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High-Entropy Alloys Properties Prediction Model by Using Artificial Neural Network Algorithm

Sanggyu Choi

Department of Materials Science and Engineering, Inha University, 100 Inha-ro, Michuhol-Gu, Incheon 22212, Korea

Sung Yi Portland State University, syi@pdx.edu

Junghan Kim Department of Materials Science and Engineering, Inha University, 100 Inha-ro, Michuhol-Gu, Incheon 22212, Korea

Byungsue Shin Department of Materials Science and Engineering, Inha University, 100 Inha-ro, Michuhol-Gu, Incheon 22212, Korea

Soongkeun Hyun Department of Materials Science and Engineering, Inha University, 100 Ienha-ro, Michuhol-Gu, Incheon 22212, Korea

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Sanggyu Choi¹, Sung Yi², Junghan Kim¹, Byungsue Shin¹ and Soongkeun Hyun^{1,*}

- 1 $\,$ Department of Materials Science and Engineering, Inha University, 100 Inha-ro, Michuhol-Gu,
- Incheon 22212, Korea; sanggyuchoi@inha.edu (S.C.); jhkim2292@inha.ac.kr (J.K.); kzzsc@naver.com (B.S.)
 ² Department of Mechanical and Materials Engineering, Portland State University, Portland, OR 97207-0751, USA;
- syi@pdx.edu
- * Correspondence: skhyun@inha.ac.kr; Tel.: +82-32-850-0215

Abstract: A new approach method has been studied for the efficient and accurate prediction of highentropy alloys (HEAs) properties. The artificial neural network (ANN) algorithm was employed to predict the mechanical properties such as yield strength, microstructure, and elongation of the alloy by training from the mole fraction and post-process information that has an influence on the mechanical properties. The mean error rate of prediction for the yield strength was 19.6%. Microstructure predictions were consistent for all test data. On the other hand, the ANN model trained only with mole fraction data had a yield strength prediction error of 33.9%. Omission of post-process data caused a decrease in the accuracy. In addition, the prediction was performed with the lasso regression model in the same way. The mean error rate of the lasso model trained with only a mole fraction was 26.1%. The lasso model trained with a mole fraction and post-process data had a yield strength prediction error of 31.1%. The linear regression equation showed limitations, as the accuracy decreased as the number of independent variables increased. As there are more variables affecting metal properties, the ANN approach is more advantageous, and the more data there are, the more accuracy increases, making it possible to design HEAs alloys that are simpler and more efficient than conventional methods. This approach predicted HEAs properties using only mole fraction and post-processing information, without the need to use conventional physicochemical theories or perform derived complex calculations.

Keywords: prediction; properties; high-entropy alloys; yield strength; microstructure; artificial neural network

1. Introduction

High-entropy alloys (HEAs) are alloys that are formed by mixing equal or relatively large proportions of usually five or more elements. HEAs systems are in contrast to traditional alloys, which contain just one or two primary constituent chemical species. As a result of their unique microstructure and properties, these HEAs have attracted the research interest of the scientific community and have been under development. However, there are thousands of combinations for experiments with all elements including mole fractions. It is impossible to carry out experiments in all cases. An empirical design through trial and error has been replaced by computer-based alloy designs. In terms of the formulation and accuracy of the predictive model, most of it comes from experimental data, which requires a significant amount of experimental input. HEAs have been generally known to require high entropy to obtain a stable phase of a single solid solution [1]. Atomic size mismatch, mixed enthalpy, valence electron concentration, and thermodynamic parameters have been studied for the purpose of predicting these HEA properties [2–5]. The calculation of phase diagram (CALPHAD) which consists of thermodynamic databases from extensive experimental and thermodynamic calculations based on Gibbs free energy has been studied [6-8]. The molecular dynamics simulation method also has been used to



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). predict alloy properties [9]. The method of predicting properties through thermodynamic calculations requires calculating various indices that determine HEA properties such as the parameters of the entropy of mixing, enthalpy of mixing, atomic size difference, valence

parameters of the entropy of mixing, enthalpy of mixing, atomic size difference, valence electron concentration, Allen, and Pauling electronegativity every time the component ratio changes [10]. However, these methods do not always derive accurate results. In addition, calculations require exclusive software or equipment.

In this study, based on the ANN algorism, we propose an efficient framework for selecting the optimal component elements and post-process conditions in the most important step, HEA design. Research on efficient alloy design by machine learning has been performed. Manzoor et al. [11] used machine learning and density functional theory calculations to predict the vibrational entropy of FCC solids and reduce complex computations. Zhang et al. [12] studied the prediction accuracy of the phase formation problem of HEAs using genetic algorithms. Pei et al. [13] predicted 93% of the formation of the solid solution by machine learning. HEA is being studied not only in the metallurgical industry but also in the medical field because of its superior properties such as high strength, high ductility, corrosion resistance, and thermal stability compared to other alloys [14–16]. If the mole fraction of elements and process conditions required to obtain the properties of HEA can be known in advance, the number of experiments can be reduced in the design stage. As input data for ANN learning, mole fraction and post-process data were used. In order to improve the model prediction performance even with a small dataset, the accuracy was verified through the model optimization process. The ANN prediction model showed a similar prediction tendency to the linear regression method compared to the lasso regression model, and the effects of variables on the alloy properties were compared. As the number of variables and data increased, the ANN prediction model made more accurate predictions. This methodology greatly simplifies calculation and opens a new way to predict the properties of HEA with less data, which can be utilized to predict properties in advance through alloy design.

2. Methodology

2.1. HEAs Data Information

From the reference [9,14–37], the experimental data for various HEAs were collected to train the model for predicting HEA characteristics. The collected data are mole fraction, post-process information, yield strength, phase, and elongation. There are two groups of HEA: the refractory metal group consisting of Al, Hf, Nb, Ta, Ti, Zr, V, Mo, and W, and the transition group containing Al, Co, Cr, Fe, Ni, Cu, and Mn. All data were obtained after the casting process. Post-process data were arranged in order heat treatment, cooling condition, cold-roll conditions, hot-roll conditions, heat treatment, forging condition, hot isostatic pressing (HIP) conditions, and heat treatment. For the post-process that did not proceed, the 0 value was put. The reason that the heat treatment condition is in three columns is that there are cases in which heat treatment is performed after each post-process is finished. These post-process and mole fraction data were used as input data for training the ANN prediction model. Yield strength, elongation, and microstructure were set as the output data to predict. The training data set was a total of 36 data. After the model was derived, 8 test data were used to evaluate the accuracy of metal group data. All data are shown in Table 1.

where	N (D (Alloy Elements Mole Fraction (at %) P												operties of Alloy								
	No., [Ref]	Alloy		Al	Co	Cr	Fe	Ni	Cu	Mn	Hf	Nb	Ta	Ti	Zr	v	Мо	w	σ ^y *(MPa)	Phase	ε **(%)	
All All B <td>1, [9]*** 2, [14]</td> <td colspan="2">NbCrMo_{0.5}Ta_{0.5}TiZr Al_{0.5}CoCrCu_{0.5}FeNi₂</td> <td>0 8.3</td> <td>0 16.7</td> <td>20 16.7</td> <td>0 16.7</td> <td>0 33.3</td> <td>0 8.3</td> <td>0 0</td> <td>0 0</td> <td>20 0</td> <td>10 0</td> <td>20 0</td> <td>20 0</td> <td>0 0</td> <td>10 0</td> <td>0 0</td> <td>1595 215</td> <td>FCC BCC</td> <td>5 39</td>	1, [9]*** 2, [14]	NbCrMo _{0.5} Ta _{0.5} TiZr Al _{0.5} CoCrCu _{0.5} FeNi ₂		0 8.3	0 16.7	20 16.7	0 16.7	0 33.3	0 8.3	0 0	0 0	20 0	10 0	20 0	20 0	0 0	10 0	0 0	1595 215	FCC BCC	5 39	
	3, [15] 4, [16]	Al _{0.5} CoCrCuFeNi AlNhTiV		Ni	9.1 25	18.2 0	18.2 0	18.2 0	18.2 0	18.2 0	0	0	0 25	0	0 25	0	0 25	0	0	360 1020	BCC	19 5
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	7, [19]		oCrFeNi		0	25	25	25	25	0	0	0	0	0	0	0	0	0	0	273	BCC	38
Nobelow Image: Description Image: Description <thimage: description<="" th=""> Image: Description<</thimage:>	8, [20] 9, [21]	AIC Al ₀	3CoCrFeNi 3CoCrFeNi	l	16.7 7.0	16.7 23.3	16.7 23.3	16.7 23.3	16.7 23.3	16.7 0	0	0	0	0	0	0	0	0	0	1040 224	BCC + FCC BCC	1 48
12 Edit Alternation 0 0	10, [22]	Me	oNbTaVW	_	0 91	0	0 18 2	0 18 2	0 36.4	0 18.2	0	0	20	20	0	0	20	20	20	1246 704	FCC BCC + FCC	1.7
NAMPAZ NAMPAZ No No No <	12, [24]	Cr	HfNbTiZr	2	0	0	20	0	0	0	0	20	20	0	20	20	0	0	0	1375	FCC	2.8
Bible Cachebany B B D <	13, [21] 14, [25]	Al _{0.}	3CoCrFeNi NbTiVZr	l	0	23.3	23.3	23.3	23.3	0	0	0	20	0	20	20	0 40	0	0	310 918	FCC	44 50
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NAME NAME N </td <td>17, [21]</td> <td>Al_{0.}</td> <td>3CoCrFeNi</td> <td>1.5</td> <td>7.0</td> <td>23.3</td> <td>23.3</td> <td>23.5</td> <td>23.5</td> <td>0</td> <td>240</td> <td>BCC</td> <td>45</td>	17, [21]	Al _{0.}	3CoCrFeNi	1.5	7.0	23.3	23.3	23.5	23.5	0	0	0	0	0	0	0	0	0	0	240	BCC	45
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	24, [29]	AlMo	oCrFeNi	·7-	0	25	25	25	25	0	0	0	0	0	0	0	0	0	0	300	BCC	42
27.210 ACCCCMMA 0	25, [50] 26, [31]	Hf	MoNbTiZr	IZI	0	0	0	0	0	0	0	20	0	20	20	20	0	20	0	1575	FCC	9
Philo AlgeContents 91 91 91 9	27, [32] 28, [20]	Crt AlC	CrFeMnNi oCrCuFeNi	i	0 16.7	20 16.7	20 16.7	20 16.7	20 16.7	0 16.7	20 0	0 0	0	0 0	0 0	0	0 0	0 0	0 0	410 790	BCC BCC + FCC	57 0.2
All of	29, [23] 30 [27]	Al _{0.5}	CrCuFeNi	$\frac{2}{2}$	9.1 10	0	18.2	18.2	16.4 0	18.2	0	0	0 20	0 16	0 30	0 20	0	0	0	630 2035	BCC + FCC	4.2
Alg. Alg. Stab. Star. No No <td>31, [18]</td> <td>Alo</td> <td>.25NbTaTiV</td> <td>0.2</td> <td>5.9</td> <td>0</td> <td>0</td> <td>0</td> <td>0</td> <td>0</td> <td>0</td> <td>0</td> <td>23.5</td> <td>23.5</td> <td>23.5</td> <td>0</td> <td>23.5</td> <td>0</td> <td>0</td> <td>1330</td> <td>FCC</td> <td>50</td>	31, [18]	Alo	.25NbTaTiV	0.2	5.9	0	0	0	0	0	0	0	23.5	23.5	23.5	0	23.5	0	0	1330	FCC	50
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jship*net	34, [22] 35, [34]	M	loNbTaW NbTaTiV		0	0	0	0	0	0	0 0	0	25 25	25 25	0 25	0	0 25	25 0	25 0	1058 1092	FCC FCC	2.6 50
	36, [27]	AlNb _{1.5}	Ta _{0.5} Ti _{1.5} Z	Zr _{0.5}	20	0	0	0	0	0	0	0	30	10	30	10	0	0	0	1280	FCC	3.5
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	3t, [27]	Al _{0.3} NbTa	0.8 ^{Ti} 1.4 ^V 0.	.2Zr1.3	6	0	0	0	0	0	0	0	20	16	28	26	4	0	0	1965	FCC	5
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Table 1. Collected data set of high-entropy alloys mole fraction with post-process conditions and properties results data
used for input and output in an artificial neural network prediction model.

