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The Influence of Process Parameters on the Deformability of the Copper-Carbon Steel Bimetal Composite Fabricated by Hot Rolling

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Abstract: This paper presents the numerical simulation results of the hot rolling process of the copper-carbon steel bimetal sheet using ABAQUS software. The response surface methodology (RSM) based on a central composite experiment design (CCD) was used to study the influence of process parameters on the deformability of the copper - carbon steel bimetal sheet fabricated by hot rolling. Researched process parameters include rolling temperature T (^{0}C), degree of deformation ε (%), the rotational speed of the roll v (rpm). Deformability is assessed through the maximum rolling force P_{max} (tons) and the maximum stress of the workpiece σ_{max} (MPa). The obtained results allow analysis and selection of reasonable process parameter ranges of the bimetal sheet preparation.

Keywords: Copper-carbon steel bimetal composite, Process parameters, Deformability, Hot rolling

1. Introduction

Metals and alloys have definite physical and mechanical properties. No metal and alloy can satisfy all the good mechanical properties and fabrication requirements at the same time. Therefore, in recent years, bimetal composites have been interested and promoted in research. Bimetal composites, which are made of two metals with different physical, chemical, and mechanical properties and become metallic bonded at the interface [1,2].Composed of two different metals, bimetal composites have all their respective advantages. Therefore, bimetal composites can not only overcome their weaknesses, but also take full advantage of their synthetic properties.Among them, copper-steel bimetal composites are very popularly studied. Because, copper-steel bimetal composites have corrosion resistance, frictional and mechanical properties and save expensive metal. In the future, copper-steel bimetal composites will have broader application prospects to replace many traditional materials [3].

B. Fei et al. [4] studied the fabrication of copper-steel bimetal materials, with the tensile strength and impedance of copper-clad steel wire at a domain-specific frequency more than twice as high and nearly 8% lower compared with that of copper wire of the same diameter, respectively. T. Sasaki et al. [5] reported research results showing that copper-steel bimetallic alloys not only provide outstanding performance of structural properties, but also preferred applications from the economic and commercial points of view because some expensive copper has been replaced by cheap iron alloys and as a result, the cost of the material is reduced. Concerning these desirable properties, copper-steel bimetallic composites have been widely used in many fields such as telecommunications equipment, medical and biomedical instruments, automotive industry, aerospace, and petrochemical industry [6,7].

There are many methods of preparation and fabrication of bimetallic materials, among which are common methods, including [8,9,10]: a) liquid-liquid phase preparation methods, b) liquid-solid phase preparation methods, c) solid-solid phase production methods. Which, solid-solid phase production methods are widely applied due to the simplicity of the technological process. Bonding between metal surface layers is achieved by normal plastic deformation.

This paper presents the numerical simulation results of the hot rolling process of the copper-carbon steel bimetal sheet using ABAQUS software. The response surface methodology (RSM) based on a central composite experiment design (CCD) was used to study the influence of process parameters on the deformability of the copper-carbon steel bimetal sheet fabricated by hot rolling. Researched process parameters include rolling temperature T (^{0}C), degree of deformation ε (%), the rotational speed of the roll v (rpm). Deformability is assessed through the maximum rolling force P_{max} (tons) and the maximum stress of the workpiece σ_{max} (MPa). The obtained results allow analysis and selection of reasonable process parameter ranges of the bimetallic sheet preparation.

2. Materials and Methods

The chemical composition of copper and carbon steel for fabrication of bimetal composites is shown in Table I.

