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Determining the optimal reduction ratio in temper rolling in terms of residual stress distribution across thickness

Temper haddelemede kalınlık boyunca artık gerilme dağılımı açısından optimum ezme oranının belirlenmesi

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Abstract

Materials with compressive stresses on the surface withstand fatigue failures, cracking, galling, and corrosion. This compressive stress at the surface can be created by temper rolling. The rolling process must be conducted with an appropriate reduction to obtain the desired benefit from temper rolling. A 1% thickness reduction is usually applied to endow flatness and surface texture to the strip, and this reduction is sufficient to eliminate the discontinuous yielding phenomenon. In this study, 2.5-mm-thick low-carbon steel sheet (DC01 grade) samples were annealed at approximately 600°C for 5 minutes, temper-rolled at room temperature at various reduction ratios subsequently, and the residual stresses formed along the thickness by rolling were investigated. This study has revealed that a 1% reduction ratio is insufficient for developing compressive stresses on the surface, but this can only be achieved with a 1.5% reduction ratio. When the reduction ratio was increased to 1.8%, tensile stresses began to occur inside, along with compressive stresses on the surface. It was observed that at a reduction ratio of 2%, the situation was reversed again; tensile stresses began to regenerate at the surface, and this became more pronounced up to a 10% reduction ratio.

Keywords: Compressive and tensile stresses, Discontinuous (obvious) yield phenomenon, Reduction ratio (Thickness reduction), Temper (Skin-pass) rolling

Öz

Yüzeyinde basma gerilmeleri içeren malzemeler, yorulma hasarlanmalarına, çatlamaya ve aşınmaya karşı dayanıklıdır. Yüzeydeki bu basma gerilmeleri temper haddeleme ile oluşturulabilir. Temper haddelemeden beklenen faydayı elde etmek için haddeleme işlemi uygun bir ezme oranında yapılmalıdır. Şerit yüzeyine düzgünlük ve pürüzlük kazandırmak için genellikle %1'lik ezme oranı uygulanır ve bu ezme miktarı süreksiz akma olayını ortadan kaldırmak için yeterlidir. Bu çalışmada, 2,5 mm kalınlığındaki düşük karbonlu çelik sac (DC01 kalite) numuneler yaklaşık 600°C'de 5 dakika tavlanmış, ardından oda sıcaklığında çeşitli ezme oranlarında temper haddelemeye tabi tutulmuş ve haddelemeden dolayı kalınlık boyunca oluşan artık gerilmeler incelenmiştir. Bu çalışma, yüzeyde basma gerilmeleri oluşturmak için %1'lik ezme oranının yetersiz olduğunu, bunun ancak %1,5'lik bir oran ile sağlanabileceğini ortaya koymuştur. Ezme oranı %1,8'e çıkarıldığında, yüzeyde basma gerilmeleri ile birlikte içeride çekme gerilmeleri oluşmaya başlamıştır. %2'lik ezme oranında ise durumun tekrar tersine döndüğü; çekme gerilmeleri yüzeyde yeniden oluşmaya başladığı ve bu durumun %10 ezme oranına kadar daha belirgin hale geldiği gözlenmiştir.

***Anahtar kelimeler**: Basma ve çekme gerilmeleri, Süreksiz (belirgin) akma olayı, Ezme oranı, Temper haddeleme*

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1. Introduction

Residual stresses are multiaxial internal stresses in a solid body due to inhomogeneous plastic deformation, local cooling rate differences, or structural changes (phase transformation). Asymmetrical rolling, which results in a heterogeneous microstructure and generates residual stresses, can lead to higher residual stresses throughout the thickness. The regions subjected to elastic tensile stress may suffer localized corrosion in aggressive environments. In addition, tensile residual stresses on the surface can lead to micro- and macro-cracks forming, especially during deep drawing. Therefore, it is more inconvenient that the tensile stress is on the material surface. It is well known that compressive residual stresses at the surface play an important role in prolonging material life (Azarhoushang & Kadivar, 2021). A %6- to 200% improvement in fatigue life has been noted for steel plates (Kanchidurai et al., 2017). Morikage et al. used hammer-peened material to show how the compressive residual stress layer affects fatigue resistance. They found that materials with compressively stressed surfaces had the slowest fatigue crack growth rate (Morikage et al., 2015). According to the mathematical model aiming to suppress the fatigue effect of inclusions in the microstructure of bearings, the level of compressive stresses should be optimal. If it is excessive, there is no improvement, even deterioration of fatigue properties (Mahdavi et al., 2019). Because the crack opening is suppressed at the sample surface, compressive stress close to the sheet surface provides higher ductility and prevents tearing during forming (Yu et al., 2019). Cold deformation methods such as shot peening, hammer peening, rolling, or low-temperature fine abrasive processes can induce this residual stress on the material surface. It should be considered that some of the compressive stress on the surface is quickly relieved with the deformation of the material.

