longitudinal defects (ELD).

Deformation parameters of cold pilger rolling, ini-tial and final sizes of tubes as well as characteristic dimensions of investigated ELD are presented in **Table 1**

Relationship between calculated values of Rd and RdW0 as well as Rd and IF are presented in **Fig. 3**.

Table 1. Deformation parameters of cold pilger rolling, initial and final sizes of tubes as well as characteristic dimensions of investigated ELD

Type of defect	Route	D_0 mm	t_0 mm	D_1 mm	t_1 mm	ε_Σ, %	*IF*	b_0 mm	h_0 mm	RdW_0	h_1 mm	RdH_0 %	RdH_1 %	Rd
Peak notches	1a	50	5,5	28	3,5	64,96	0,68	0,28	0,11	2,52	0,10	2,02	2,86	1,42
	1b	50	5,5	28	3,5	64,96	0,68	0,33	0,11	2,95	0,08	2,04	2,29	1,12
Rectangular notches	2a	57	3,2	32	1,8	68,42	0,64	0,55	0,31	1,79	0,25	9,63	14,06	1,46
	2a	57	3,2	45	1,5	62,10	0,34	0,81	0,45	1,80	0,19	14,06	12,67	0,90
Rounded defects	3a	57	6	28	4	68,63	0,74	0,15	0,38	0,39	0,77	6,33	19,25	3,04
	3b	57	6	28	4	68,63	0,74	5,00	1,30	3,85	0,35	21,67	8,75	0,40
	3c	57	9	31	6,8	61,91	0,74	7,00	0,90	7,78	0,15	10,00	2,26	0,23
	3d	57	9	31	6,8	61,91	0,74	6,00	2,50	2,40	1,70	27,78	25,00	0,90

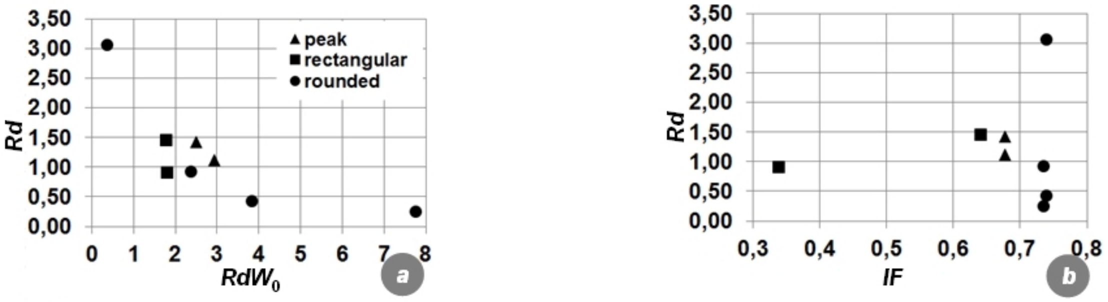

Figure 3. External defects. Influence of initial relative defect`s width $RdW_0$ (a) and part of diameter reduction in cross section contraction *IF* (b) at cold pilgering on change of relative defect`s depth *Rd*

According to the analysis of propagation of external defects the following observations were made:

- *External peak defects*. The relative depth of this defect increases in both researched cases, especially in case of sharper defect (Route 1a, **Table 1**). This means that for such shape of cross section of defect the allowed RdH0 should be more than 3. Therefore, the tubes with such defects should be rolled through routes with $IF \leq 0,7$.

- *External rectangular defects*. Such type of defects is more sensitive to the rolling route. The analysis of these defects revealed that decreasing of *IF* value can provide good mechanical properties as well as reduce RdH_1 below one. On the other hand, such defects tend to close at cold rolling stage and develop in near surface layers and thus, its width is always reduced after rolling. Hence, the presented method to characterize the transformation of such defects is not very useful.

- *External rounded defects*. For analysis of behavior of these defects the rolling routes had the maximal values of IF. In these conditions threshold between increase and decrease of relative defect's depth crossed at values of relative defect's width about 2,5.

Internal longitudinal defects (ILD).

Deformation parameters of cold pilger rolling, initial and final sizes of tubes as well as characteristic dimensions of investigated ILD are presented in **Table 2.**

Relationship between calculated values of Rd and RdW0 as well as Rd and IF are presented in **Fig. 4.**

Table 2. Deformation parameters of cold pilger rolling, initial and final sizes of tubes as well as characteristic dimensions of investigated ILD

Type of defect	Route	D_0 mm	t_0 mm	D_1 mm	t_1 mm	ε_Σ, %	*IF*	b_0 mm	h_0 mm	RdW_0	h_1 mm	RdH_0 %	RdH_1 %	Rd
Peak notch	4a	50	5,5	25	2,35	78,25	0,64	0,04	0,06	0,67	0,08	1,09	3,40	3,12
Rectangular defects	5a	57	8	32	6	60,20	0,73	1,00	0,80	1,25	0,60	10,00	10,00	1,00
	5b	57	8	40	6	47,96	0,62	1,00	1,00	1,00	0,70	12,50	11,67	0,93
	5c	57	3,2	32	1,8	68,42	0,64	1,00	0,56	1,80	0,47	17,38	26,11	1,50
Folds	6a	50	5	28	3,5	61,89	0,71	0,00	0,06	0,00	0,20	1,12	5,66	5,05
	6b	57	9	32	4	74,07	0,59	0,00	0,07	0,00	0,05	0,72	1,25	1,73