Table I. Weight percentages of elements in copper and carbon steel sheet

<table>
<tr><td rowspan="3">Steel sheet</td><td>Element</td><td>C</td><td>Mn</td><td>Al</td><td>Si</td><td>P</td><td>S</td><td>Cr</td><td>Ni</td><td>Cu</td></tr>
<tr><td rowspan="2">wt%</td><td rowspan="2"><0,11</td><td rowspan="2">0,30÷
0,55</td><td rowspan="2">0,02÷
0,10</td><td colspan="6">≤</td></tr>
<tr><td>0,06</td><td>0,03</td><td>0,035</td><td>0,15</td><td>0,03</td><td>0,20</td></tr>
<tr><td rowspan="3">Copper sheet</td><td>Element</td><td>Cu</td><td>Zn</td><td>Pb</td><td>Fe</td><td>Sb</td><td colspan="2">Bi</td><td>P</td><td>Other</td></tr>
<tr><td rowspan="2">wt%</td><td rowspan="2">88,0÷
91,0</td><td rowspan="2">Balance</td><td colspan="6">≤</td><td rowspan="2"><0,20</td></tr>
<tr><td>0,03</td><td>0,10</td><td>0,005</td><td colspan="2">0,002</td><td>0,01</td></tr>
</table>

ABAQUS software is used to simulate the hot rolling process of copper-carbon steel bimetal sheets. The experimental planning method is applied to study the influence of process parameters on the deformability when bonding single metals together. Geometric models include tooling and workpieces based on product shape and dimensional accuracy requirements. The hot rolling model consists of two rollers and the workpiece shown in Figure 1a. The workpiece is the bimetal sheet, the inner layer is carbon steel with a thickness of 8mm, the two sides are a copper layer with a thickness of 0.5mm (Figure 1b), the meshing model is shown in Figure 1c. Material models of carbon steel and copper are shown in Figure 2.

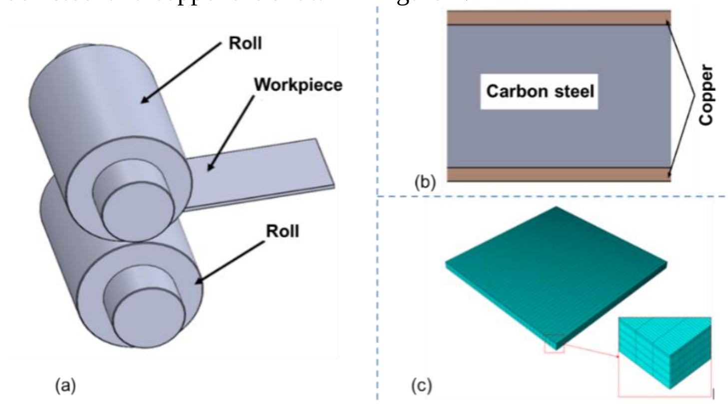

Figure 1. Geometric model of hot rolling process (a) and geometric model of the bimetal composite sheet (b)

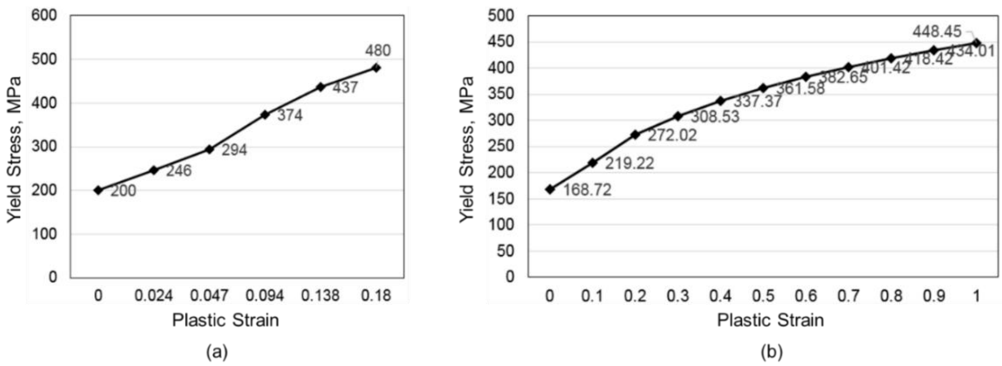

Figure 2. Material models of carbon steel (a) and copper (b)

The input parameters affecting the hot rolling process of bimetal materials include: rolling temperature (^{0}C) coded as variable A, degree of deformation (%) coded as variable B and rotational speed of the roll (rpm) coded as variable C. The limits of variables are denoted as -1, 0, and +1 for the lower value, middle value, and higher value. Two output parameters include: maximum rolling force (ton) coded as function R_1 and maximum stress of the workpiece (MPa) coded as function R_2. The levels and their values of the input parameters are presented in Table II.