Sheet metal is often subjected to a final process to impart essential properties. These are the improved mechanical properties and flatness, the texture on the strip surface, and the absence of obvious yielding phenomenon in the material. Temper rolling (skin-pass rolling) is the final step, which involves giving the annealed sheet a slightly cold thinning at room temperature. This slight reduction ratio applied in a temper rolling significantly affects the material's properties. A 1% thickness reduction is usually sufficient to endow flatness and surface texture to the strip and to eliminate the discontinuous yielding phenomenon (Çolak, 2021; Çolak & Kurgan, 2018, 2019; Fang et al., 2002; Grassino et al., 2012; Jafarlou et al., 2014; Kurgan & Özakın, 2020; Lake, 1985; Luis et al., 2009; Ma et al., 2009; Mazur, 2012, 2015; Özakın et al., 2021). As the reduction ratio increases, the microstructural and microhardness changes differ (Özakın & Kurgan, 2022). The yield strength reaches its minimum value at a reduction ratio of 1% and begins to rise again above this ratio, so the material loses its plasticity without an obvious yield area (Ma et al., 2009; Mazur, 2012). According to Koohbor & Serajzadeh (2011), when the type of stress at the surface shifts from tensile to compressive, the time it takes to attain maximum hardness, where it loses its plasticity during ageing, almost doubles. This reduction value was determined to be 1.3% to 2.0% to remove the obvious yield region (Lake, 1985). Grassino et al. (2012) also found this ratio to be 1.3% for low-carbon steel.

Slight reductions and/or small rolls and low friction coefficients create compressive stresses on or near the surface, whereas tensile stresses arise in the interior parts (Kalpakjian & Schmid, 2007; Yu et al., 2019). In this situation, the sheet cross-section shows a non-uniform stress-strain distribution (Figure 1a). The plastic flow begins in the stretched middle layers and progresses to the surface. This decreases the flow strength, and the stress-strain curve no longer shows an obvious yield phenomenon (Mazur, 2012). Suppose the reduction ratio or roll diameter is more significant than a specific value. In that case, tensile stresses occur on the surface, and compressive stresses on the inside (Figure 1b). The stress distribution induced by rolling is not the same not only across the thickness of the sample but also across its width. It was proved that the stress type and value also differ across the width of the sample (Koohbor & Serajzadeh, 2011). They showed that after single-pass rolling, tensile stress occurs in the middle of the sample, and compressive stress occurs at the edges in the residual stress distribution, which varies along the thickness.

Much research has been done on the impact of temper rolling on mechanical properties, but the number of studies on residual stresses could be much higher. In selecting the reduction ratio, the requirement of exerting compressive stresses on the material surface in terms of life should also be addressed. This study investigates the optimal reduction ratio to create residual compressive stresses at the surface. It was demonstrated that using the finite element approach, the rigid roller model might be utilized to determine residual stresses in rolling simulations (Sae et al., 2012). In the study that tried to fabricate gradient-structured aluminum, the plastic strain was observed in the core of the sheet when a reduction ratio of 2%. This means that the stress is only at the surface, yet there is no tension in the core layer of the plate until this reduction (Yu et al., 2019). In the present study, steel sheet samples were subjected to temper rolling with different thickness reductions, and rolling-induced residual stresses that occurred in the cross-section of the material were investigated.

