1. Introduction

During forming of metallic sheets in the shapes ranging from kitchenware to automobile components, some defects may develop on their surfaces. These defects may arise from the microstructure or occur through the influence of the processing parameters or by corrosion. Orange peeling and stretcher strains marks are the main types of surface defects that originate from the microstructure. Orange peel effect is the consequence of independent deformation of individual grains, where the existence of stretcher strains is directly associated with the presence of discontinuous yielding on the stress–strain curves. In the metal forming industries, occurrence of such surface defects during forming is known as deformation-induced roughening. Since rough surfaces require more effort for polishing and/or painting after forming processes, deformation induced surface roughening of metallic sheets has been widely examined.

In the present study deformation induced surface roughening behavior of two austenitic stainless steel sheets was compared. These steel sheets had been imported from two different countries by a Turkish firm for production of cups and other kitchenware by sheet metal forming processes. The firm claimed that, one of these steels exhibited very high surface roughness after forming processes, which resulted in extension of polishing time and decrease of productivity at the final production step. Therefore, the goal of this investigation was twofold. First we aimed to examine the roughening of these steel sheets by uniaxial tensile tests and second, to evaluate the biaxial forming process from the viewpoint of surface roughening.

2. Experimental Procedure

The chemical compositions of the steel sheets examined in the present study are given in Table 1. These steels were coded as Steel 1 and Steel 2, and their thickness were 0.62 mm and 0.58 mm, respectively. Mechanical properties of the sheets were determined by uniaxial tensile and Erichsen cup tests. Tensile test specimens were machined at different angles to the rolling direction and the results of the tensile tests were averaged by the formula of:

\[ X = \frac{(X_0 + 2X_{45} + X_{90})}{4} \]  

where \( X \) is any tensile property at the angles of 0°, 45° and 90° to the rolling direction.

The surface quality and topography of the sheets were evaluated by roughness measurements and light optical microscopic examinations. Surface roughness was measured by a Perthen profilometer with an optical probe. In order to characterize the surface roughening during forming process, tensile test specimens cut in the angle of 90° to the rolling direction were elongated up to 35% in five individual steps. After each step, the roughness of the specimen was measured at six different locations. The results of the roughness measurements repeated at these locations were
then averaged for each deformation step.

3. Results and Discussion

3.1. Characteristics of the Steels

The results of the uniaxial tensile and Erichsen cup tests are given in Table 2. The chemical compositions (Table 1) and the mechanical properties (Table 2) meet the requirements of relevant standard for annealed AISI 304 quality austenitic stainless steels. During tensile tests, higher yield and lower ultimate tensile strength values were obtained from Steel 1 than Steel 2. Both steels exhibited almost similar ductility up to fracture. The values of work hardening coefficient and anisotropy factor of Steel 2 are slightly higher than those of Steel 1. The results of the Erichsen cup tests, which simulate sheet metal performance under stretching conditions, also indicate that Steel 2 has better formability than Steel 1.

Profiles and light optical micrographs of the surfaces of the examined steel sheets are depicted in Figs. 1 and 2, respectively. Even in as-received condition, surface grain structures were detectable due to the etching effect of the pickling operation of finishing process route of sheet metal production. When compared to Steel 2, Steel 1 exhibited higher surface roughness and lower grain size. Traces of linear scratches were also visible on the surface of fine-grained Steel 1. It is well known that, the initial surface quality and topography of the sheet metals are mainly related with finish rolling stage of the production process. Smoother surfaces are obtained by using smoother rolls especially in finish rolling pass. Mean surface roughness ($R_a$) values, which define the arithmetic mean of departure of a surface profile from a mean line, and the grain sizes are given in Table 3. $R_a$ values of the both steels confirm the typical data of 2D surface finish quality for stainless steel flat products. The grain sizes of the investigated steels were quantified according to the planimetric procedure. ASTM grain size numbers were found as 8 and 7 for Steel 1 and Steel 2, respectively. It is reported that grain size numbers below ASTM 5 is unacceptable for many sheet metal forming applications because of very serious deformation induced roughening. Grain size numbers of ASTM
7 or 8 are usually a good compromise between formability and surface appearance.\textsuperscript{11)\textsuperscript{\textdagger}}

As shown in Table 2, fine-grained Steel 1 (ASTM 8) exhibited higher yield strength during tensile testing than coarse-grained Steel 2 (ASTM 7) in accordance with Hall-Petch equation. Lower work hardening coefficient and anisotropy factor values of Steel 1 than those of Steel 2 are also related with its fine-grained structure.\textsuperscript{1}\textsuperscript{1)