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Table II. Levels and their values of the input parameters

Parameters	level-1	level 0	level+1
A: rolling temperature (^{0}C)	800	850	900
B: degree of deformation (%)	25	30	35
C: rotational speed of the roll (min)	35	40	45

Using a CCD with an expansion factor of 1.682 to study the influence of rolling temperature, degree of deformation and rotational speed of the roll. With the selected variables, the CCD table with 17 experiments including 8 basic experiments, 6 extended experiments and 3 experiments at the center is presented in Table III.

Table III. The simulation experiment plan

Number of experiments	Factor 1	Factor 1	Factor 1	Responses	
	A: Rolling temperature	B: Degree of deformation	C: Rotational speed of the roll	R_1: Maximum rolling force	R_2: Maximum stress of the workpiece
1	-1	-1	-1	140	470
2	1	-1	-1	135	460
3	-1	1	-1	145	480
4	1	1	-1	135	455
5	-1	-1	1	138	435
6	1	-1	1	135	438
7	-1	1	1	142	475
8	1	1	1	136	438
9	1,682	0	0	145	480
10	-1,682	0	0	135	460
11	0	1,682	0	132	450
12	0	-1,682	0	140	470
13	0	0	1,682	135	460
14	0	0	-1,682	140	455
15	0	0	0	130	400
16	0	0	0	132	405
17	0	0	0	130	410

3. Results and Discussion

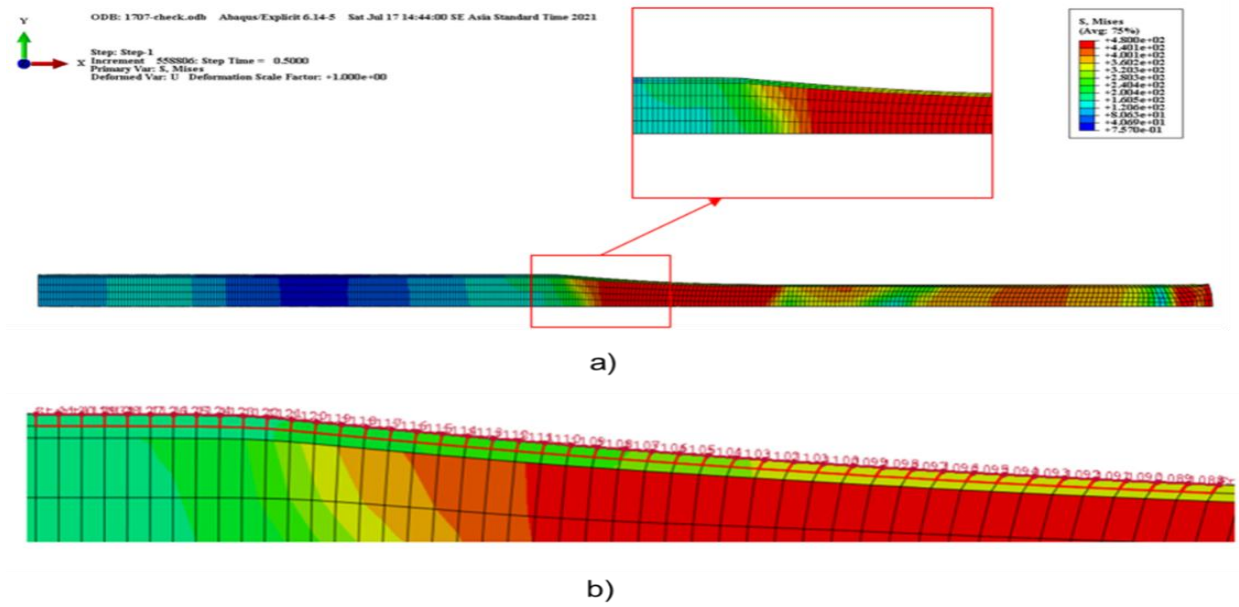

Figure 3. Von Mises stress distribution in cross section of the workpiece (a) and the intermediate plane of lamination to determine stress values (b)

The simulation results of the hot rolling process of copper-steel bimetal materials show the distribution of stress fields in the workpiece, distinguishing between two layers of steel and copper sheet. The Von Mises stress distribution in the cross-section of the workpiece when rolling is shown in Figure 3. Figure 4 shows that the stress value determined by ABAQUS software is the stress value passing through the intermediate plane which is the intermediate face of the steel sheet. The rolling force diagram of hot rolling processes of bimetal materials by rolling time is shown in Figure 4. The results of the maximum rolling force and the maximum stress of the workpiece are presented in Table III.

