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Research Article

A New Stainless Steel Cold Rolling Algorithm from Raw Material Selection to Final Product

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Abstract

Stainless steels have a wide range of applications in industry due to their high corrosion resistance and high formability properties. Stainless steel flat products are produced by casting, hot rolling, annealing, cold rolling and, optionally, annealing and skin pass processes. Since all processes in stainless steel cold rolling mills are carried out sequentially on the same material, stainless steel cold rolling mills operate continuously. A change in continuous processes directly affects both product properties and process costs, as production is carried out in large tonnages. This study examines how process costs are reduced and how products with new properties are produced by changing the raw material selection and heat treatment processes without altering the chemical properties of AISI 304 and AISI 304L stainless steels. Using the proposed algorithms, an alternative material was produced instead of the 304 DDQ (deep drawing quality) material, which is in significant demand in the industry, and this production was achieved without the need to increase the nickel element ratio in the alloy. The newly produced material was named 304E/U, and the algorithm created was named TRX-EDDQ/TRX-UDDQ. The product generated by the new algorithm has been tested in customer processes and the algorithm's functionality has been verified.

Introduction

The production of stainless steel flat products can generally be divided into the following stages

a) Mining preparation and refining
b) Slab casting
c) Hot rolling and surface pickling
d) Cold rolling and surface pickling
e) Service centre operations

This study examines the cold rolling and surface pickling stages (Table 1). Generally, this process is referred to as cold rolling, and the facilities where the process is carried out are called cold rolling mills (Figure 1). The process flow of the stainless steel cold rolling process is as follows:

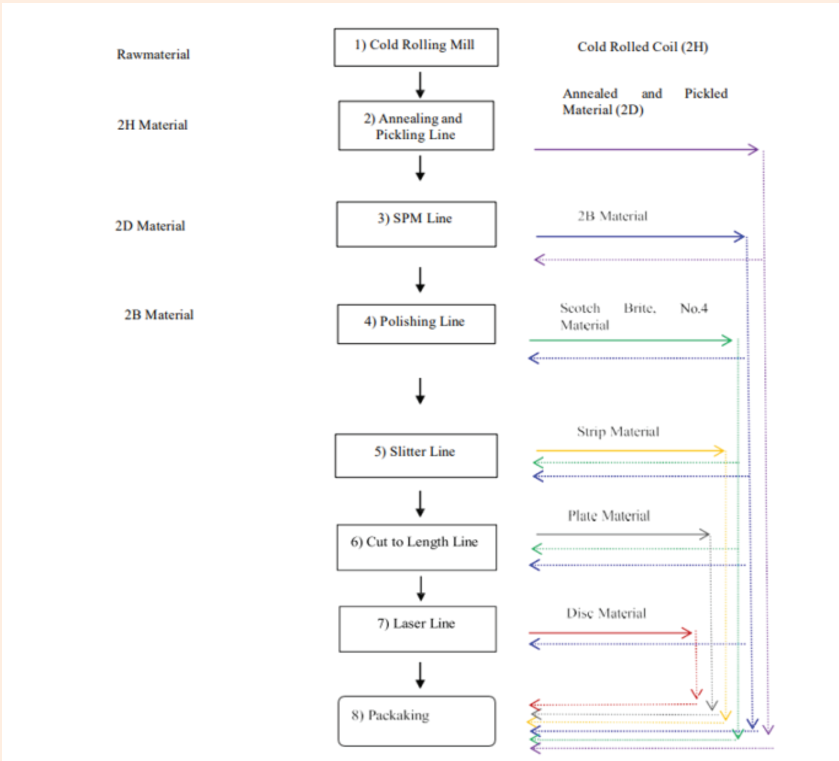

Figure 1: Stainless steel cold rolling and service operations process flow [1].

The list of some of the stainless steels that can be processed in these facilities and their chemical composition limit values are as follows:

Table 1: Some of stainless steel flat alloys [2].