* yield strength. ** elongation. *** reference number. **** test data.

2.2. Data Preprocessing and Model Evaluation

From the collected data, three ANN models were derived based on three result data such as yield strength, microstructure, and elongation. These are the alloy properties that are basic information of metal alloy to use in mechanical systems. The three models are independent models because each model has different weights and biases even though they are using same input data. Yield strength and elongation prediction models are predicting the results as numeric. The output of the microstructure phase was encoded according to FCC, BCC, and FCC + BCC. When predicting the microstructure phase, the results were expressed as probabilistic using the softmax algorithm. All data have been normalized to a range of 0–1 with a maximum of 1 and a minimum of 0. Normalizing is expressed as shown in Equation (1).

$$X_i^{norm} = \frac{X_i - X_{min}}{X_{max} - X_{min}} \tag{1}$$

where X_{max} and X_{min} are the maximum and minimum values of descriptor X of our training data, respectively.

A mean square error (*MSE*) was used to estimate the accuracy of the prediction model. Until *MSE* value is minimized through a training data set, weights and biases are updated repeatedly. *MSE* is expressed as in Equation (2).

min
$$MSE = \frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2$$
 (2)

where y_i is measured output data from the result of alloy analysis in previous research. \hat{y}_i is a calculated output data from the prediction model. *i* is the test number in Tables 1–3.

Table	2. Particular	r parameter used	in artificial ne	eural networl	< prediction mod	el on all	layers.
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Layer	Parameter							
Input data	Post-process Mole fraction	15 conditions 15 elements						
Hidden layer 1	Node Activation function Optimizer	3 ReLU Adam						
Hidden layer 2	Node Activation function Optimizer	47 ReLU Adam						
Output layer	Node Activation function Optimizer	1 Regression, Softmax (phase) Adam						
Results	Yield strength Microstructure phase Elongation							

Table 3. The prediction results of high-entropy alloy phases.

Input Data	1 Test Data	2 Test Data	3 Test Data	4 Test Data	5 Test Data	6 Test Data	7 Test Data	8 Test Data
Observed Phase	(1, 0) *	(1,0)	(0, 1) **	(0, 1)	(1, 0)	(0, 1)	(0, 1)	(1, 0)
Predicted Phase	(1, 0)	(1, 0)	(0, 1)	(0, 1)	(1, 0)	(0, 1)	(0, 1)	(1, 0)
Accord/ Discord	Accord							

* BCC (body-centered cubic). ** FCC (face-centered cubic).

Optimization Process for ANN Prediction Model

A total of 36 input data that consist of a mole fraction and post-process information are used as input data. When the hidden layer of the model was one layer, the model was evaluated by increasing the number of nodes from 1 to 100 by 1. In the case of two hidden layers, the model was evaluated by increasing the number of nodes from 1 to 50 by 1 in each layer. The results of the two models were evaluated by recording the *MSE* value and mean error value. The results of the model optimization process are shown in Figure 1.



Figure 1. Accuracy change according to the number of nodes. (a) In the case of one hidden layers; (b) In the case of two hidden layers.

An optimal model size should be found in the ANN model to get an accurate prediction model. For the ANN model with one hidden layer, the *MSE* value decreased as the number of nodes increased. The *MSE* value converges to 11,000 when the number of nodes is more than 40. The average error rate converges to a value of 24% after 60 nodes. For ANN models with two hidden layers, the accuracy increases rapidly even with a small increase in the number of nodes, regardless of a node number in the first or second layer. The *MSE* value converges to 100,000, and the mean error converges to 20%. The optimized layer size representing the minimum mean error was (3, 47). The model training process involves choosing the gradient descent optimizer and the type of activation function to find the optimal parameters. In this study, an Adam optimizer was used that was introduced by Diederik P. [37]. Features are a fast search for optimal parameters and high accuracy. ReLU was used as the activation function. ReLU is an activation function for deep neural network algorithms. The parameter values applied to the ANN algorithm are given in Table 2.

2.3. Optimization Process for Lasso Linear Regression Prediction Model

A conventional linear regression is described as shown in Equation (3).

$$\hat{y} = w[0] \cdot X[0] + w[1] \cdot X[1] + \dots + w[n] \cdot X[n] + b$$
(3)

where w [0-n] is the weights to multiply to each independent variable X[0-n]. b is a constant called the bias. Each independent variable is multiplied by a weight and added a bias. The calculated prediction result is compared with the actual measurement result by the MSE equation of loss function. The purpose is to find the parameter that minimizes the MSE value through gradient descent. For higher accuracy, these calculations are iteratively calculated to find the optimal parameters of the weights and bias values.

The lasso regression finds the optimal parameters of weight and bias by imposing an L1-norm penalty on the MES equation. This penalty allows the sum of the absolute values of the weights to be minimized so that the weight of a particular independent variable can be zero. Therefore, the influence of the independent variable term that does not have a large effect on a dependent variable is ignored. At this time, the effect of the penalty is adjusted by multiplying the α -constant. In this study, α was set to 0.01. The number

of lessons was 10,000. The formula to which we added the L1-norm penalty is given in Equation (4).

$$\min MSE = \frac{1}{n} \sum_{i=1}^{n} (y - \hat{y})^2 + \alpha \sum_{j=1}^{m} |w_j|$$
(4)

where w_j is the weight value, and α is the constant. When the α value is increased, more weights values are zero. In this study, the α value was set at 0.01.

3. Results and Discussion

3.1. Evaluation Predicting Accuracy of ANN Models

Figure 2 shows the prediction results of the ANN model trained by mole fraction and post-process information for eight test data. The mean error rate of yield strength on the test data excluding the training data was 19.6%. The average difference was 205 MPa, and the coefficient of determination was 0.9068. In the elongation model, the mean error was 40.2%, the mean difference was 4.3%, and the coefficient of determination for all data predictions was 0.7950. Yield strength had high accuracy in the prediction of mechanical properties of HEAs than elongation prediction results. This low accuracy for elongation was no different in result between the model trained by all input data and the model trained by only mole fraction data. As for the elongation, the accuracy of prediction was low because there was a difference in the result value depending on the shape of the specimen to be measured or the measurement method. In order to accurately predict the elongation in the future, unification of the measurement method and more independent variables affecting elongation are needed. The results of the microstructure were accurately predicted for all data. The BCC, FCC, and BCC + FCC phases were encoded to (1, 0), (0, 1), and (1, 1) each. The result is shown in Table 3.



Figure 2. Accuracy of an ANN model trained with elemental mole fraction and process data.

Figure 3 shows the accuracy of an ANN model trained only on mole fraction information. For the yield strength prediction, the mean error was 33.9%. The mean difference was 241 MPa, and the coefficient of determination was 0.8117. Compared with the results in Figure 2, it had a higher accuracy of prediction results than the model trained with only the mole fraction information. In addition to HEA, existing alloys and metals have a post-process to control the mechanical properties. Even data having the same mole fraction show different mechanical properties depending on the post-process conditions. These facts influenced the accuracy of the model regarding data. The yield strength prediction results of eight test data calculated from both ANN models are given in Table 4.



Figure 3. Accuracy of an ANN model trained only on elemental mole fractions.

Table 4. Comparison of the predicted results data calculated by the ANN model, which was trained on post-process and mole fraction data vs. mole fraction data.

No	HEA	$\sigma^m *$	ANN N Post-Proc	Model Traine ess and Mol	ed from e Fraction	ANN Model Trained from Mole Fraction				
[Ref]	Group	(MPa)	$\sigma_y^p **$ (MPa)	Error (MPa)	Error Rate (%)	$\sigma_y^p **$ (MPa)	Error (MPa)	Error Rate (%)		
1, [35]	Transition	1284	735	549	42.8	617	667	52.0		
2, [25]	Transition	197	244	47	24.0	317	120	60.9		
3, [26]	Refractory	1965	1651	314	16.0	1791	174	8.8		
4, [24]	Refractory	1298	1141	157	12.1	1114	184	14.1		
5, [18]	Transition	175	148	27	15.5	331	156	89.1		
6, [24]	Refractory	1105	1231	126	11.4	1343	238	21.5		
7, [30]	Refractory	1841	1537	304	16.5	1489	352	19.1		
8, [36]	Transition 655		536	119	18.2	617	38	5.8		

* Measured yield strength. ** Predicted yield strength.

