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Taguchi Analysis of Hardness and Strength of Hot Compressed Duplex Steel Using Gleeble Thermomechanical System †

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Abstract: Duplex stainless steels, well known for their excellent mechanical properties and high corrosion resistance, are used in high concentration chloride environments. However, the formation of intermetallic phases when they are exposed to high temperatures for extended periods limits their application in such scenarios. Hence, to determine their mechanical behavior, a study was conducted to determine the optimum parameters for obtaining good strength and hardness in duplex stainless steel. The Gleeble Physical testing system was used to test 2002 duplex stainless steel under hot compression while varying strain, strain rate, and temperature. Using an L9 orthogonal array, the optimal parameters for achieving high strength and hardness were arrived at using Taguchi techniques. It was identified that, at 1000 °C, a 10 s^{-1} strain rate in samples strained to 60% provided the best results. Lastly, the microstructure was analyzed and correlated with the experimental results.

Keywords: duplex stainless steel; Taguchi analysis; compressive strength; Gleeble thermomechanical system; compression; mechanical properties

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1. Introduction

There is a need to study the high temperature properties of materials in a more systematic way according to their applications. Some work has been carried out in this regard using aluminum alloys and steel. However, there has been very little work conductedon duplex steels. The Gleeble testing machine is a state-of-the-art facility which can carry out a whole range of physical simulations of metallurgical processes, such as testing for susceptibility of hot cracking [1,2], Electrical–Thermal–Mechanical modeling, and heat-affected zone studies [3–5]. There have also been instances of new tubular design technology being developed on Chromium–Nickel steels [1]. The 5454 aluminum alloy was studied in detail with regards to its microhardness and compression data. The strain rate exponent was also determined for this material using Gleeble simulation [2].

Since Gleeble can simulate realistic scenarios, it is therefore also possible to study the material behavior behind such deformations. For example, the ferrite grain size distribution was studied by S. Patra et al. [6] and the mechanisms of grain formation and grain refinement were studied by Anish Karmarkar et al. [7]. The heat-affected zones of Chromium Molybdenum steels were studied by Nikhil et al. [8] and thermomechanical processing studies were alsocarried out by S.K. Rajput et al. [9]. A comprehensive work modeling stress–strain curves was conducted by Nicholas et al. [10], while hot pipe extrusion and pipe upsetting technologies were developed by Kosmatsky et al. [1]. Considering the wide application of these tests, this work tests the microhardness and compressive response of Duplex Steel 2205 under high temperatures.

2. Materials and Methods

The Gleeble 3800-GTC offered by Dynamic Systems Inc. (Austin, TX, USA) is capable of exerting as much as 20 tons of static force while also providing a heating rate of up to 10,000 °C/s. It can also perform high strain rate testing by providing a stroke rate of 2000 mm/s. This facility was hence used to carry out tests on Duplex Stainless Steel 2205.

The composition of Duplex Stainless Steel 2205 is presented in Table 1. Using three input parameters at three different levels, an L9 array was developed to carry out the experiments. These three parameters include temperature, strain, and strain rate. The factors and their levels are shown in Table 2. These values were digitally set, and the expected output values were hardness and toughness. While five readings for hardness were taken using a Vicker's hardness tester, the toughness was calculated as the area under the stress–strain curve. Based on the L9 array, 9 specimens were taken, turned, and faced to appropriate dimensions. These samples were later tested under hot compression.

Table 1. Composition of duplex stainless steel 2205.

Material	Elements in Composition								
	C	Mn	Si	P	S	Cr	Mo	Ni	N
ALDSS 2205	0–0.30	2.00	1.00	0.030	0.020	21.0–23.0	2.5–3.5	4.5–6.5	0.08–0.20

Table 2. Factors and levels considered in the L9 array.

Parameter	Level 1	Level 2	Level 3
Temperature	900 °C	1000 °C	1100 °C
Strain	50%	60%	70%
Strain Rate	5	10	15

3. Results and Discussion

The stress–strain curves were generated post hot compression tests and are shown in Figure 1. The area under the stress–strain curves gives an indication of toughness. In all the experiments, it is evident that the toughness values are maximum when the strain parameter is set to 70% and the lowest is obtained when the strain percentage is set to 50%. Hence, the variation in toughness can be concluded to increase with an increase in strain induced.

Micrographs, as shown in Figure 2, were taken for all nine specimens using an inverted Metallurgical microscope IM 5000 and were analyzed. All micrographs were found to contain α Ferrite and α Austenite, but the morphologies of both phases were different for different input conditions. The microstructure at 900 °C showed elongated grains. However, as the temperature increased to 1000 °C, the grains seemed to elongate further with a few broken grains observed at 50% strain and a 10 s^{-1} strain rate. This trend also continued to be visible at 1100 °C.