AISI	EN	Chemical Composition % (max.-weight)									
		C	Mn	Si	P	S	Cr	Ni	Mo	N	Others
Austenitic Stainless Steels											
201	1.4372	0.15	5.50-7.50	1.00	0.06	0.03	16.00-18.00	3.50-5.50	-	0.25	-
301	1.431	0.15	2	1.00	0.045	0.03	16.00-18.00	6.00-8.00	-	-	-
304	1.4301	0.08	2	1.00	0.045	0.03	18.00-20.00	8.00-10.50	-	-	-
304L	1.4306	0.03	2	1.00	0.045	0.03	18.00-20.00	8.00-10.50	-	-	-
309	1.4828	0.2	2	1.00	0.045	0.03	22.00-24.00	12.00-15.00			
310	1.4841	0.25	2	1.50	0.045	0.03	24.00-26.00	19.00-22.00			
310S	1.4845	0.08	2	1.50	0.045	0.03	24.00-26.00	19.00-22.00			
316	1.4401	0.08	2	1.00	0.045	0.03	16.00-18.00	10.00-14.00	2.00-3.00	-	-
316L	1.4404	0.03	2	1.00	0.045	0.03	16.00-18.00	10.00-14.00	2.00-3.00	-	-
321	1.4541	0.08	2	1.00	0.045	0.03	17.00-19.00	9.00-12.00	-	-	(5*C)*Ti
Ferritic Stainless Steels											
409	1.4512	0.08	1.00	1.00	0.045	0.03	10.50-11.75	-	-	-	(6*C)*Ti
430	1.4016	0.12	1.00	1.00	0.040	0.03	16.00-18.00	-	-	-	-
430Ti	1.45	0.1	1.00	1.00	0.040	0.03	16.00-19.50	0.75	-	-	(5*C)*Ti
439	1.451	0.07	1.00	1.00	0.040	0.03	17.00-19.00	0.50	-	-	0.2+4*(C+N)*Ti
Martensitic Stainless Steels											
410	1.4006	0.15	1.00	1.00	0.04	0.03	11.50-13.00	-	-	-	-
420	1.4021	min. 0.15	1.00	1.00	0.04	0.03	12.00-14.00	-	-	-	-
440A	-	0.60-0.75	1.00	1.00	0.04	0.03	16.00-19.50	-	0.075	-	-
440C	1.4125	0.95-1.20	1.00	1.00	0.04	0.03	16.00-18.00	-	0.075	-	-
Duplex Stainless Steels											
2205	1.4462	0.03	2.00	1.00	0.03	0.02	1.00-23.00	4.50-6.50	2.50-3.50	0.08-0.20	-
329	1.446	0.20	1.00	0.75	0.04	0.03	23.00-28.00	2.50-5.00	1.00-2.00	-	-
Precipitation Hardening Stainless Steels											
631	1.4568	0.09	1.00	1.00	0.04	0.04	16.00-18.00	6.50-7.50	-	-	0.75-1.50 Al
632	1.4532	0.09	1.00	1.00	0.04	0.03	14.00-16.00	6.50-7.50	2.00-3.00	-	0.75-1.50 Al

Method

As shown in (Table 1), each element has a range value in stainless steels. For example, stainless steel with both an Ni content of 8% and 10.5% can be designated as 304. However, the properties of the two materials will affect the cold rolling process separately.

Various calculation methods have been developed to understand the effect of alloy element quantities on the phase structure of stainless steels. For example, according to Schaeffler, to determine the phase structure of stainless steels, two separate equivalent element sums are calculated: the nickel equivalent and the chromium equivalent. The mass ratios of the elements are multiplied by coefficients and calculated using the following equations: [3]

$$C_{req} = (Cr\%) + (Mo\%) + 1.5(Si\%) + 0.5(Nb\%) \quad (1)$$

$$Ni_{eq} = (Ni\%) + 0.5(Mn\%) + 30(C\%) \quad (2)$$

When the minimum and maximum values of the elements affecting the nickel and chromium equivalents in these equations are substituted, the nickel and chromium equivalents can vary within the following range in the same alloy:

$$C_{req} = 17.50 to 21.00$$

$$Ni_{eq} = 8.00 to 13.60$$

These calculations are used to determine the phase structure of stainless steels and to show where they are located on the phase diagram according to their chemical composition. The most commonly used stainless steel phase diagram is the Schaeffler-De Long diagram (Figure 2).