3.2. Evaluation Predicting Accuracy of Lasso Linear Models

Figure 4 shows the prediction results of the lasso linear model for eight test data. The mean error of yield strength was 31.1%. The mean difference was 233 MPa, and the coefficient of determination was 0.8475. The number of independent variables used in the lasso regression model was 28. The hot rolling rate and forge data's weights were zero from a total of 30 independent variables. The lasso linear regression model predicted yield strength as 14% of accuracy for 36 training data but showed low accuracy for the eight test data. When new HEA data were input, the output would be low accuracy. Thus, this model cannot be used as a prediction model. Although lasso linear regression is a more improved model than conventional linear regression, it had an error when predicting the yield strength of HEA. The mechanical properties of HEA cannot be expressed as simply linear regression. The HEA model has complex interaction by atomic radius, valance electron concentration, and shear modulus.

Figure 5 shows the results of the lasso linear model trained by only mole fraction data. The mean error was 26.1%. The mean difference was 233 MPa, and the coefficient of determination was 0.8363. Compared with the results in Figure 4, the model trained by mole fraction information showed higher accuracy than the model trained by the mole fraction and post-process data to predict the mechanical properties of HEA. This result is contrary to the prediction result of the ANN model. As the many numbers of independent variables increased, the inaccuracy of the calculation result was also increasing. Due to this feature of the linear regression method, it was difficult to express complex data in a linear model. Despite imposing a lasso penalty that made the insignificant independent variable zero, the lasso linear model with a few independent variables of the only mole fraction was

more accurate. The yield strength prediction results of eight test data calculated from both lasso linear models are given in Table 5.



Figure 4. Accuracy of a lasso model trained with elemental mole fraction and process data.



Figure 5. Accuracy of a lasso model trained only on elemental mole fractions.

Table 5. Comparison of the predicted results data calculated by the lasso linear model, which was trained by post-process and mole fraction data vs. mole fraction data.

No	HEA	$\sigma^m *$	Lasso 1st Post-Proc	Model Trainess and Mol	ned from e Fraction	Lasso 1st Model Trained from Mole Fraction				
[Ref]	Group	(MPa)	$\sigma_y^p **$ (MPa)	Error (MPa)	Error Rate (%)	$\sigma_y^p **$ (MPa)	Error (MPa)	Error Rate (%)		
1, [35]	Transition	1284	773	511	39.8	742	542	42.2		
2, [25]	Transition	197	256	59	30.0	257	60	30.6		
3, [26]	Refractory	1965	2024	59	3.0	2007	41.5	2.1		
4, [24]	Refractory	1298	1056	242	18.6	1026	273	21.0		
5, [18]	Transition	175	0	175	100.0	81	94	53.8		
6, [24]	Refractory	1105	1213	108	9.7	1271	166	15.0		
7, [30]	Refractory	1841	1223	618	33.6	1217	624	33.9		
8, [36]	Transition	655	750	95	14.5	722	67	10.2		

* Measured yield strength. ** Predicted yield strength.

3.3. Effect of Process Input Data on Transition Metals and Refractory Metals

In Table 4, when the results of the refractory metal group and the transition metal group were calculated separately, the results accuracy calculated from a model trained by mole fraction and post-process information was higher than that of the model trained by only mole fraction. The transition metal group improved the accuracy by 25.0% from 52.0%

to 27.0%. The refractory metal group improved the accuracy by 1.9% from 15.9% to 14.0%. In particular, the transition metal showed significant improvement. The characteristic of the transition metal group is basically a group with a low yield strength. Yield strength is largely changed according to post-treatment process conditions. To get higher prediction accuracy of the transition metal group, post-process information that has more effect on the mechanical properties was important. When post-process information is more detailed, such as at a big data level, the accuracy of the prediction model is likely to improve. The lasso prediction results in Table 5 showed the opposite results to the ANN prediction results. In the transition metal group, the error rate of the model trained only with the mole fraction was 34%, and the model trained with the post-process showed an error rate of 46%, which actually decreased the accuracy by 12%. Similarly, the refractory metal group showed a 2% reduction in error rate from 18% to 16%. This result also reflected the character of the linear regression equation through which the prediction accuracy decreases as the number of variables increases.

3.4. Assessment of the Influence of Elements in Alloys

Figure 6 shows the coefficient ratio of each variable in the lasso regression analysis derived from only element data. The absolute value of the coefficient is expressed as a percentage, and the coefficient having a negative value is indicated as a minus in the variable name. It is correct to derive the model by dividing the transition and refractory groups, but since the elements included in the alloy are often manufactured by mixing them, they were used as input data without classifying all elements. Mn and W are not indicated because the coefficients are 0, as the characteristics of the lasso regression analysis make the coefficients 0 if there is no influence. Elements that had a positive effect on strength were Al, Mo, Zr, Ti, Ta, Cu, and Cr, whereas elements that had a negative effect were V, Nb, Hf, Ni, Co, and Fe.



Figure 6. Influence of coefficients in the lasso regression model.

Table 6 shows the effect of the change of each variable value on the yield strength in the ANN model derived from elemental data and process data. These data are obtained by calculating the value that changes when 1 is increased in the normalized data. It is similar to the coefficient value of each variable derived from lasso regression. Unlike lasso regression, the effect of the same element on the 44 data used for training and testing each piece of data is different for each piece of data. Due to the nature of the neural network, each and every datum has an effect on all nodes, resulting in a yield strength value, so the correlation between input variables is strong. Elements that had a positive influence on strength were Al, Cr, Cu, Nb, Ta, Ti, Zr, Mo, and W, whereas elements that had a negative influence were Co, Fe, Ni, Mn, Hf, and V. Compared with the lasso regression analysis, only Nb elements showed different results, but other elements showed the same results. In Table 6, the ratio of whether the effect of a specific element on the yield strength is positive or negative for each data is shown. The effect of each element on the yield strength of

the alloy was confirmed similarly, but the ANN model shows higher accuracy because it reflects the different correlations due to different elements and post-process for each data. In the case of Cr, the yield strength increased as the amount of Cr increased in most HEAs, but the 28 AlCoCrCuFeNi and eight Al0.5CoCrCuFeNi alloys in Table 6 resulted in a decrease in yield strength. This was the result of a complex causal relationship.

Table 6. Yield strength prediction data set that changes when the input data increases by 1.