Using Design expert software 11.1.0.1 to calculate and determine the regression equation for the maximum rolling force R_1 and the maximum stress of the workpiece R_2 shown in equations (1) and (2) below :

$R_1 = 130.67 - 2.99A + 1.72B + 0.32C - AB + 0.75AC + 3.3A^2 + 1.88B^2 + 2.41C^2$	(1)
$R_2 = 405.62 - 7.52A + 5.76B - 6.4C - 6.87AB + 0.13AC + 4.38BC + 20.85A^2$ $+17.31B^2 + 116.43C^2$	(2)

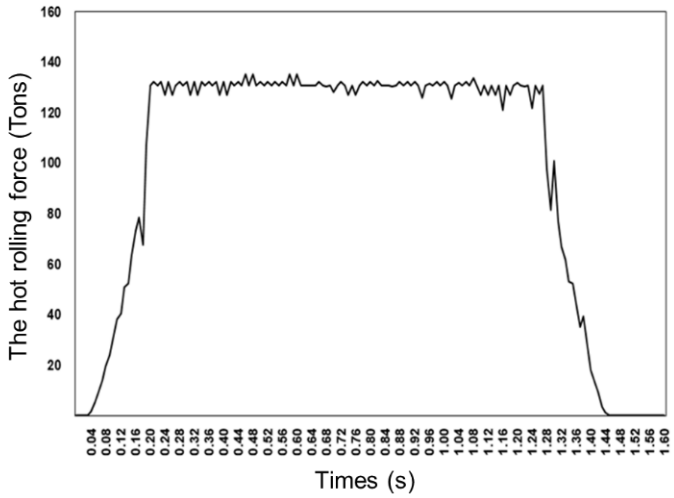

Figure 4. Hot rolling force diagram

Figures 5(a) and 5(b) show the normal probability chart for the maximum rolling force and the maximum stress of workpiece, which are used to check the completeness of the models. Since all the points lie on a straight line, it can be concluded that the model of regression equations (1) and (2) is suitable.

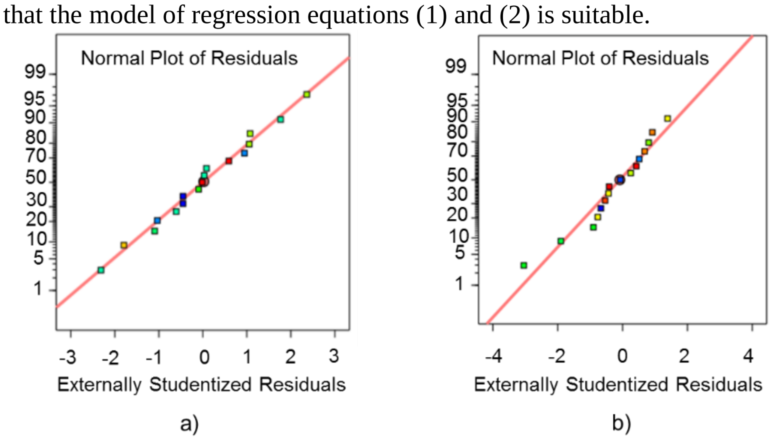

Figure 5. A Probability chart was used to check the correctness of the regression model

ANOVA analysis was used to determine the adequacy and significance of the model. In addition, to evaluate the effect of the mismatch (lack of fit) on the model and the significance of the coefficients in the model. The ANOVA analysis for the terms of the maximum rolling force and the maximum stress of the workpiece are described in Tables IV and Table V. The values of F are 12.4 and 10.9 for maximum rolling force and maximum stress of the workpiece, respectively. The value of F shows that the model is very meaningful. There is only a 0.15% chance that the value of F in the regression model for the maximum rolling force can occur due to noise. Meanwhile, with the maximum stress of the workpiece of 0.24%, the F value can cause interference.