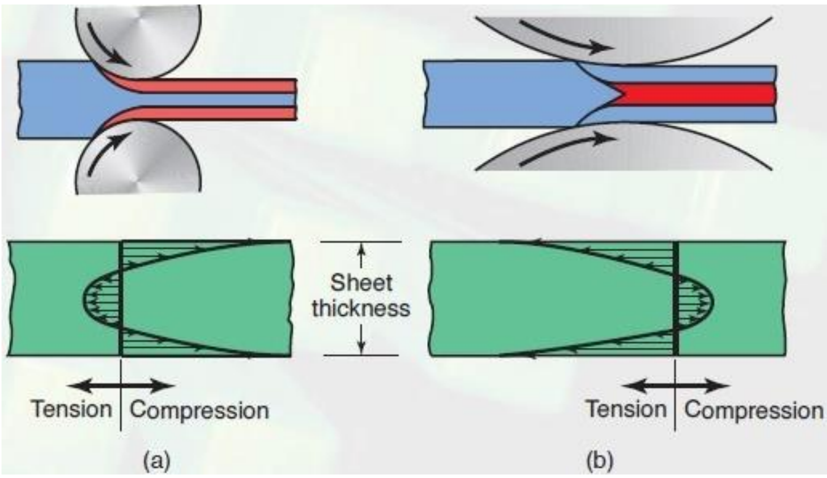

Figure 1. The type of residual stress distribution developed in flat rolling. a) small rolls and/or small thickness reduction, b) large rolls and/or large thickness reduction (Kalpakjian & Schmid, 2007).

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2. Experimental procedure

In the rolling experiments, 2.5 mm thick DC01 grade low-carbon steel with a chemical composition of 0.036C–0.204Mn–0.010P–0.006S–0.007Si–0.070Al (wt.-%) whose tensile properties are given in Table 1. was used. For the rolling tests, two-high rolling equipment in which the radius and width of the pair of rolls were 75 mm and 200 mm, respectively, allowing the accurate setup of the required speed and gap used (Figure 2). The test samples were cut 500 mm long by 30 mm wide and annealed at 600°C for 5 mins to remove the effects of previous cold treatment history. The cutting method was used to measure the residual stresses on the rolled samples. The residual strain is the difference between the original and final strains. The strain was measured using strain gauges attached to the sample surface before cutting. According to Hooke's law, the magnitude of the localized residual compressive stress was found by multiplying the strain by the elasticity modulus. To investigate the impact of the thickness reduction on the stress type on the surface, the samples were subjected to temper rolling with different thickness reductions (1%, 1.5%, 1.8%, 2%, 3%, 3.4%, 10%) at a constant speed (10 rpm).

Table 1. Material properties

Standard	Grade	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)
DIN-EN 10130-2006	DC01	248.1	332.4	32

Figure 2. The two-high rolling setup.

In this study, the samples' reduction ratios (r) were found according to Eq. 1 (Grassino et al., 2012; Özakin, 2023).

$$r = \left[\left(t_0 - t_1 \right) / t_0 \right] \times 100 \qquad (1)$$

where t_0 and t_1 are the thickness before and after rolling, respectively.

Residual stress measurements (cutting tests) were performed in the Laboratory Margem at Karabük University.

3. Results and discussion

Residual measurement tests of all rolled samples were performed to reveal the residual stress distribution across the thickness. One of the annealed but not rolled samples was also subjected to a cutting test to ensure it was free of residual stresses. Despite annealing, it was observed that the effects of the previous cold workings could not be eliminated, and a compressive stress of approximately 1.5 MPa remained in the material section, as seen in Figure 3. All samples were assumed to have this residual stress distribution and were subtracted from the residual stress distribution of all rolled samples to reveal the rolling-induced residual stresses.

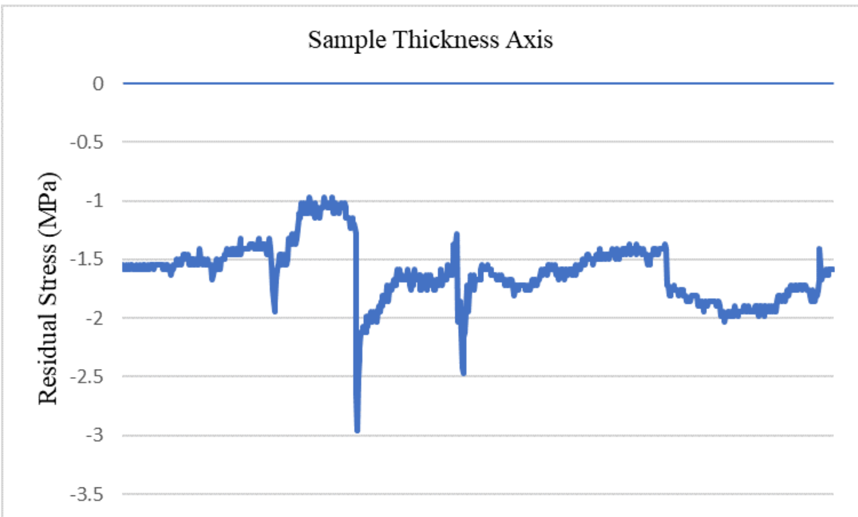

Figure 3. Residual stress distribution of an annealed but unrolled sample.