### 3.2. Surface Roughening during Uniaxial Loading

Figure 3 compares the surface roughening behaviors of the investigated sheet metals during the uniaxial tensile deformation. Deformation induced roughening is additive to initial surface roughness and surface roughness of both steels increased linearly with the increasing longitudinal strain ($\varepsilon_l$). The linear relationship between $R_m$ and $\varepsilon_l$ can be expressed as:

$$R_m = R_{m0} + m \cdot \varepsilon_l$$

(2)

where, $R_m$ is mean roughness for a given strain, $R_{m0}$ is the initial surface roughness (Table 3) and $m$ is the roughening rate. The value of $m$ is calculated as 0.053 $\mu$m for fine-grained Steel 1 and 0.067 $\mu$m for coarse-grained Steel 2 from the slope of Fig. 3. If $m$ is normalized with respect to the grain size ($d$):

$$K = \frac{m}{d}$$

(3)

normalized roughening rate ($K$) is obtained as $K = 2.2 \times 10^{-3}$ for both of the examined steel sheets as a material property. Similar conclusion was also made by Mahmudi and Meh dizadeh\textsuperscript{1}) for a 70/30 brass sheet.

On the other hand, Fig. 3 depicts that, $R_m$ values of both steels crosses at $\varepsilon_l$ of 11%. Thus, 11% is the critical strain value of uniaxial tensile loading condition above which coarse-grained Steel 2 exhibits higher surface roughness than fine-grained Steel 1.

### 3.3. Analysis of Roughening during Biaxial Loading

It is common way to express the amount of effective strain for a deep drawn cup as thickness strain ($\varepsilon_t$), which can be calculated by assuming constancy of the volume\textsuperscript{2,3;\textdagger}$

$$\varepsilon_t + \varepsilon_w + \varepsilon_p = 0$$

(4)

where $\varepsilon_w$ is the width strain. The principal surface strains ($\varepsilon_l$ and $\varepsilon_p$) involved during deep drawing of a cylindrical cup can be expressed in terms of the diameter of the blank ($D_b$) and the diameter ($D_p$) and the height ($h$) of the formed cup as,

$$\varepsilon_l = \varepsilon_w = \frac{\left[D_p + 2h - D_b\right]}{D_b}$$

(5)

Constancy of the volume also leads to the following equation;

$$h = \frac{\left(D_p^2 - D_b^2\right)}{4D_p}$$

(6)

A typical cup deep drawn from the studied steels has $D_p$ of 240 mm and $h$ of 145 mm, which correspond to $h/D_p$ ratio of 0.6. By utilizing Eq. (6), $D_p$ required to produce the cup having the given dimensions can be calculated as 444 mm.

Since $\varepsilon_t$ of uniaxial tensile loading is 11% (Fig. 3), by taking the anisotropy factor as 1 (Table 2), $\varepsilon_t$ can be calculated as $-5.5\%$ from Eq. (4) for uniaxial loading condition. In biaxial loading condition, which resembles deep drawing operations, $\varepsilon_l$ and $\varepsilon_w$ are equal to each other. Therefore, maximum allowable surface strain that corresponds to $\varepsilon_t$ of $-5.5\%$ during deep drawing can be obtained as 2.8% from Eq. (4). In this case, the critical $h$ can be calculated as 108 mm from Eq. (5). This approximation leads to a critical $h/D_p$ ratio of 0.45. If Steel 2 is used for forming a cup having $h/D_p$ ratio lower than 0.45, relatively smoother surface will be obtained than Steel 1. Since in industrial applications these steels are used in production of cups having typical $h/D_p$ ratio of 0.6, Steel 2 will exhibit rougher surface than Steel 1 after forming. Therefore, Steel 1 is more suitable for production of a cup having $h/D_p$ ratio of about 0.6, to lower the polishing time after forming.

### 4. Conclusion

Deformation induced surface roughening of annealed AISI 304 quality austenitic stainless steels obeys following empirical equation during uniaxial tensile loading;

$$R_m = R_{m0} + 2.2 \times 10^{-3} \cdot d \cdot \varepsilon_l$$

(7)

where, $R_m$ is mean roughness for a given strain, $R_{m0}$ initial surface roughness, $d$ grain size and $\varepsilon_l$ is longitudinal strain. For certain amount of plastic deformation, fine-grained steel exhibits lower roughening than coarse-grained steel if
their $R_m$ values are the same. Two steels having $d$ values of 23 $\mu$m and 31 $\mu$m, and $R_m$ values of 0.76 $\mu$m and 0.64 $\mu$m, respectively, will exhibit almost the same roughness values during uniaxial tensile loading after $\varepsilon$ of 11% which corresponds effective strain of $\sim$5.5%. This effective strain can be achieved at surface strains of 2.8% in biaxial loading condition, where the surface roughness of both steel sheets is almost the same.

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