In these models, the values of the coefficient of determination R^2 and the adjusted coefficient of determination (Adjusted R^2) are both greater than or equal to 80%, which indicates that the models are found to be statistically significant. In the maximum rolling force model R^2 = 0.94 means 94% of the total variation observed in this model. In the model of the maximum stress of the workpiece, the value of R^2 = 0.93. In both models, the Adeq Precision value measures the signal-to-noise ratio. These ratios are greater than 4 (10.94 and 10.17), respectively, showing the statistical significance of the obtained model.

Table IV. ANOVA analysis for maximum rolling force

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	328.59	9	36.51	12.49	0.0015	**significant**
A-A	122.00	1	122.00	41.73	0.0003	
B-B	40.28	1	40.28	13.78	0.0075	
C-C	1.42	1	1.42	0.4868	0.5078	
AB	8.00	1	8.00	2.74	0.1421	
AC	4.50	1	4.50	1.54	0.2547	
BC	0.0000	1	0.0000	0.0000	1.0000	
A^2	122.46	1	122.46	41.88	0.0003	
B^2	39.91	1	39.91	13.65	0.0077	
C^2	65.58	1	65.58	22.43	0.0021	
Residual	20.47	7	2.92			
Lack of Fit	17.80	5	3.56	2.67	0.2946	**not significant**
Pure Error	2.67	2	1.33			
Cor Total	349.06	16				
R^2	0.9414					
Adjusted R^2	0.8660					
Predicted R^2	0.5929					
Adeq Precision	10.9412					

Table V. ANOVA analysis for maximum stress of workpiece

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	9528.26	9	1058.70	10.90	0.0024	**significant**
A-A	771.34	1	771.34	7.94	0.0259	
B-B	452.78	1	452.78	4.66	0.0677	
C-C	559.45	1	559.45	5.76	0.0475	
AB	378.12	1	378.12	3.89	0.0891	
AC	0.1250	1	0.1250	0.0013	0.9724	
BC	153.13	1	153.13	1.58	0.2496	
A^2	4899.32	1	4899.32	50.44	0.0002	
B^2	3378.43	1	3378.43	34.78	0.0006	
C^2	3042.25	1	3042.25	31.32	0.0008	
Residual	679.98	7	97.14			
Lack of Fit	629.98	5	126.00	5.04	0.1738	**not significant**
Pure Error	50.00	2	25.00			
Cor Total	10208.24	16				
R^2	0.9334					
Adjusted R^2	0.8477					
Predicted R^2	0.5095					
Adeq Precision	10.1710					