In a temper rolling, a reduction ratio of 1% is usually sufficient to obtain a material with no obvious yielding and a smooth, flat, and textured surface (Çolak, 2021; Çolak & Kurgan, 2018, 2019; Fang et al., 2002; Grassino et al., 2012; Jafarlou et al., 2014; Kurgan & Özakın, 2020; Lake, 1985; Luis et al., 2009; Ma et al., 2009; Mazur, 2012, 2015; Özakın et al., 2021). However, it is seen that this reduction ratio is not sufficient in terms of compressive stress on the surface (Figure 4a). Since a slight reduction causes only tensile deformation of the skin and not internal deformation of the body, compressive residual stress is theoretically expected to occur at the surface (Figure 1a). To prove the consistency of the measurement result (Figure 4a), the residual stress measurement for 1% reduction was repeated with another sample, and the result was found to be almost the identical (Figure 4b). There are still tensile stresses on the surface and compressive stresses on the inside. This should be considered a disadvantage in the manufacturing phase if the material is to be resistant to surface cracking, fatigue, or corrosion.

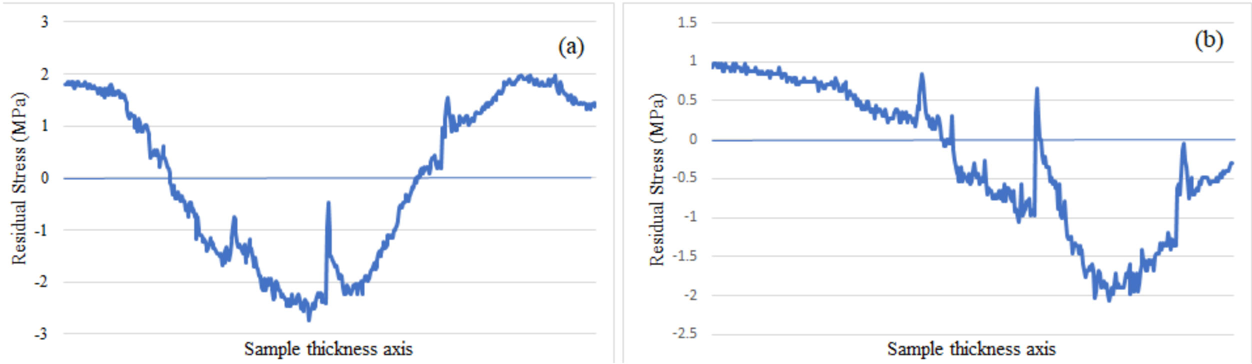

Figure 4. Residual stress distributions for a reduction ratio of 1%. (a) Primary test (b) Verification test.

When the reduction ratio is increased to 1.5%, residual compressive stress is expected to only occur at the surface. However, the measurements show that the residual stress distribution completely turns into increasing compressive stress throughout the thickness (Figure 5a). The residual stress measurement was repeated to verify this result, and a similar distribution was obtained (Figure 5b). Positive and negative residual stresses across the thickness balance each other. However, since a single type of residual stress was generated here, which varies throughout the thickness, the material was bent during rolling to maintain internal stress balance (Figure 6).

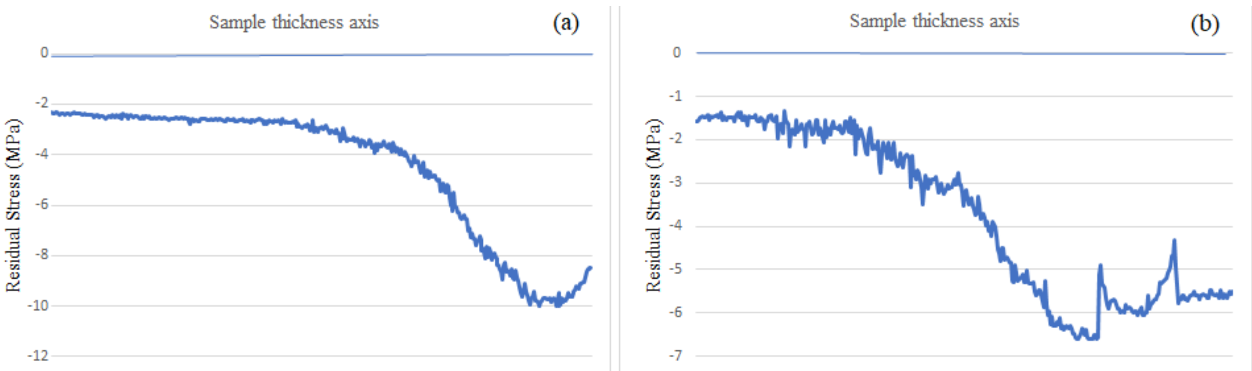

Figure 5. Residual stress distributions for a reduction ratio of 1.5%. (a) Primary test (b) Verification test.