Microhardness measurements were taken in earlier research by Churyumov [2] and C.R.Das [5]. In this case, microhardness measurements were taken using a Vickers' hardness test and the average of five measurements is listed in Table 3. The objective function of 'the larger the better' was chosen; the same was calculated and is shown in the last column of Table 3. The values of these objective functions were then analyzed using ANOVA and the factor effects are plotted in Figure 3. From Figure 3, it is evident that the maximum hardness was obtained when 60% strain was induced in the sample at a strain rate of 10 s^{-1} and at a temperature of 1000 °C. Similarly, the minimum hardness was obtained when 50% strain was induced in the sample at a strain rate of 5 s^{-1}, and at a temperature of 1100 °C.

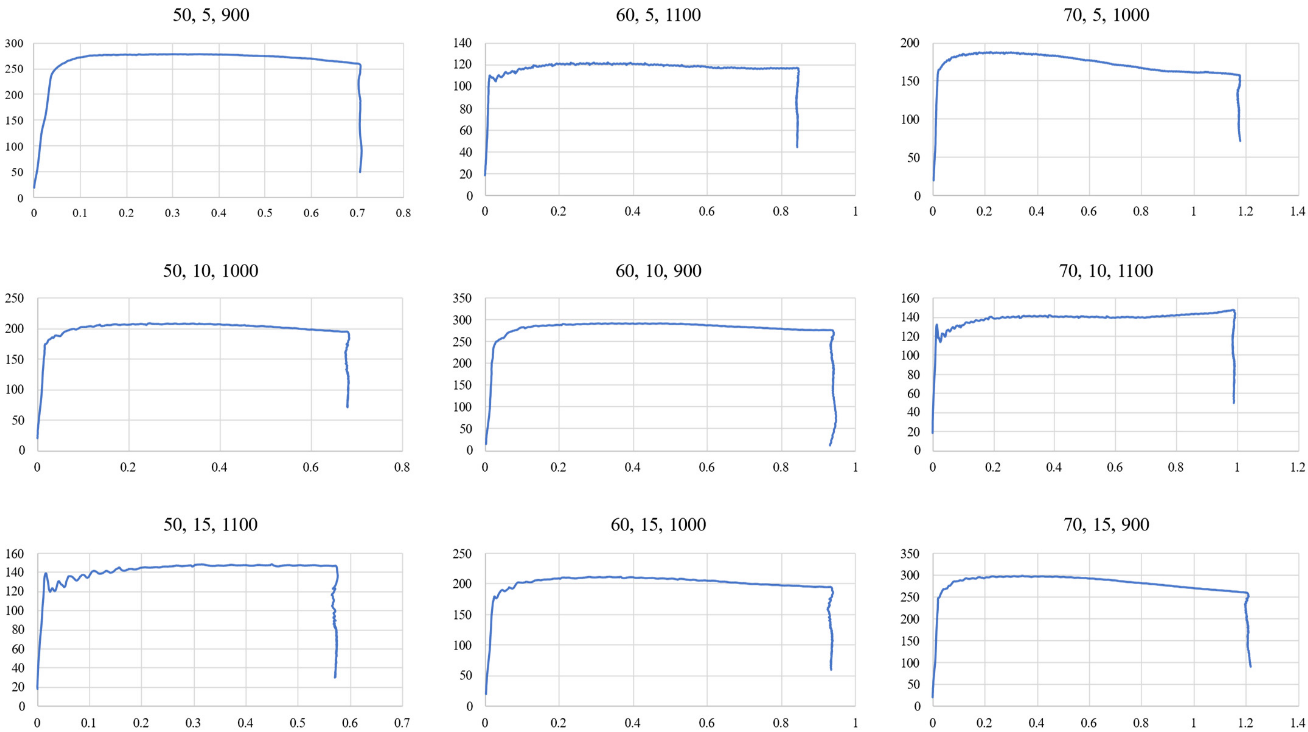

Figure 1. Stress–strain curves for the L9 array.