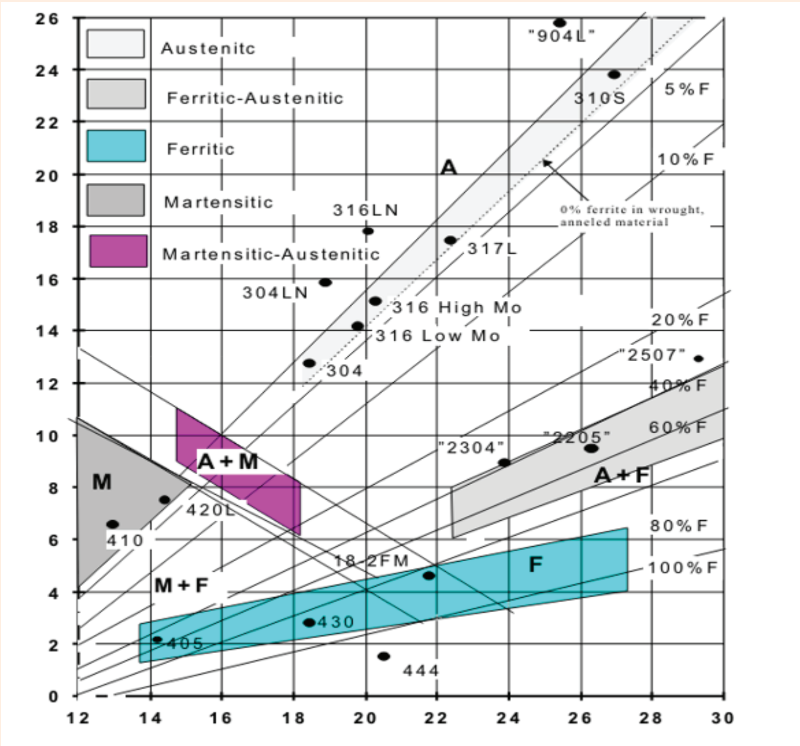

Figure 2: Schaeffler-DeLong diagram [7].

After calculating the chromium and nickel equivalents, the chromium equivalent result is plotted on the x-axis and the nickel equivalent result on the y-axis. The location of the relevant alloy is then identified on the diagram, thereby determining the phase structure (Table 2). With advancing technology and different empirical results, new calculations have been made regarding the coefficients of alloying elements to calculate the nickel and chromium equivalents in stainless steels. The findings of various scientists and engineers regarding the coefficients of alloying elements are as follows:

Table 2: Nickel-Chromium equivalence coefficients calculated by various researchers [4].

References	Ni_{eq}						Cr_{eq}									
Year/Researcher	Ni	Co	Mn	N	C	Cu	Cr	Mo	W	Si	V	Nb	Al	Ti	Ta	Co
1949, Schaeffler	1	0	0,5	0	30	0	1	1	0	1,5	0	0,5	0	0	0	0
1973, DeLong	1	0	0,5	30	30	0	1	1	0	1,5	0	0,5	0	0	0	0
1973, Hull	1	0,41	0,11	18,4	24,5	0,44	1	1,21	0,72	0,48	2,27	0,14	2,48	2,2	0,21	0
1978, Pickerling	1	1	0,5	25	20	0,3	1	1,5	0,75	2	5	1,75	5,5	1,5	0	0
1979, Hammar et al	1	0	0,3	14,2	22	1	1	1,37	0	1,5	5	2	0	3	0	0
1986, cheng et al	1	0	0,5	0	30	0	1	1	0,75	1,5	1,3	0,5	0	0	0	0
1987, samal	1	0	0,5	0	30	0	1	1,76	0,97	1,58	2,02	1,7	0	2,44	1,22	-0,177
1988, WRC	1	0	0	20	35	0	1	1	0	0	0	0,7	0	0	0	0
1992, WRC	1	0	0	20	35	0,25	1	1	0	0	0	0,7	0	0	0	0
1998, Tchizhik et al	1	0,5	0,5	30	40	0,3	1	1	0,5	1,5	2,5	1,5	2,8	2	0	0
1998, Bres	1	0	0,3	0	10	0	1	1	0	1,5	0	0	0	0	0	0
1999, Uggowitzer et al	1	1	0,1	18	30	0	1	1,5	1,5	0,48	2,3	1,75	2,5	0	0	0
zhzng et al	1	0	0,9-3,2	9,2-16,7	9,3-31,8	0,8-1,8	1	1-2,3	0,9-1,4	1,8-3,8	2,4-2,5	2,1	3,5-7,1	4,3-7,9	1,5	0-0,1