This distribution is acceptable regarding material life compared to the tensile stress-weighted distribution. Fatigue cracks usually initial at the surface. As compressive stresses at the surface suppress the possibility of yielding, it increases fatigue life (Mahdavi et al., 2019). For the surface cracks not to propagate, the surface must be subjected to compressive stresses, and its hardness must be higher. If the whole body has a high hardness, processing will be more difficult due to insufficient ductility. If the compressive stresses at the surface are balanced with the tensile stresses in the body, the toughened material, thanks to the residual compressive stress at the surface, becomes more resistant to cracks. Therefore, compressive stress occurs only at the surface, and the tensile stresses in the interior are more favourable in terms of life.

Figure 6. Curvature tendency due to unbalanced residual internal stresses.

When the reduction ratio was increased to 1.8%, it was observed that the desired stress distribution appeared in the material cross-section. In a temper rolling, where compression stresses are desired to be created at the surface, this occurs at a reduction ratio of 1.8%, not 1%.

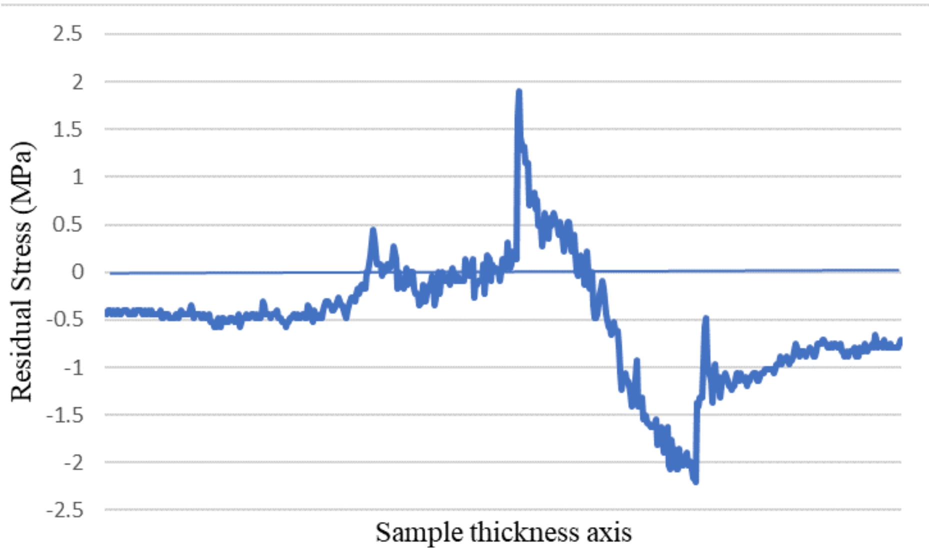

Figure 7. Residual stress distribution for a reduction ratio of 1.8%.

However, the situation reversed when the reduction ratio exceeded 1.8%; with a 2% reduction ratio, tensile stresses started to occur again on the surface. It is seen that the distribution is similar at higher reduction ratios (Figure 8 a,b,c,d), and when the reduction ratios of 3%, 3.4%, and 10% are considered, the tensile stress magnitude at the surface increases and the compressive stress value inside decreases as the reduction increases. Increasing the difference between residual compressive and tensile stress exhausts the fatigue performance of components (Ren et al., 2022). Since this difference increases at higher reductions (Figure 8 a,b,c,d), it creates a disadvantage for the rolled material regarding fatigue life.