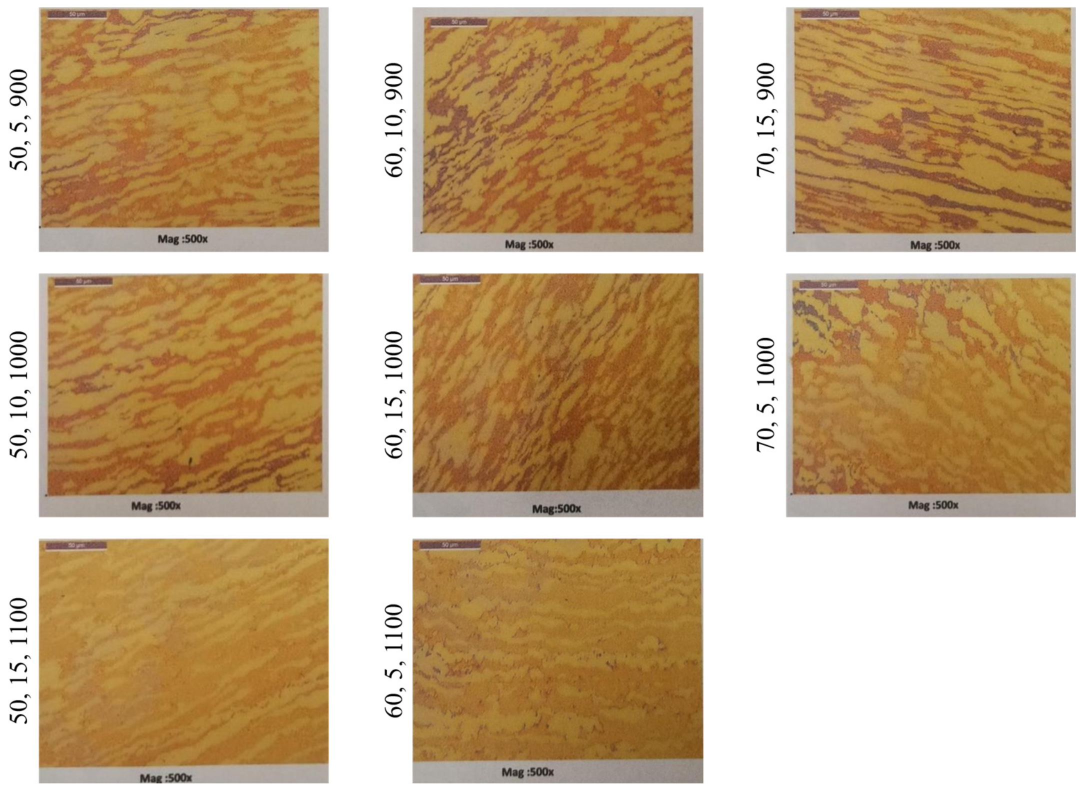

Figure 2. Microstructure images for the L9 array.

Table 3. Results of hardness and the objective functions.

Temperature (°C)	Strain (%)	Strain Rate (s^{-1})	Average Hardness	Objective Function ($-10\log\left(\frac{1}{y^2}\right)$)
900	50	5	269.2	48.6015
900	60	10	303.6	49.6461
900	70	15	271.4	48.6722
1000	50	10	280.0	48.9432
1000	60	15	300.6	49.5598
1000	70	5	270.0	48.6273
1100	50	15	259.8	48.2928
1100	60	5	283.4	49.0480
1100	70	10	279.0	48.9121

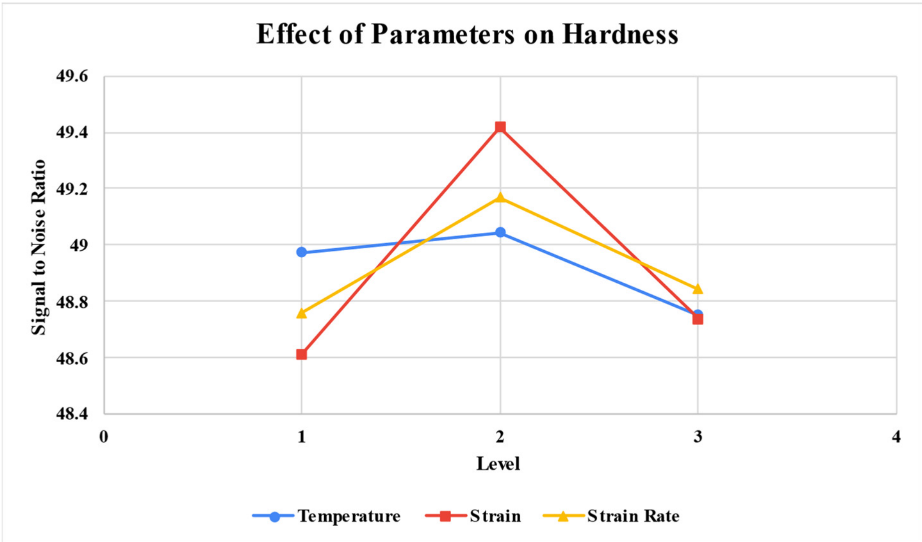

Figure 3. Effect of different parameters on hardness.

4. Conclusions

The optimum parameters for maximum hardness were identified as a temperature of 1000 °C and a 10 s^{-1} strain rate in samples strained to 60%. The maximum toughness, however, was achieved when samples were strained to 70%. The Gleeble setup is extremely useful in characterizing the mechanical behavior of materials at high temperatures and high strain rates.

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