Considering Schaeffler's equation established in 1949, as seen in equations (1) and (2), the nickel equivalent of any AISI 304 stainless steel can vary between 8.00 and 13.60, and the chromium equivalent can vary between 17.50 and 21.00. In this case, all alloys with this range of values, which occupy different positions on the Schaeffler diagram, can be designated as AISI 304. However, occupying a different position on the Schaeffler diagram means that the alloys have different properties, even if they share the same name. The areas are shown in (Figure 3).

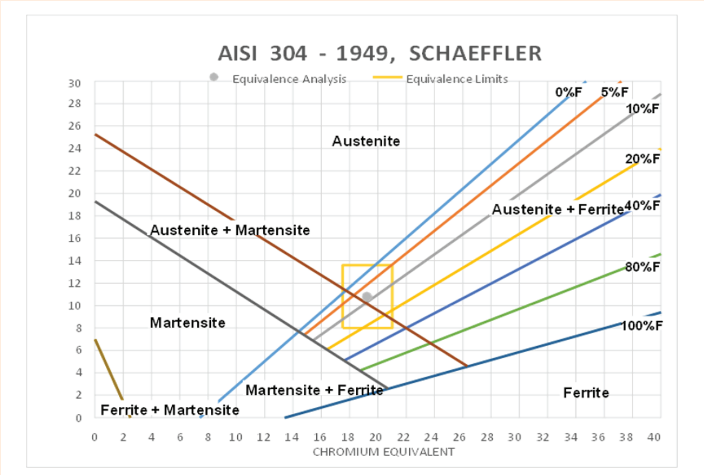

Figure 3: Area Where AISI 304 can be included in the diagram according to 1949, Schaeffler Calculation.

In (Figure 3), the central point indicates the position on the diagram when the AISI 304 alloy is at the midpoint between the lower and upper limits of all alloy values, while the orange frame shows the boundaries of the possible positions for an AISI 304 alloy based on the values of its alloying elements.

The position of the alloy limit values within the entire diagram can be calculated as follows:

$$\text{Alloy Area} = ((21-17.50)*(13.60-8.00))/(40*30) = (3.50*5.60)/1200=19.60/1200 = 1.63\% \quad (3)$$

Any AISI 304 alloy can occupy any part of the 1.63% area of the entire stainless steel map. In this case, it is impossible for part of the boundaries of the AISI 304 alloy not to overlap with part of the boundaries of another alloy. Therefore, the AISI 304 alloy may exhibit similar behavior to another alloy in terms of certain properties. Similarly, AISI 304 alloys may exhibit different behaviors among themselves.

Phase Transformation by Mechanical Deformation

Cold rolling is the process of cold plastic shaping of the material between two rotating rollers acting against each other under pressure. Cold rolling is performed after continuous casting, hot rolling and annealing-pickling in the production of stainless steel sheets. Stainless steel sheets are subjected to annealing and pickling processes again after cold rolling and are then directed to service operations (Figure 4). During the cold forming of metallic materials, grain elongation is generally observed in the rolling direction. This causes an increase in strength at certain ratios. In some materials, however, grain elongation, grain fracture and phase transformation are observed together during cold rolling due to high pressure forces [5,6].

In AISI 304 austenitic stainless steels, this phase transformation occurs in the form of austenite = martensite [7].