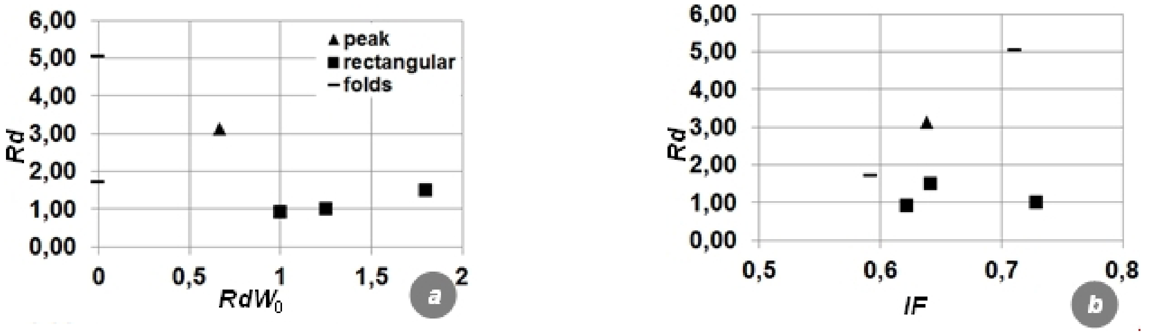

Figure 4. Internal defects. Influence of initial relative defect`s width $RdW_0$ (a) and part of diameter reduction in cross section contraction *IF* (b) at cold pilgering on change of relative defect`s depth *Rd*

ILD are more sharp compare to ELD that corresponds with practical experience. That is the reason of the absence of rounded defects in these experiments. The propagation of ILD at cold pilger rolling less homogenously than ELD.

Peak defect in current study according to above mentioned classification can be arranged to the sharp defect. These type of defects presents threefold increase of RdH_1 compare to RdH_0 at cold pilger rolling with relatively small IF value (less than 0,7).

Internal rectangular defects. These defects are not influenced by investigated parameters. Furthermore, they tend to close their edges and transform to the undersurface folds that is the same to the behavior of *external rectangular defects*.

Internal folds. Their evolution at cold pilger rolling confirms a well-known opinion: internal folds are most dangerous defects of tubes. Intensive wall thickness reduction at investigated rolling route has almost any effect on propagation of RdH_1 of these defects. Growth of *IF* index on 20% (from 0,59 to 0,71) provokes 2,9 times increase of *Rd* value.

External transversal defects (ETD)

Deformation parameters of cold pilger rolling, initial and final sizes of tubes as well as characteristic dimensions of investigated ELD are presented in **Table 3**.

Relationship between calculated values of Rd and RdW_0 as well as Rd and IF are presented in **Fig. 5**.

Table 3. Deformation parameters of cold pilger rolling, initial and final sizes of tubes as well as characteristic dimensions of investigated ETD

Type of defect	Route	D_0 mm	t_0 mm	D_1 Mm	t_1 mm	ε_Σ, %	*IF*	b_0 mm	h_0 mm	RdW_0	h_1 mm	RdH_0 %	RdH_1 %	Rd
Transversal peak defect	4a	57	3,2	32	1,8	68,42	0,64	6,70	0,82	8,17	0,39	25,63	21,39	0,83
	5a	57	3,2	32	1,8	68,42	0,64	4,30	0,82	5,24	0,44	25,63	24,17	0,94
	5b	57	3,2	25	1,6	78,25	0,72	6,70	0,82	8,17	0,12	25,63	7,50	0,29
	5c	57	3,2	25	1,6	78,25	0,72	4,30	1,20	3,58	0,32	37,50	19,69	0,53

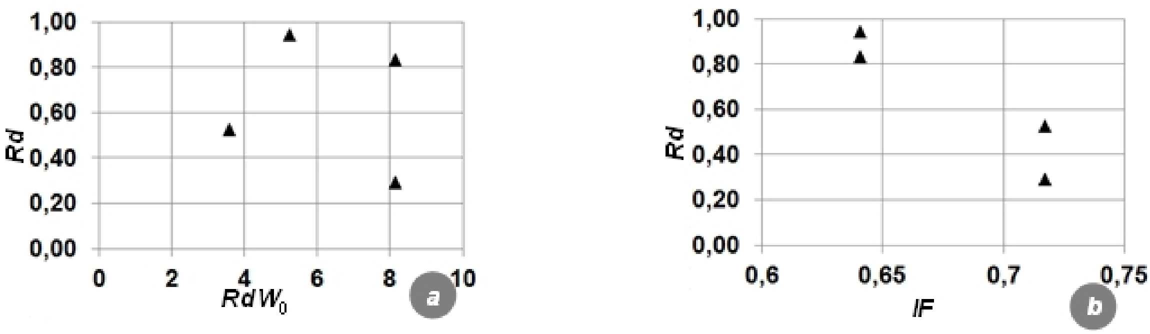

Figure 5. External transversal peal defects. Influence of initial relative defect`s width $RdW_0$ (a) and part of diameter reduction in cross section contraction *IF* (b) at cold pilgering on change of relative defect`s depth *Rd*