3.1. Influence of process parameters on the maximum rolling force

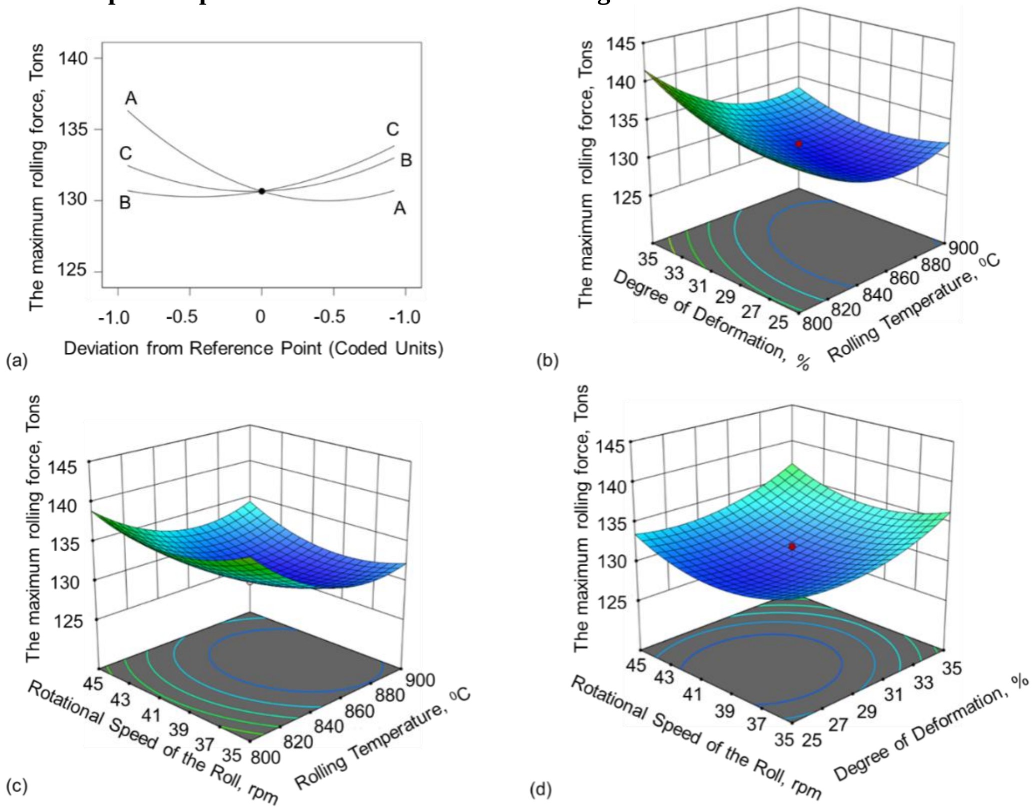

Figure 6. Effect of process parameters to the maximum rolling force

The influence of rolling process parameters on the objective function of maximum rolling force was investigated using contour plots (2D and 3D) shown in Figure 6. From Figure 6a, it can be seen when As the degree of deformation increases, the rolling force increases. When the temperature increases, the rolling force decreases, this is explained as when the temperature increases, the yield stress of the rolled billet decreases, the tensile stress decreases, and the plasticity of the material increases. However, when the temperature is too high (approximately 900^{0}C), the rolling force tends to increase slightly. This phenomenon is due to the fact that when the temperature is high, the crystal grains grow, reducing the possibility of plastic deformation. Also according to Figure 6a, the change of the rolling speed of the rolling shaft does not significantly affect the rolling force. When the rotation speed of the rolling shaft is small or large, the rolling force increases, but the increase is not much.

3.2. Influence of process parameters on the maximum stress of the workpiece

The influence of rolling process parameters on the objective function of maximum stress of the workpiece was investigated using contour plots (2D and 3D) shown in Figure 7.

From Figure 7, it can be seen that when the rolling temperature, the degree of deformation, and the rotational speed of the roll increase to a certain limit, the maximum stress of the workpiece tends to decrease. This is explained that when the rolling temperature increases, the yield stress of the rolled workpiece decreases, the maximum stress decreases, and the plasticity of the material increases. The increased rotational speed of the roll reduces the contact time of the roll and the workpiece, reduces the loss of workpiece temperature, and increases the deformation ability.

As the process parameters continue to increase (to higher value), the maximum stress of the workpiece tends to increase. This phenomenon is due to the fact that when the temperature is high, the crystal grains grow, reducing the ability to plastic deformation. The high rotational speed of the roll makes the recovery of the workpiece not yet complete, thus reducing the possibility of deformation of the workpiece.