No., [Ref]	Alloy			neio strengtn increase per 1 increase in input Data													
			Al	Co	Cr	Fe	Ni	Cu	Mn	Hf	Nb	Та	Ti	Zr	v	Мо	w
1 [0] *	NbCrMo Ta	-TiZr	245	82	105	102	107	110	166	246	248	152	609	810	221	228	658
2 [14]	Alo = CoCTCuo	0.5 HZr FeNia	243 155	-63	195	-195	-107	99	-100	-340	240	68	405	598	-161	199	451
3, [15]	Al ₀ 5CoCrCi	1FeNi	231	-26	179	-134	-43	109	-92	-220	332	137	596	796	-228	323	644
4, [16]	AlNbTiv	/	236	-89	186	-199	-113	111	-171	-352	339	144	600	801	-337	329	649
5, [9]	NbCrMo _{0.5} Ta	0.5 TiZr	414	90	362	-2	85	286	35	-138	515	320	779	979	-136	506	828
6, [18] 7 [19]	AI0.5IND IA CoCrEeN	Ji Ji	255 175	-70	205	-181	-94	104	-152	- 333	338 267	163	494	694	-319	348 261	544
8, [20]	AlCoCrCuI	eNi	238	-87	188	-197	-111	113	-170	-350	341	146	602	803	-335	331	651
9, [21]	Al _{0.3} CoCrH	² eNi	199	-9	164	-111	-22	104	-81	-166	299	113	564	764	-159	291	613
10, [22]	MoNbTaV	W	235	-90	185	-201	-114	110	-172	-353	338	143	599	799	-339	328	647
11, [23]	Al _{0.5} CrCuF	eNi2 Zr	237	-78	187	-198	-115	111	-175	-319	339	144	601	802	-312	330	650
12, [24]	Alo 2CoCrE	zr FeNi	200	-45	161	-175	-57	86	-147	-240	314	109	578	778	-236	305	626
14, [25]	NbTiVZ	r	254	-43	202	-136	-48	127	-98	-272	355	160	619	819	-270	346	668
15, [<mark>26</mark>]	CrCrFeMr	ıNi	200	-3	186	-99	-15	117	-76	-143	305	135	543	743	-141	299	594
16, [27]	Al _{0.3} NbTaTi _{1.}	4 ^{Zr} 1.3	62	-265	13	-375	-289	-62	-348	-528	166	-29	426	627	-513	155	475
17, [21]	Al _{0.3} CoCri CoCrMn	veini Ni	258 188		206	-88	-59	130	-112	-1/7	339 293	164	622 522	823 722	-1/2	350 287	573
19, [18]	AlNbTaT	iV	297	-28	247	-139	-52	172	-110	-291	400	205	660	861	-277	389	709
20, [24]	HfNbTiV.	Zr	148	-177	98	-288	-201	23	-260	-441	251	56	512	712	-426	241	560
21, [28]	HfNbTaTi	Zr	344	14	292	-96	-10	216	-69	-249	445	250	708	909	-234	436	757
22, [26]	CrNbTi7	11N1 'r	747	-18/	-3	-286	- 198	-72	-263	- 332	850	- 54	339	1312	-331	840	409
24, [29]	CoCrFeN	Ji	52	-119	29	-199	-116	-15	-181	-249	152	-21	395	595	-236	143	445
25, [30]	AlMo _{0.5} NbTa	0.5 TiZr	-127	-454	-177	-564	-478	-252	-537	-717	-24	-219	237	437	-702	-34	285
26, [31]	HfMoNbT	iZr	-38	-363	-88	-474	-387	-163	-445	-626	65	-130	326	526	-612	55	374
27, [32]	AlCoCrCuE	DIN1 GoNii	524 	-410	472	84 	-428	396 	_478	-53	625	430	239	1088	-54 -627	616 	936
29, [23]	Al _{0 5} CrCuF	eNi ₂	315	-3	264	-122	-38	189	-97	-246	417	222	679	879	-237	408	727
30, [27]	Al _{0.5} NbTa _{0.8} Ti ₁	.5V0.2Zr	-172	-499	-221	-609	-523	-296	-582	-762	-68	-263	192	393	-747	-79	241
31, [18]	Al _{0.25} NbTa	TiV	-75	-400	-125	-510	-424	-200	-483	-663	28	-167	289	489	-648	18	337
32, [14]	Al _{0.5} CoCrCu _{0.}	5 FeNi2	125	-95	81	-197	-106	24	-157	-270	226	31	490	690 1278	-277	217	539
34, [22]	MoNbTa	W	872	547	822	437	523	747	465	284	975	780	1236	1436	299	965	1284
35, [34]	NbTaTiV	7	150	-175	101	-285	-199	25	-258	-438	254	59	514	715	-423	243	563
36, [27]	AlNb _{1.5} Ta _{0.5} Ti	1.5Zr _{0.5}	466	139	417	29	115	342	56	-118	570	375	830	1031	-109	559	879
1t**, [35]	Alo = CoCrCi	ıFeNi	-618	-847	-640	-968	-878	-705	-965	-1071	-518	-691	-254	-54	-1075	-526	-206
2t, [26]	CrCrFeMr	Ni	175	-26	161	-124	-38	92	-100	-169	279	110	520	720	-167	274	571
3t, [27]	Al _{0.3} NbTa _{0.8} Ti _{1.}	4V0.2Zr1.3	5	-322	-44	-432	-346	-119	-405	-585	109	-86	369	570	-570	98	418
4t, [25]	CrNbTiV	Zr	193	-137	141	-247	-161	65	-220	-400	294	99	557	758	-385	285	606
ot, [19] 6t [25]	NhTiVZ	N1 r	-2 505	-144 176	-46 454	-157	- 124	- 54 379	- 146 95	-157	97 607	-/4 412	258 869	439	-157	598	318 918
7t, [30]	Al ₀₄ Hf ₀₆ Nb	TaTiZr	-308	-638	-360	-749	-662	-436	-716	-889	-208	-403	55	256	-886	-216	104
8t, [36]	Al _{0.5} CoCrCı	ıFeNi	4	-225	-18	-346	-256	-83	-341	-447	105	-69	368	569	-453	96	417
Pos	ative effect ratio (%)		82	20	75	14	18	70	16	7	89	70	98	98	7	89	98
100	nure encer nullo (70)		02	20		**	+		10		0,		,0	,0	,	07	20
								Post-Pro	ocess Input I	Data							
	Heat		Cor	ling		'R	н	Post-Pro	ocess Input I He	Data eat	For	-me		нір		н	eat
No., [Ref]	Heat Treatmen	t1	Сос	oling	С	R	н	Post—Pro	ocess Input I He Treatn	Data eat nent 2	For	ge		HIP		H Treat	eat ment 3
No., [Ref]	Heat Treatmen	t1	Coc	bling	C	^{CR}	H	Post-Pro R HR	ocess Input I He Treatn Temp	Data eat nent 2	For	ge	Temp	HIP Press		H Treat Temp	eat ment 3
No., [Ref]	Heat Treatmen Temp (^O C)	t 1 h	Coc	oling SC	C	°R (%)	HI Temp (°C)	Post-Pro R HR (%)	ocess Input I He Treatn Temp (° C)	Data eat nent 2 h	For	-ge	Temp (° C)	HIP Press (MPa)	h	H Treats Temp (°C)	eat ment 3 h
No., [Ref]	Heat Treatmen Temp (° C) -142	t 1 h 190	Coc WQ -104	oling SC 9	CR 15	CR (%)	Hi Temp (°C) 56	Post-Pro R HR (%) 8	Decess Input I He Treatm Temp (° C) -12	Data eat nent 2 h 301	For For	-ge 19	Temp (° C) -39	HIP Press (MPa) -38	h -77	H Treati Temp (° C) -56	eat ment 3 h 1595
No., [Ref]	Heat Treatmen Temp (° C) -142	t 1 h 190	Coc WQ -104	oling SC 9	C CR 15	CR (%) 53	HI Temp (°C) 56	Post-Pro R HR (%) 8	Temp (° C) -12	Data eat nent 2 h 301	For For	rge 19	Temp (° C) -39	HIP Press (MPa) -38	h -77	H Treat Temp (° C) -56	eat ment 3 h -1595
No., [Ref]	Heat Treatmen Temp (° C) -142 -63	t 1 h 190 86	Coc WQ -104 -2	SC 9 5	C CR 15	2 R (%) 53 15	HI Temp (°C) 56 51	Post-Pro R HR (%) 8 -8	reating the second seco	Data eat nent 2 h 301 195	For For 60 35	rge 199 18	Temp (° C) -39 -20	HIP Press (MPa) -38 -40	h -77 -55	H Treats (° C) -56 6	eat ment 3 h -1595 -215
No., [Ref]	Heat Treatmen Temp (° C) -142 -63 -90	t 1 h 190 86 175	Coc WQ -104 -2 -29	SC 9 5 15	CR 11 11	CR (%) 53 15 51	H1 Temp (° C) 56 51 55	Post-Pro R (%) 8 -8 10	reass Input I He Treatm (° C) -12 -25 -8	Data eat nent 2 h 301 195 285	For 60 35 55	rge 199 18	Temp (° C) -39 -20 -30	HIP Press (MPa) -38 -40 -41	h -77 -55 -50	H Treat (° C) -56 6 -9	eat ment 3 h -1595 -215 -360
No., [Ref]	Heat Treatmen Temp (° C) -142 -63 -90	t 1 h 190 86 175	Coc WQ -104 -2 -29	SC 9 5 15	CR 15 11 15	(%) 53 15 51	HI Temp (°C) 56 51 55 48	Post-Pro R HR (%) 8 -8 10	Cocess Input I He Treatm (° C) -12 -25 -8 20	Data eat nent 2 h 301 195 285 202	For 60 35 55	rge 19 18 15	Temp (° C) -39 -20 -30	HIP Press (MPa) -38 -40 -41	h -77 -55 -50	H Treat (° C) -56 6 -9	eat ment 3 h -1595 -215 -360
No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16]	Heat Treatmen Temp (° C) -142 -63 -90 -148	h 190 86 175 181	Coc WQ -104 -2 -29 -110	SC 9 5 15 1 1	CR 15 11 15 14	(%) 53 15 51 44	HI Temp (°C) 56 51 55 48	Post—Pro R HR (%) 8 8 10 2	Teems Constraint Teems (° C) -12 -25 -8 -20	Data eat nent 2 h 301 195 285 292	For 60 39 59 60	rge 19 18 15 10	Temp (° C) -39 -20 -30 -47	HIP Press (MPa) -38 -40 -41 -45	h -77 -55 -50 -83	H Treat Temp (° C) -56 6 -9 -9 -62	eat ment 3 h -1595 -215 -360 -1020