Peak defects. In all researched cases these defects show decrease of their RdH_1. In comparison with peak ELD, growth of diameter reduction decreases RdH_1. Therefore, it can be concluded that for such defect type the rolling routes with primarily reduction of diameter are favorable. However, stress concentration in these defects is dangerous and can provoke failure of tube at rolling.

All performed observations demonstrate that longitudinal folds on the internal tube`s surface are most dangerous type of defects. It should be noticed, while the defect's depth decreases at cold pilgering, the shape of this defect can be transformed into crack. Furthermore, defected areas become more local strain and deformation hardening, especially in case of austenitic stainless steels. Intensive localized strain commonly exacerbates the metal structure and deteriorates corrosion resistance of finished tubes.

Thus, a synthetic *DAP* index, which connects deformation parameters of cold pilger rolling with initial defect's shape, can be used for characterization of defect propagation at certain rolling route. Definition of this index presents equation (11):

$$DAP = \frac{RdW_0}{IF} \tag{11}$$

Figure 6 illustrates the dependence of change of initial relative defect's depth at cold pilger rolling on the index DAP (11). Rd values of all investigated defects continuously decrease with a growth of DAP values.

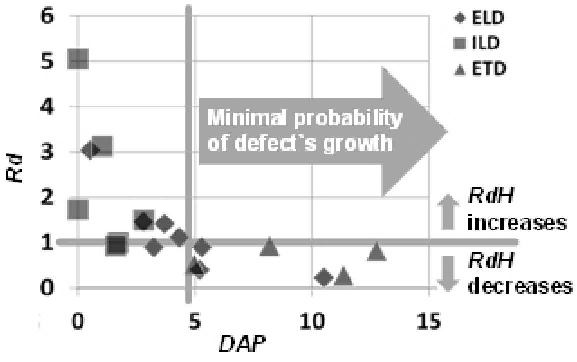

Figure 6 All researched defects. Scheme of influence of index DAP (9) on change of initial relative defect`s depth Rd (9); ELD – external longitudinal defects; ILD – internal longitudinal defects; ETD – external transversal defects

At DAP values of approximately 4,5 Rd values of all investigated defects lay lower than 1. It means that the combination of initial defect's parameters and strain conditions of cold pilgering can with certain limitations both increase or decrease values of *Rd* (8).

Such illustration could help to predict defect's growth basing on previous identified initial dimensions of defects and planned deformation parameters of cold pilgering.

For instance, route 1a (Table 1) has IF of 0,68. Here peak defect exhibits RdW_0 of 2,52. *DAP* index in this case is 3,7 that is less than 4,5. Therefore this defect at such rolling route has a high possibility to grow further at cold rolling. After rolling the value of RdH_0 was increased from 2,02% to 2,86%. Index Rd in this case equals 1,42. Thus, the part of damaged wall thickness has increased and this billet cannot be rolled through this rolling route.

Therefore, this billet can be further rolled, for example, in tube 28x2 mm instead of 28x3,5 (see rout 1a, Table 1) with other deformation parameters. In this case, *IF* index is 0,56 and DAP index is 4,51 that This value of DAP index corresponds to the minimal possibility of defect growth and thus, suggested rolling route is appropriate for billet with such defect.

Conclusions

1. Cold pilger rolling due to their favorable deformation conditions allows to decrease the depth of some types of defects. Mostly it is right for transversal gentle defects on external surface. In this case reduction of diameter in rolling route plays a positive role.

2. For describing of evolution of defects as a function of strain conditions, elongation factor, contraction of cross section of tube as well as part of diameter reduction in cross section contraction (*IF* index) should be taken into account.

3. Behavior of external longitudinal defects depends on shape of its cross section and *IF* index. Such defects can be partially eliminated at cold pilger rolling.

4. Relative depth of internal longitudinal defects in all investigated cases increases or remains unchanged at rolling. Maximal intensity of growth shows inner longitudinal folds. Such growth points to the propagation of cracks.

5. Studied gentle external transversal defects show ability to decrease with an increase of proportion of diameter reduction in cross section contraction.

6. The main result of this study presents the dependence of change of initial relative defect`s depth of defect at cold pilger rolling on the index DAP. With help of this index the threshold between zones with low and high possibility of defect`s growth has been defined. In present work this threshold of DAP index equals approximately 4,5. Thus, prediction of defect`s growth at cold pilger rolling should be carried out basing on previous identified initial dimensions of defects and planned deformation parameters of cold pilgering.

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