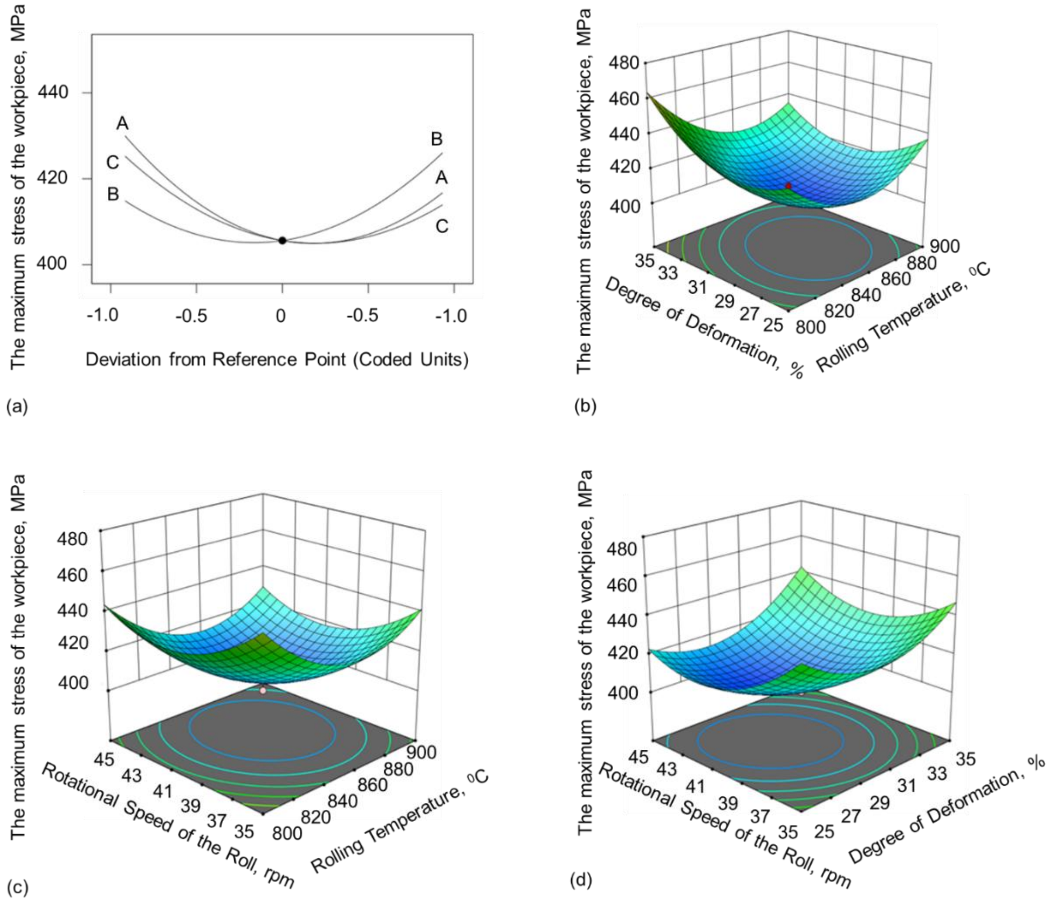

Figure 7.Effect of process parameters to the maximum stress of the workpiece

3.3. Optimization Results

After building a statistical regression equation showing the relationship between the process parameters and the reaction process, the equation is used to solve the optimization problem. According to the above discussion, it can be concluded that the process parameters of rolling temperature, degree of deformation, the rotational speed of the roll have significant and complex influences on the maximum rolling force and maximum stress of the workpiece models. The optimization problem can be solved using RSM. Table VI shows that a maximum rolling force of 130 tons and maximum stress of the workpiece of 404.3 MPa were observed at T = 862^{0}C, ε = 29%, and v= 40.5rpm.

Table VI. Optimization results using RSM

Constraints						
Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:A	In range	800	900	1	1	3
B:B	In range	25	35	1	1	3
C:C	In range	35	45	1	1	3
R1	Minimize	130	145	1	1	3
R2	Minimize	400	480	1	1	3
Solutions						
Number	A	B	C	R1	R2	Desirability
1	862	29	40.5	130	404.3	0.973

4. Conclusion

The main conclusions from the research results of the current work can be drawn as follows:

1) ABAQUS software was used to simulate the hot rolling process of the copper-carbon steel bimetal sheet. The effect of process parameters (the rolling temperature, the degree of deformation, the rotational speed of the roll) on the maximum rolling force and the maximum stress of the workpiece is carried out and analyzed.
2) The mathematical model of the maximum rolling force and the maximum stress of the workpiece developed using CCD and RSM predicts the response values with sufficient accuracy.
3) In the range of studied parameters, the maximum rolling force of 130 tons and the maximum stress of the workpiece of 404.3 MPa are achieved at $T = 862^0C$, $\varepsilon = 29\%$, and $v= 40.5$ rpm.
4) The experimental results according to the optimal mode are similar to the numerical simulation results. These results are the basis for selecting process parameters for the hot rolling process of the copper-carbon steel bimetal sheet.

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