No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9]	Heat Treatmen Temp (° C) -142 -63 -90 -148 31	t 1 h 190 86 175 181 358	Coc WQ -104 -2 -29 -110 73	SC 9 5 15 1 1 175	CR 15 11 15 14 32	CR (%) 53 15 51 44 20	HI Temp (°C) 56 51 55 48 223	Post—Pro R HR (%) 8 -8 10 2 175	Temp Control -12 -25 -8 -20 155 -25	Data eat nent 2	For 60 39 59 60 77	rge 199 188 155 100 178	Temp (° C) -39 -20 -30 -47 133	HIP Press (MPa) -38 -40 -41 -45 129	h -77 -55 -50 -83 112	H Treats Temp (° C) -56 6 -9 -62 136	eat ment 3 h -1595 -215 -360 -1020 -929
No., [Ref]	Heat Treatmen Temp (° C) -142 -63 -90 -148 31 -129	t 1 h 190 86 175 181 358 199	Coc WQ -104 -2 -29 -110 73 -91	SC 9 5 15 1 175 19	CR 15 11 15 14 35	(%) (%) (53 15 51 44 20 62	HI Temp (°C) 56 51 55 48 223 67	Post-Pro R HR (%) 8 8 10 2 175 20	Teense Teense -12 -25 -8 -20 155 -2	Data at ment 2 h 301 195 285 292 468 311	For 60 39 55 60 77 61	rge 199 188 155 100 188	Temp (°C) -39 -20 -30 -47 133 -28	HIP Press (MPa) -38 -40 -41 -45 129 -26	h -77 -55 -50 -83 112 -64	H Treats Temp (° C) -56 6 -9 -62 136 -43	eat ment 3 h -1595 -215 -360 -1020 -929 -1012
No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18]	Heat Treatmen Temp (° C) -142 -63 -90 -148 31 -129	t 1 h 190 86 175 181 358 199	Coc WQ -104 -2 -29 -110 73 -91	bling SC 9 5 15 1 175 19	CC CR 11 11 12 14 32 16	R (%) 53 15 51 44 20 62	HI Temp (°C) 56 51 55 48 223 67	Post-Pro R HR (%) 8 8 10 2 175 20	Ceess Input I He Treatm C ^e CP -12 -25 -8 -20 155 -2 -2	Data at nent 2 h 301 195 285 292 468 311	For 60 39 55 60 77 61	rge 19 18 15 15 10 10 18 8 8	Temp (°C) -39 -20 -30 -47 133 -28	HIP Press (MPa) -38 -40 -41 -45 129 -26	h -77 -55 -50 -83 112 -64	H Teatr CC -56 6 -9 -62 136 -43	eat ment 3 h -1595 -215 -360 -1020 -929 -1012
No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18] 7, [19]	Heat Treatmen 7emp (° C) -142 -63 -90 -148 31 -129 -90	t 1 h 190 86 175 181 358 199 123	Coc WQ -104 -2 -29 -110 73 -91 -29	sling SC 9 15 1 175 19 4	CC CR 11 11 12 14 32 16 16	R (%) 53 15 51 44 20 62 56	Hi Temp (°C) 56 51 55 48 223 67 29	Post-Pro R HR (%) 8 8 10 2 175 20 4	Cecess Input I Here Teemp (°C) -12 -25 -8 -20 155 -2 2	bata tate n 301 195 285 292 468 311 249	For 60 35 55 60 77 61 45	rge 199 188 155 100 188 188 133	Temp (°C) -39 -20 -30 -47 133 -28 -47	HIP Press (MPa) -38 -40 -41 -45 129 -26 -59	h -77 -55 -50 -83 112 -64 -82	H Treath Temp (°C) -56 6 -9 -62 136 -43 -21	eat ment 3 h -1595 -215 -360 -1020 -929 -1012 -273
No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18] 7, [19] 8, [20]	Heat Treatmen Temp (° C) -142 -63 -90 -148 31 -129 -90 -146	h 190 86 175 181 358 199 123 183	Coc WQ -104 -2 -29 -110 73 -91 -29 -108	sting SC 9 5 15 1 175 19 4 3	C CR 15 11 11 14 14 33 16 15 14	(%) 53 15 51 20 62 56 46	HI Temp (°C) 56 51 55 48 223 67 29 50	Post-Pro R HR (%) 8 8 10 2 1075 20 4 4	Cecess Input I He Treatur (° C) -12 -25 -8 -20 155 -2 155 -2 2 -18	bata teat and 2 h 301 195 285 292 468 311 249 294	For 60 35 55 60 77 61 45 60	rge 199 188 155 100 188 188 188 133	Temp (° C) -39 -20 -30 -47 133 -28 -47 -45	HIP Press (MPa) -38 -40 -41 -45 129 -26 -59 -43	h -77 -55 -50 -83 112 -64 -82 -81	H Treatu Temp (°C) -56 6 -9 -62 136 -43 -21 -60	eat ment 3 h -1595 -215 -360 -1020 -929 -1012 -273 -1040
No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18] 7, [19] 8, [20] 9, [21]	Heat Treatmen Temp (° C) -142 -63 -90 -148 31 -129 -90 -146 -69	k1 h 190 86 175 181 358 199 123 183	Coo WQ -104 -2 -29 -110 73 -91 -29 -108	sling SC 9 5 15 1 175 19 4 3 14	CC CR 15 11 14 14 33 16 16 16	(%) 53 53 15 51 44 20 62 56 64 63 7	HI Temp (°C) 56 51 55 48 223 67 29 50 54	Post-Pro R HR (%) 8 8 10 2 175 20 4 4 6	Cecess Input I Hefe Treatin Cecess -12 -25 -8 -20 155 -2 155 -2 2 2 -18 -18	Data tatatent 2 h 301 195 285 292 468 311 249 294 253	For 60 35 55 60 777 61 45 60	ge ge 19 18 15 15 10 10 18 8 8 33 12 12 13	Temp (°C) -39 -20 -30 -47 133 -28 -47 -45 -26	HIP Press (MPa) -38 -40 -41 -45 129 -26 -59 -43 -24	h -77 -55 -50 -83 112 -64 -82 -81	H Treatu Temp (° C) -56 6 -9 -62 136 -43 -21 -60	eat ment 3 h -1595 -215 -360 -1020 -929 -1012 -273 -1040 -224
No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18] 7, [19] 8, [20] 9, [21]	Heat Treatmen Temp (° C) -142 -63 -90 -148 31 -129 -90 -146 -69	h 190 86 175 181 358 199 123 183 143	Coo WQ -104 -2 -29 -110 73 -91 -29 -108 -8	sling SC 9 5 15 15 175 19 4 3 16	CC CR 18 11 14 33 16 15 14 14 15	(%) 53 55 51 51 20 62 56 446 37	HT Temp (°C) 56 51 55 48 223 67 29 50 50 54	Post-Pro R HR (%) 88 10 2 175 204 4 6	Access Input I Hermitian Treatin	Data at ment 2 h 301 195 285 292 468 311 249 294 253	For 60 35 55 60 77 61 45 60 60 56	rge 199 195 100 188 105 100 188 188 188 183 183 183 183 183 183 183	Temp (°C) -39 -20 -47 133 -28 -47 -45 -26	HIP Press (MPa) -38 -40 -41 -45 -26 -59 -26 -59 -43 -34	h -77 -55 -50 -83 112 -64 -82 -81 -46	H Teatr Temp (°C) -56 6 -9 -62 136 -43 -21 -60 0	eat ment 3 h -1595 -215 -360 -1020 -929 -1012 -273 -1040 -224
No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18] 7, [19] 8, [20] 9, [21] 10, [22]	Heat Treatmen Temp (° C) -142 -63 -90 -148 31 -129 -90 -146 -69 -149	h 190 86 175 181 358 199 123 183 143 179	Coc WQ -104 -2 -29 -110 73 -91 -91 -29 -108 -8 -111	sc 9 5 15 1 175 19 4 3 16 -1	CC CR 15 11 15 14 14 14 15 14 14 15 14	(%) (%) 553 553 551 551 200 562 566 566 377 42	HI Temp (°C) 56 51 55 48 223 67 29 50 54 47	Post-Pro R HR (%) 8 8 10 2 175 20 4 4 6 0	Cecess Input I Herreatin Teemp (° C) -12 -25 -8 -20 155 -2 2 -18 -18 -18 -22	Data at ment 2 h 301 195 285 292 468 311 249 294 253 291	For 60 35 55 60 777 61 61 61 62 60 55 55	rge ge 99 88 55 00 78 8 8 33 33 22 33 88	Temp (°C) -39 -20 -47 133 -28 -47 -45 -26 -48	HIP Press (MPa) -38 -40 -41 -45 129 -26 -59 -43 -34 -34 -46	h -77 -55 -50 -83 112 -64 -82 -81 -46 -84	H Treat Temp (°C) -56 6 -9 -62 136 -43 -21 -60 0 -63	eat ment 3 h -1595 -215 -360 -1020 -929 -1012 -273 -1040 -224 -1246
No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18] 7, [19] 8, [20] 9, [21] 10, [22] 11, [23]	Heat Treatmen Temp (° C) -142 -63 -90 -148 31 -129 -90 -146 -69 -149 -141	h 190 86 175 181 358 199 123 183 143 179 182	Coc WQ -104 -2 -29 -110 73 -91 -29 -108 -8 -111 -86	sc 9 5 15 1 175 19 4 3 16 -1 0	CR 15 15 16 16 16 16 16 16 16 16 16 16 16 16 16	(%) 53 55 51 51 51 52 56 56 56 56 56 57 42 44 44 44	HT Temp (°C) 56 51 55 48 223 67 29 50 54 47 48	Post – Pro R HR (%) 8 8 10 2 175 20 4 4 6 0 0 0	Cecess Input I Herreatin Teemp (°C) -12 -25 -8 -20 155 -2 2 2 -18 -18 -18 -22 -21	Data tat tat h 301 195 285 292 468 311 249 294 253 291 293	For For 60 35 55 60 77 61 45 60 55 55 60 60 60 60 60 60 60 60 60 60	ge ge 19 15 15 15 10 10 15 15 10 10 12 13 13 12 13 14 11	Temp (° C) -39 -20 -30 -47 133 -28 -47 -45 -26 -48 -48	HIP Press (MPa) -38 -40 -41 -45 129 -26 -59 -26 -59 -43 -34 -34 -46 -47	h -77 -55 -50 -83 112 -64 -82 -81 -46 -84 -84 -86	H Treatu Temp (°C) -56 6 -9 -62 136 -43 -21 -60 0 -63 -63 -64	eat ment 3 h -1595 -215 -360 -1020 -929 -1012 -273 -1040 -224 -1246 -704