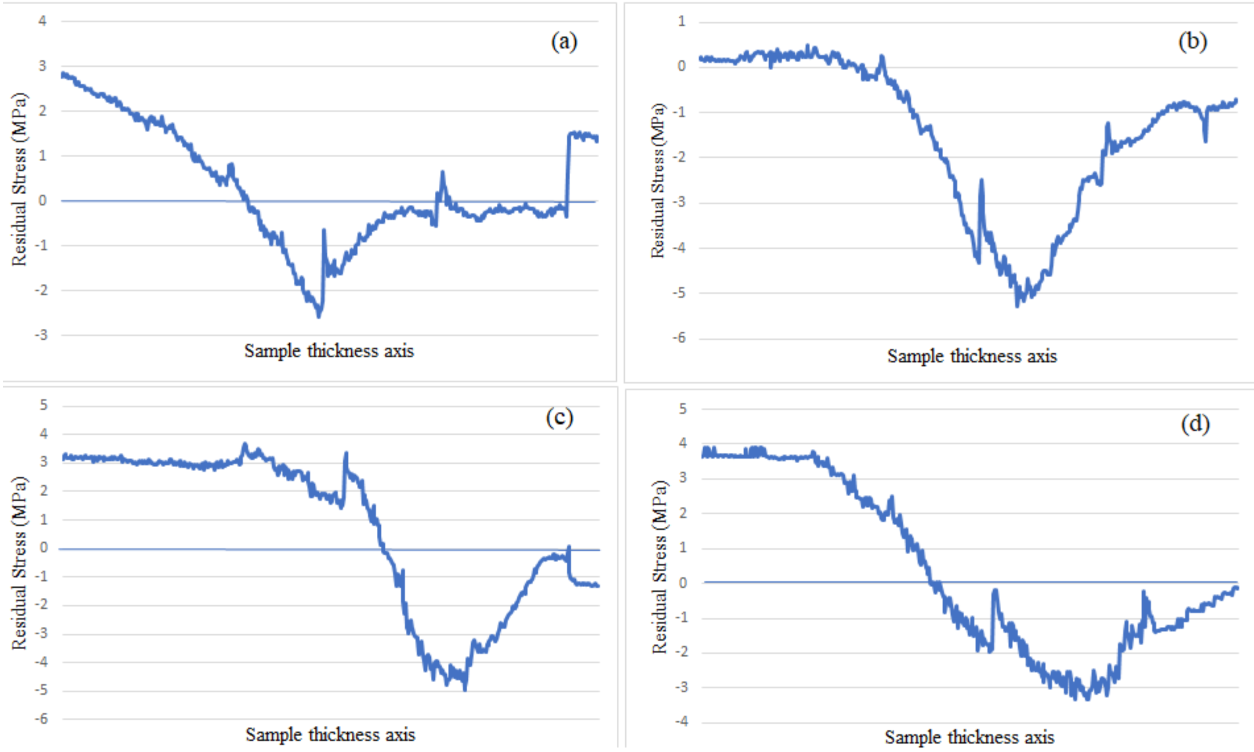

Figure 8. Residual stress distributions for higher reduction ratios. (a) a reduction ratio of 2%. (b) a reduction ratio of 3%. (c) a reduction ratio of 3.4 (d) a reduction ratio of 10%.

This study explored the impact of the reduction in thickness on the residual stress distribution; however, its influence on the obvious yield phenomenon, flatness, surface roughness, and strip surface topography was not considered. None of these requirements should be violated throughout the temper rolling procedure. It is more difficult to find the rolling circumstances that result in the rolled material having all the necessary qualities. Future research will go deeper into this topic.

4. Conclusions

Temper rolling is performed to impart various properties to the material, including flatness and smoothness of the surface, improved mechanical properties, elimination of the discontinuous yield point, and obtaining a rough surface. In this study, residual stresses varying depending on the reduction in the cross-section of the temper-rolled materials were investigated, and the obtained results are summarized below.

1. Tensile stress on the surface and compressive stress on the inside occurred in the samples rolled with a 1% reduction ratio.
2. Compressive stress was formed with a reduction ratio of 1.5%, although it was not homogeneous throughout the thickness of the rolled samples.
3. The distribution with compression stress on the surface and tensile stress on the inside could only be obtained at a reduction ratio of 1.8%.
4. When the reduction ratio reaches 2%, tensile stresses occur again at the surface and compressive stresses inside.
5. As the reduction ratio rises above 2%, the difference between the surface's tensile stress and the inside's compressive stress gradually increases.

Considering all these results in a temper rolling, the 1.8% reduction ratio is the most appropriate for creating compressive stresses on the material surface.

Material durability depends on the type of residual stress across the thickness and the magnitude and depth of the compressive surface tension. This study looked at the effect of thickness decrease on the type of residual stress caused by cold deformation. The effect on the magnitude and depth of the surface compressive stress may be the subject of further research.

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Author contributions

Bilal Çolak completed all stages of the study, including the preparation of samples, tests, research, etc.

Declaration of ethical code

The author declares that this study complies with Research and Publication Ethics.

Conflicts of interest

There are no apparent conflicts.

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