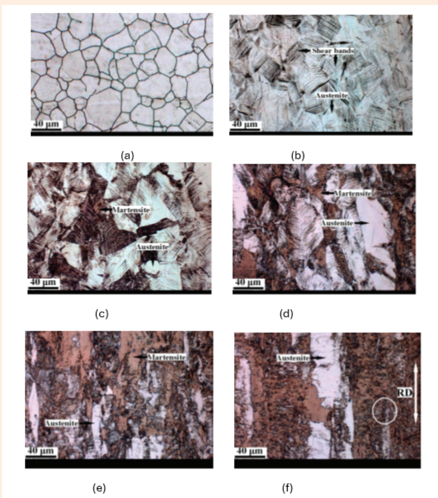

Figure 4: Phase Transformation of AISI 304 stainless steel due to cold deformation (a:%0, b:%10, c:%30, d:%50, e:%70, f:%90).

During cold deformation, the amount of deformation, the number of passes, and the phase ratios of the material significantly affect the increase in strength of stainless steels [7,8]. Following the cold rolling process, AISI 304 stainless steels undergo annealing. The purpose of annealing is to bring the material to the austenite temperature to achieve the martensite-austenite phase transformation, relieve internal stresses, dissolve metal carbides precipitated at grain boundaries, and reduce the material to its final hardness [9].

Creating the Algorithm

Since cold rolling of stainless steels causes a phase transformation from austenite to martensite and hardening, the greater the amount of austenitising elements in a material, the greater the amount of martensite transformation and hardening per unit deformation. Therefore, the hardening capacity of stainless steels through cold deformation will increase with an increase in nickel equivalent. Similarly, as the chromium equivalent decreases, the amount of hardening will increase. Based on this, the Hardening Capacity (HC) formula can be expressed as follows.

$$HC = \frac{Ni_{eq}}{Cr_{eq}} \quad (3)$$

This also means that material with high hardening capacity will exhibit greater martensitic transformation during cold rolling, resulting in faster grain growth during the heat treatment following cold rolling [10]. An algorithm has been designed for all these properties as follows:

a. Calculate the HC value of AISI 304/L raw materials.
b. Classify those with HC values below the average as Group A and those above as Group B.
c. After cold rolling Group A raw material, anneal it at 1080 °C for 90 seconds per mm of sheet thickness.
d. Anneal Group B raw materials after cold rolling at 1120 °C for 120 seconds per mm of sheet thickness.
e. Apply the standard SPM process to both groups.
f. Produce Group A material for product groups and customers requiring more than 55% elongation but where surface orange peel is undesirable.
g. Produce Group B material for product groups and customers requiring more than 60% elongation.

Conclusion and Discussion

This study aimed to develop an alternative material with high deep drawing capability by optimizing raw material selection and heat treatment parameters without altering the chemical compositions of AISI 304 and AISI 304L stainless steels. The developed production approach has been named TRX-EDDQ and TRX-UDDQ, and the new materials produced using this algorithm have been defined as 304E and 304U [1]. As a result of the calculations and process applications carried out, it has been observed that the phase structure of stainless steels changes significantly not only with the nominal alloy name but also with its position within the nickel equivalent and chromium equivalent ranges (Figure 5-8). According to the Schaeffler approach, the wide composition range within the AISI 304 class allows materials within the same standard to exhibit different microstructures and mechanical behaviors. This indicates that, with appropriate optimization of cold rolling and annealing processes, products with different properties can be obtained without altering the chemical composition. Within the scope of the algorithm, the chemical composition ranges of slab and hot-rolled strips were first evaluated, followed by the re-adjustment of cold rolling deformation rates and intermediate annealing parameters. This approach aimed to maintain the stability of the austenitic phase in the microstructure of the material while controlling the martensitic transformation that could occur during deformation. This increased the formability of the material and achieved the high ductility values required for deep drawing applications [1].

Figure 5: 304E microstructure image after heat treatment (100x).

Figure 6: 304U microstructure image after heat treatment (100x).

Figure 7: 304E microstructure image after cold deformation (100x).

Figure 8: 304U microstructure image after cold deformation (100x).

One of the key outcomes of the study is the ability to produce an alternative product to the DDQ class without the need to increase nickel content. As nickel is one of the most significant cost items in stainless steel production, achieving the same performance by keeping the chemical composition constant or using raw materials with lower nickel content provides a significant economic advantage. This approach has the potential to significantly reduce total production costs, particularly in cold rolling mills with large tonnage production.

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