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No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18] 7, [19] 8, [20] 9, [21] 10, [22] 11, [23] 12, [24]	Heat Treatmen Temp (° C) -142 -63 -90 -148 31 -129 -90 -146 -69 -149 -141 -124	h 190 86 175 181 358 199 123 183 143 179 182 205	Coo WQ -104 -2 -29 -110 73 -91 -29 -108 -8 -111 -86 -85	SC 9 5 15 1 175 19 4 3 16 1 0 25	CCR 15 11 14 14 14 14 14 16 16 16 16 16 16 16 16 16 16 16 16 16	(%) 53 55 55 55 55 55 56 56 56 56 56 56 37 37 42 44 68	HI Temp (°C) 56 51 55 48 223 67 29 50 54 47 48 73	Post-Pro	Cocess Input I Herreatin Teemp (° C) -12 -25 -20 155 -2 2 2 -18 -18 -18 -22 -21 4	Data at ment 2 h 301 195 285 292 468 311 249 294 253 291 293 316	For 60 35 55 60 777 61 61 61 61 62 55 55 60 60 62	rge ge 19 18 15 15 15 10 10 18 8 8 33 12 23 33 12 11 14	Temp (°C) -39 -20 -47 133 -28 -47 -45 -26 -48 -48 -22	HIP Press (MPa) -38 -40 -41 -45 129 -26 -59 -43 -34 -46 -47 -21	h -77 -55 -50 -83 112 -64 -82 -81 -46 -84 -84 -86 -58	H Treat Temp (°C) -56 6 -9 -62 136 -43 -21 -60 0 -63 -64 -64 -38	eat ment 3 h -1595 -215 -360 -1020 -929 -1012 -273 -1040 -224 -1246 -704 -1375
No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18] 7, [19] 8, [20] 9, [21] 10, [22] 11, [23] 12, [24] 13, [21]	Heat Treatmen 7emp (° C) -142 -63 -90 -148 31 -129 -90 -146 -69 -149 -141 -124 -103	h 190 86 175 181 358 199 123 183 143 179 182 205 158	Coc WQ -104 -2 -29 -110 73 -91 -29 -108 -8 -111 -86 -85 -42	sc 9 5 15 1 175 19 4 3 16 -1 0 25 -12	CR 15 15 16 16 16 16 16 16 16 16 16 16 16 16 16	(%) 53 55 51 51 44 20 62 56 62 56 62 44 44 68 82 24	HI Temp (°C) 56 51 55 48 223 67 29 50 54 47 48 47 48 73 38	Post-Pro R HR (%) 88 10 2 10 2 175 204 4 6 0 0 0 2618	Cecess Input I Herreatin Temp (°C) -12 -25 -8 -20 155 -2 2 2 -18 -18 -18 -22 -21 4 -31	Data att ment 2 h 301 195 285 292 468 311 249 294 253 291 293 316 268	For 60 35 55 60 61 45 60 55 55 60 60 62 55	rge ge 99 88 55 00 78 88 33 32 33 33 14 44 77	Temp (° C) -39 -20 -30 -47 133 -28 -47 -45 -26 -48 -48 -48 -22 -46	HIP Press (MPa) -38 -40 -41 -45 129 -26 -59 -43 -34 -46 -47 -21 -60	h -77 -55 -50 -83 112 -64 -82 -81 -46 -84 -84 -86 -58 -68	H Treatu Temp (°C) -56 6 -9 -62 136 -43 -21 -60 0 -63 -64 -38 -34	eat ment 3 h -1595 -215 -360 -1020 -929 -1012 -273 -1040 -224 -1246 -704 -1375 -310
No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18] 7, [19] 8, [20] 9, [21] 10, [22] 11, [23] 12, [24] 13, [21] 14, [27]	Heat Treatmen Temp (° C) -142 -63 -90 -148 31 -129 -90 -146 -69 -149 -141 -124 -103	h 190 86 175 181 358 199 123 183 143 179 182 205 158	Coc WQ -104 -2 -29 -110 73 -91 -29 -108 -8 -111 -86 -85 -42	SC 9 5 15 1 175 19 4 3 16 -1 0 25 -12	C CR 15 11 15 16 16 16 16 16 16 16 16 16 16 16 16 16	(%) 53 15 51 44 20 62 56 44 56 44 62 44 62 44 68 22 42	HT Temp (°C) 56 51 55 48 223 67 29 50 54 47 48 73 38	Post - Pro R HR (%) 88 10 2 175 204 4 6 0 0 0 2 6 -18	Cecess Input I Herreatin Teemp (°C) -12 -25 -8 -20 155 -2 2 2 -18 -18 -18 -22 -21 4 4 -31	Data at tent 2 h 301 195 285 292 468 311 249 253 291 293 316 269	For For 60 35 55 60 77 61 45 60 55 55 60 62 57 77 77 77 77 61 45 55 55 60 60 77 77 61 61 61 77 77 77 77 77 77 77 77 77 7	ge ge 19 19 15 15 10 10 18 8 8 13 13 13 14 11 14 17 7 12	Temp (° C) -39 -20 -30 -47 133 -28 -47 -45 -26 -48 -48 -22 -48 -22 -46	HIP Press (MPa) -38 -40 -41 -45 129 -26 -59 -43 -34 -46 -47 -21 -60 -61 -21 -60 -12	h -77 -55 -50 -83 112 -64 -82 -81 -46 -84 -84 -86 -58 -68	H Treatu Temp (°C) -56 6 -9 -62 136 -43 -21 -60 0 -63 -64 -64 -38 -38 -34	eat ment 3 h -1595 -215 -360 -1020 -929 -1012 -273 -1040 -224 -1246 -704 -1375 -310 -310
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No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18] 7, [19] 8, [20] 9, [21] 10, [22] 11, [23] 12, [24] 13, [21] 14, [25] 15, [26]	Heat Treatmen Temp (° C) -142 -63 -90 -148 31 -129 -90 -146 -69 -149 -141 -124 -103 -103 -62	h 190 86 175 181 358 199 123 183 143 179 182 205 158 198 143	Coo WQ -104 -2 -29 -110 73 -91 -29 -108 -8 -111 -86 -85 -42 -60 -1	SC 9 5 15 1 175 19 4 3 16 -1 0 25 -12 16 -23	CCR 15 11 14 14 14 14 15 14 14 16 16 16 16 16 16 16	(%) 53 55 55 55 55 55 56 56 56 56 56 56 56 56	HI Temp (°C) 56 51 55 48 223 67 29 50 54 47 48 73 38 85 57	Post-Pro	Cecess Input I Herreatin Teemp (° C) -12 -25 -20 155 -2 2 2 -18 -18 -18 -22 -21 4 -18 -22 -21 4 -31 -5 9	Data at ment 2 h 301 195 285 292 468 311 249 253 291 293 316 293 316 293 306 293	For 60 35 55 60 777 61 44 60 60 56 55 60 60 62 57 61	rge ge 99 88 55 50 00 78 88 33 33 22 33 33 22 33 34 22 33 34 22 33 34 22 33 34 22 33 34 22 33 34 22 33 34 22 33 34 34 34 34 34 34 34 34 34 34 34 34	Temp (°C) -39 -20 -47 133 -28 -47 -45 -26 -48 -48 -22 -46 -1 -1 -19	HIP Press (MPa) -38 -40 -41 -45 129 -26 -59 -43 -34 -46 -47 -21 -60 -13 -31	h -77 -55 -50 -83 112 -64 -82 -81 -46 -84 -84 -86 -58 -68 -21 -35	H Treat Temp (°C) -56 6 -9 -62 136 -43 -21 -60 0 -63 -64 -63 -64 -38 -34 3 7	eat ment 3 h -1595 -215 -360 -1020 -929 -1012 -273 -1040 -224 -1246 -704 -1375 -310 -918 -171
No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18] 7, [19] 8, [20] 9, [21] 10, [22] 11, [23] 12, [24] 13, [21] 14, [25] 15, [26] 16, [27]	Heat Treatmen Temp (° C) -142 -63 -90 -148 31 -129 -90 -146 -69 -149 -141 -124 -103 -103 -103 -62 222	h 190 86 175 181 358 199 123 183 143 1779 182 205 158 198 143	Coc WQ -104 -2 -29 -110 73 -91 -29 -108 -8 -111 -86 -85 -42 -60 -1 -29	sling 9 5 15 1 175 19 4 3 16 -1 0 25 -12 16 23 172	C CR 15 11 14 14 14 14 14 14 14 14 14 14 14 14	(%) 553 15 51 44 20 62 56 44 60 63 30	HI Temp (°C) 56 51 55 48 223 67 29 50 54 47 48 73 38 85 57 -125	Post-Pro	Cecess Input I H Treatn C ⁰ C -12 -25 -8 -20 155 -2 2 -18 -18 -18 -18 -22 -21 4 -31 -5 9 9	Data att ment 2 h 301 195 285 292 468 311 249 253 291 293 316 268 308 268 308 265	For 60 35 55 60 61 45 60 55 60 60 60 60 55 60 60 60 60 55 55 60 60 60 60 55 55 60 60 60 55 55 55 60 60 777 777 777 777 777 777 777 777 7	rge ge 19 18 15 15 10 18 18 13 12 13 18 11 14 17 19 13 14 17 19 13 16 17 19 19 10 10 10 10 10 10 10 10 10 10	Temp (°C) -39 -20 -30 -47 133 -28 -47 -45 -26 -48 -48 -48 -22 -46 -1 -19 -23	HIP Press (MPa) -38 -40 -41 -45 129 -26 -59 -43 -34 -46 -47 -21 -60 -13 -31 -220	h -77 -55 -50 -83 112 -64 -82 -81 -46 -84 -84 -86 -58 -68 -21 -35 -250	H Treat Temp (°C) -56 6 -9 -62 136 -43 -21 -60 0 -63 -64 -38 -34 3 7 -32°	eat ment 3 h -1595 -215 -360 -1020 -929 -1012 -273 -1040 -224 -1246 -704 -1246 -704 -1375 -310 -918 -171 -195
No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18] 7, [19] 8, [20] 9, [21] 10, [22] 11, [23] 12, [24] 13, [21] 14, [25] 15, [26] 16, [27]	Heat Treatmen Temp (° C) -142 -63 -90 -148 31 -129 -90 -146 -69 -149 -141 -124 -103 -62 -323	h 190 86 175 181 358 199 123 183 143 175 182 205 158 198 145 7	Coo WQ -104 -2 -29 -110 73 -91 -29 -108 -8 -111 -86 -85 -42 -60 -1 -285	SC 9 5 15 1 175 19 4 3 16 -1 0 25 -12 16 23 -173	CR 11 11 14 14 14 14 14 15 14 14 14 14 14 14 14 14 14 14 14 14 14	(%) 53 55 55 51 52 56 44 56 44 56 42 44 68 224 60 53 30	HT Temp (°C) 56 51 55 48 223 67 29 50 54 47 48 73 38 85 57 -125	Post - Pro R HR (%) 8 8 10 2 175 20 4 4 6 0 0 26 -18 16 18 -173	Cecess Input I Herreatin Cecess Input I Cecess -12 -25 -25 -20 155 -20 155 -20 155 -22 2 -18 -18 -22 -21 4 4 -31 -5 9 9 -194	Data att ment 2 h 301 195 285 292 468 311 249 253 291 253 293 316 268 308 265 118	For For 55 60 77 61 45 60 60 56 55 60 60 62 55 55 61 61 54 42	ge ge 19 18 15 15 10 18 8 13 12 13 14 17 19 13 16 16 17 16 17 17 16 16 17 17 17 17 17 17 17 17 17 17	Temp (°C) -39 -20 -30 -47 133 -28 -47 -45 -26 -48 -48 -22 -46 -1 -19 -19 -221	HIP Press (MPa) -38 -40 -41 -45 129 -26 -59 -43 -34 -46 -47 -21 -60 -13 -31 -220	h -77 -55 -50 -83 112 -64 -83 -81 -46 -84 -84 -84 -84 -86 -58 -68 -21 -35 -259	H Teenp (°C) -56 6 -9 -62 136 -43 -21 -60 0 -63 -64 -63 -64 -38 -34 3 7 -238	eat ment 3
No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18] 7, [19] 8, [20] 9, [21] 10, [22] 11, [23] 12, [24] 13, [21] 14, [25] 15, [26] 16, [27] 17, [21]	Heat Treatmen Temp (° C) -142 -63 -90 -148 31 -129 -90 -146 -69 -149 -141 -124 -103 -62 -323 -44	h 190 86 175 181 358 199 123 183 143 179 182 205 158 198 145 7 202	Coo WQ -104 -2 -29 -110 73 -91 -29 -108 -8 -111 -86 -85 -42 -60 -1 -285 17	SC 9 5 15 1 175 19 4 3 16 -1 0 25 -12 16 23 -173 37	CCR 115 114 145 146 146 146 146 146 146 146 146	'R (%) 53 15 51 20 56 44 56 44 68 224 63 300 77	HI Temp (° C) 56 51 55 48 223 67 29 50 54 47 48 73 38 85 57 -125 88	Post-Pro	Cecess Input I Herreatin Teemp (° C) -12 -25 -8 -20 155 -2 2 -21 -18 -18 -22 -18 -18 -22 -21 4 -31 -5 9 -194 23	Data at ment 2 h 301 195 285 292 468 311 249 294 253 291 265 316 265 308 265 118 312	For 60 35 55 60 77 61 45 60 55 55 60 60 62 57 61 54 42 62 62	rge ge 19 18 15 15 15 16 18 18 18 18 18 13 12 13 14 17 19 13 16 16 12 12 13 16 16 17 17 17 17 17 17 17 17 17 17	Temp (°C) -39 -20 -47 133 -28 -47 -45 -26 -48 -48 -22 -46 -1 -19 -221 8	HIP Press (MPa) -38 -40 -41 -45 129 -26 -59 -43 -34 -46 -47 -21 -60 -13 -31 -220 -10	h -77 -55 -50 -83 112 -64 -82 -81 -46 -84 -84 -86 -58 -68 -21 -35 -259 -18	H Treat Temp (°C) -56 6 -9 -62 136 -43 -43 -21 -60 0 -63 -64 -64 -38 -34 3 7 7 -238 25	eat ment 3 h -1595 -215 -360 -1020 -929 -1012 -273 -1040 -224 -1246 -704 -1246 -704 -1375 -310 -918 -171 -1965 -240
No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18] 7, [19] 8, [20] 9, [21] 10, [22] 11, [23] 12, [24] 13, [21] 14, [25] 15, [26] 16, [27] 17, [21] 18, [19]	Heat Treatmen Temp (° C) -142 -63 -90 -148 31 -129 -90 -146 -69 -149 -141 -124 -103 -410 -44 -106	h 190 86 175 181 358 199 123 183 143 179 182 205 158 198 143 7 202 133	Coo WQ -104 -2 -29 -110 73 -91 -29 -108 -8 -111 -86 -85 -42 -60 -1 -285 17 -45	SC 9 5 15 1 175 19 4 3 16 1 0 25 -12 16 23 -173 37 12	CCR 15 11 12 14 14 14 14 16 16 16 16 16 16 16 16 16 16 16 17 17 17 17 17 17 17 17 17 17 17 17 17	(%) 53 55 55 55 51 44 20 52 56 37 44 56 37 42 44 68 224 60 63 30 77 48	HI Temp (°C) 56 51 55 48 223 67 29 50 54 47 48 73 38 85 57 -125 88 32	Post-Pro	Cecess Input I Herreatin Teemp (° C) -12 -25 -8 -20 155 -2 2 -18 -18 -18 -22 -21 4 -18 -18 -22 -21 4 -18 -22 -21 -18 -19 -29 -21 -29 -21 -29 -29 -29 -29 -29 -29 -29 -29 -29 -29	Data att ment 2 h 301 195 285 292 468 311 249 253 291 293 316 293 316 293 316 268 308 265 318 312 263	For 60 35 55 60 777 61 45 60 55 55 60 60 62 55 55 60 62 55 55 60 62 55 55 60 62 55 55 60 62 55 55 55 60 60 777 777 777 60 777 777 60 777 777	ge ge 99 88 55 00 78 88 11 14 77 9 13 16 12 13	Temp (°C) -39 -20 -47 133 -28 -47 -45 -26 -48 -48 -22 -46 -1 -19 -221 8 -49	HIP Press (MPa) -38 -40 -41 -45 129 -26 -59 -43 -34 -46 -47 -21 -60 -13 -31 -220 -10 -56	h -77 -55 -50 -83 112 -64 -82 -81 -46 -84 -84 -86 -58 -68 -21 -35 -259 -18 -68	H Treat Temp (°C) -56 6 -9 -62 136 -43 -21 -60 0 -43 -21 -60 0 -63 -64 -38 -34 3 7 -238 25 -24	eat ment 3 h -1595 -215 -360 -1020 -929 -1012 -929 -1012 -273 -1040 -224 -1246 -704 -1375 -310 -918 -171 -1965 -240 -280
No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18] 7, [19] 8, [20] 9, [21] 10, [22] 11, [23] 12, [24] 13, [21] 14, [25] 15, [26] 16, [27] 17, [21] 18, [19]	Heat Treatmen Temp (° C) -142 -63 -90 -148 31 -129 -90 -146 -69 -149 -114 -124 -63 -90 -148 31	h 190 86 175 181 358 199 123 183 143 1779 182 205 158 198 143 7 202 133	Coc WQ -104 -2 -29 -110 73 -91 -29 -108 -8 -111 -86 -85 -42 -60 -1 -285 17 -45	sling 9 5 15 1 175 19 4 3 16 -1 0 25 -12 16 23 -173 37 12	CR 15 11 15 16 16 16 16 16 16 16 16 16 16 16 16 16	(%) 53 55 55 51 54 20 62 56 44 62 44 62 44 63 30 77 48	HI Temp (°C) 56 51 55 48 223 67 29 50 54 47 29 50 54 47 48 73 38 85 57 -125 88 32	Post - Pro	Corress Input I Herreatin Temp (°C) -12 -25 -8 -20 155 -2 2 2 -18 -18 -18 -22 -21 4 -18 -22 -21 4 -31 -5 9 -194 23 -194	Data att ment 2 h 301 195 285 292 468 311 249 253 291 253 316 265 308 265 118 312 253	For 60 35 55 60 61 45 60 55 60 60 55 60 60 62 55 57 61 54 42 262 52	rge ge 99 88 55 00 78 88 33 33 33 33 34 33 33 33 33 33	Temp (°C) -39 -20 -30 -47 133 -28 -47 -45 -26 -48 -48 -22 -46 -1 -19 -221 8 8 -49	HIP Press (MPa) -38 -40 -41 -45 129 -26 -59 -43 -34 -46 -47 -21 -60 -13 -31 -220 -10 -56	h -77 -55 -50 -83 112 -64 -82 -81 -46 -84 -84 -84 -86 -58 -68 -21 -35 -259 -18 -68	H Treat Temp (°C) -56 6 -9 -62 136 -43 -21 -60 0 -63 -64 -38 -34 -38 -34 3 7 -238 25 -24	eat ment 3
No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18] 7, [19] 8, [20] 9, [21] 10, [22] 11, [23] 12, [24] 13, [21] 14, [25] 15, [26] 16, [27] 17, [21] 18, [19] 19, [18]	Heat Treatmen Temp (° C) -142 -63 -90 -148 31 -129 -90 -146 -69 -149 -141 -124 -103 -103 -62 -323 -44 -106 -87	h 190 86 175 181 358 199 123 183 143 179 182 205 158 198 143 7 202 133 241	Coo WQ -104 -2 -29 -110 73 -91 -29 -108 -8 -111 -86 -85 -42 -60 -1 -285 17 -45 -49	SC 9 5 15 1 175 19 4 3 16 -1 0 25 -12 16 23 -173 37 12 61	CR 11 11 15 14 14 14 14 14 14 14 14 14 14	(%) 53 55 55 51 52 62 62 63 224 63 330 777 48 04	HT Temp (°C) 56 51 55 48 223 67 29 50 54 47 48 73 38 85 57 -125 88 32 109	Post - Pro	Ceess Input I Herreatin Ceess -12 -25 -25 -8 -20 155 -22 2 -18 -18 -22 -21 4 -18 -22 -21 4 -31 -5 9 -194 23 -11 40	Ata ata ata ata ata 301 301 195 285 292 468 311 249 253 291 293 316 265 308 265 118 312 253	For For 55 55 66 67 77 61 45 66 55 66 62 55 66 62 55 66 62 55 66 62 55 66 62 55 66 62 55 66 66 66 66 66 66 66 66 66	rge ge 19 19 18 15 55 10 18 8 8 8 8 13 33 12 2 13 33 14 11 14 17 7 9 9 13 13 16 12 2 12 12 10 10	Temp (°C) -39 -20 -30 -47 -47 -45 -28 -47 -45 -26 -48 -48 -48 -22 -46 -1 -19 -221 -8 -49 -49 -41	HIP Press (MPa) -38 -40 -41 -45 129 -26 -59 -43 -34 -46 -47 -21 -60 -13 -31 -220 -10 -56 15	h -77 -55 -50 -83 112 -64 -82 -81 -46 -84 -84 -86 -58 -68 -21 -35 -259 -18 -68 -22	H Treat Temp (°C) -56 6 -9 -62 136 -43 -21 -60 0 -63 -64 -38 -34 3 7 -238 25 -24 25 -24 -1	eat ment 3 h -1595 -215 -360 -929 -1020 -929 -1012 -273 -1040 -224 -1246 -704 -1246 -704 -1246 -704 -1375 -310 -918 -171 -1965 -240 -280 -991
No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18] 7, [19] 8, [20] 9, [21] 10, [22] 11, [23] 12, [24] 13, [21] 14, [25] 15, [26] 16, [27] 17, [21] 18, [19] 19, [18] 20, [24]	Heat Treatmen Temp (° C) -142 -63 -90 -148 31 -129 -90 -146 -69 -149 -141 -124 -103 -62 -323 -44 -106 -87 -236	h 190 86 175 181 358 199 123 183 143 179 182 205 158 198 143 205 158 198 143 205 158 198 143 202 133 241 92	Coo WQ -104 -2 -29 -110 73 -91 -29 -108 -8 -111 -86 -85 -42 -60 -1 -285 17 -45 -49 -198	SC 9 5 15 1 175 19 4 3 16 -1 0 25 -12 16 23 -173 37 12 61 -87	CR 11 11 12 14 14 14 14 14 14 14 14 14 14	'R (%) 53 15 51 20 62 56 44 60 63 30 77 48 04 55	HI Temp (°C) 56 51 55 48 223 67 29 50 54 47 48 73 38 85 57 -125 88 32 109 -40	Post-Pro	Cecess Input I Herreatin Teemp (° C) –12 –25 –3 –20 155 –2 2 –18 –18 –18 –18 –22 –21 4 –18 –22 –21 –4 –31 –5 9 –194 23 –11 40 –10 –10 –40 –20 –21 –20 –21 –21 –25 –20 –20 –20 –20 –20 –20 –20 –20 –20 –20	Pata at ment 2 h 301 195 285 292 468 311 249 253 291 293 316 265 308 265 118 312 253 308 265 318 3265 333 204	For 60 35 55 60 777 61 45 60 55 55 60 60 62 55 57 61 54 42 262 52 52 66	rge ge 99 88 55 50 00 78 88 88 33 33 22 33 33 22 33 33 77 9 9 33 66 22 22 20 00 1	Temp (°C) -39 -20 -47 133 -28 -47 -45 -26 -48 -48 -22 -46 -1 -19 -221 -8 8 -49 14 -135	HIP Press (MPa) -38 -40 -41 -45 129 -26 -59 -43 -34 -46 -47 -21 -60 -13 -31 -220 -10 -56 15 -133	h -77 -55 -50 -83 112 -64 -82 -81 -46 -84 -86 -58 -68 -21 -35 -259 -18 -68 -22 -172	H Treat Temp (°C) -56 6 -9 -62 136 -43 -43 -21 -60 0 -63 -64 -38 -34 -38 -34 3 7 7 -238 25 -24 -1 -150	eat ment 3 h -1595 -215 -360 -1020 -929 -1012 -273 -1040 -224 -1246 -704 -1375 -310 -918 -171 -1965 -240 -280 -991 -1170
No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18] 7, [19] 8, [20] 9, [21] 10, [22] 11, [23] 12, [24] 13, [21] 14, [25] 15, [26] 16, [27] 17, [21] 18, [19] 19, [18] 20, [24] 20, [24] 21, [24] 21, [24] 21, [24] 22, [24] 24, [25] 24, [26] 25, [26] 26, [27] 27, [21] 20, [24] 20, [25] 20, [Heat Treatmen Temp (° C) -142 -63 -90 -148 31 -129 -90 -146 -69 -149 -114 -124 -69 -144 -103 -62 -323 -44 -106 -87 -236	h 190 86 175 181 358 199 123 183 143 179 182 205 158 198 143 205 158 198 143 205 158 198 143 193 241 92	Coo WQ -104 -2 -29 -110 73 -91 -29 -108 -8 -111 -86 -85 -111 -86 -85 -42 -60 -1 -285 17 -45 -49 -198 -	SC 9 5 15 1 175 19 4 3 16 1 0 25 -12 16 23 -173 37 12 61 -87	CR 15 11 12 14 14 14 15 16 16 16 16 16 16 16 16 16 17 16 16 16 17 17 16 16 16 17 17 16 16 17 17 17 17 17 17 17 17 17 17 17 17 17	(%) 553 553 15 551 44 20 56 62 37 44 56 37 42 56 60 63 30 77 48 004 55	HI Temp (°C) 56 51 55 48 223 67 29 50 54 47 48 73 38 85 57 -125 88 32 109 -40	Post-Pro	Cecess Input I Herreatin Teemp (° C) -12 -25 -8 -20 155 -2 2 -18 -18 -18 -22 -21 4 -18 -22 -21 -18 -18 -22 -21 -18 -19 -22 -21 -21 -21 -25 -2 -2 -2 -2 -2 -2 -2 -2 -2 -2 -2 -2 -2	Pata att ment 2 h 301 195 285 292 468 311 249 253 291 268 316 268 318 253 118 312 253 353 353 201	For 60 35 55 60 777 61 45 60 55 55 60 60 62 55 55 60 62 55 55 60 62 55 55 60 62 55 55 60 62 55 55 66 60 62 55 55 60 60 777 777 60 777 777 60 777 777 60 777 777	ge ge ge 99 88 55 00 78 88 13 14 77 9 13 16 12 12 13 16 12 12 13 16 12 12 13	Temp (°C) -39 -20 -47 133 -28 -47 -45 -26 -48 -48 -22 -46 -1 -19 -221 8 -49 14 -135 -2-	HIP Press (MPa) -38 -40 -41 -45 129 -26 -59 -43 -34 -46 -47 -21 -60 -13 -31 -220 -10 -56 15 -133 -7	h -77 -55 -50 -83 112 -64 -82 -81 -46 -84 -84 -86 -58 -68 -21 -35 -259 -18 -68 -22 -172	H Treat Temp (°C) -56 6 -9 -62 136 -43 -21 -60 0 -43 -21 -60 0 -63 -64 -38 -34 3 7 -238 25 -24 25 -24 -1 -150	eat ment 3 h -1595 -215 -360 -1020 -929 -1012 -273 -1040 -224 -1246 -704 -1375 -310 -918 -171 -1965 -240 -280 -991 -1165 -280 -991 -1165 -280 -991 -1165 -280 -991 -1165 -280 -991 -1165 -280 -991 -1165 -280 -991 -1165 -280 -991 -1165 -280 -991 -1165 -280 -991 -1165 -280 -991 -1165 -280 -991 -1165 -280 -991 -116 -116 -280 -991 -116 -116 -116 -116 -116 -116 -116
No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18] 7, [19] 8, [20] 9, [21] 10, [22] 11, [23] 12, [24] 13, [21] 14, [25] 15, [26] 16, [27] 17, [21] 18, [19] 19, [18] 20, [24] 21, [28]	Heat Treatmen Temp (° C) -142 -63 -90 -148 31 -129 -90 -146 -69 -149 -141 -124 -103 -103 -62 -323 -44 -106 -87 -87 -236 -45	h 190 86 175 181 358 199 123 183 143 205 158 198 143 205 158 198 143 205 158 198 143 205 158 198 241 92 288	Coc WQ -104 -2 -29 -110 73 -91 -29 -108 -8 -111 -86 -85 -42 -60 -1 -285 17 -45 -49 -198 -7	SC 9 5 15 1 175 19 4 3 16 -1 0 25 -12 16 23 -173 37 12 61 -87 105	CR 11 14 14 14 14 14 14 14 14 14	(%) 53 55 55 51 52 54 62 56 62 44 56 44 62 37 42 44 68 22 43 30 77 48 04 55 50	HT Temp (°C) 56 51 55 48 223 67 29 50 54 47 29 50 54 47 48 73 38 85 57 -125 88 32 109 -40 153	Post - Pro	Cecess Input I H Treatn C°C -12 -25 -8 -20 155 -2 2 2 -18 -18 -18 -22 -21 4 -18 -22 -21 4 -18 -22 -21 -18 -19 -22 -21 -21 -21 -25 -2 -2 -2 -2 -2 -2 -2 -2 -2 -2 -2 -2 -2	Pata att ment 2 h 301 195 285 292 468 311 249 253 291 263 316 265 318 265 118 312 253 308 265 318 3253 336 265 308 265 308 265 308 265 308 265 308 265 318 312 253 353 204 398	For For 55 60 77 61 45 60 60 55 60 60 62 55 60 61 61 55 61 61 55 55 60 62 55 55 60 62 55 55 60 62 55 55 60 60 60 77 77 61 80 77 77 60 80 77 77 60 80 77 77 60 80 77 77 60 80 77 77 60 80 77 77 60 80 80 80 80 80 80 80 80 80 80 80 80 80	rge ge 99 88 55 00 78 88 33 33 33 33 33 33 33 33 3	Temp (°C) -39 -20 -30 -47 -47 -45 -28 -47 -45 -26 -48 -48 -22 -46 -1 -19 -221 -8 -49 -49 -14 -135 -58	HIP Press (MPa) -38 -40 -41 -45 129 -26 -59 -43 -34 -46 -47 -21 -60 -13 -31 -220 -10 -56 15 -133 59	h -77 -55 -50 -83 112 -64 -82 -81 -46 -84 -84 -86 -58 -68 -21 -35 -259 -18 -68 -22 -172 20	H Treat Temp (°C) -56 6 -9 -62 136 -43 -21 -60 0 -63 -64 -38 -64 -38 -34 3 7 -238 25 -24 -238 25 -24 -1 -150 41	eat ment 3
No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18] 7, [19] 8, [20] 9, [21] 10, [22] 11, [23] 12, [24] 13, [21] 14, [25] 15, [26] 16, [27] 17, [21] 18, [19] 19, [18] 20, [24] 21, [28] 22, [26]	Heat Treatmen Temp (° C) -142 -63 -90 -148 31 -129 -90 -146 -69 -149 -141 -124 -103 -62 -323 -44 -106 -87 -236 -45 -245	h 190 86 175 181 358 199 123 183 143 179 182 205 158 198 143 205 158 198 143 205 158 198 241 92 288 -44	Coo WQ -104 -2 -29 -110 73 -91 -29 -108 -8 -111 -86 -85 -42 -60 -1 -285 17 -45 -49 -198 -7 -184	SC 9 5 15 1 175 19 4 3 16 -11 0 25 -12 16 23 -173 37 12 61 -87 105 -163	C CR 119 111 115 114 115 114 115 114 115 114 115 114 116 116 116 117 116 117 117 117	'R (%) 53 15 51 52 56 44 56 44 56 42 42 44 68 63 300 77 48 55 50 29	H Temp (° C) 56 51 55 48 223 67 29 50 54 47 48 73 38 85 57 -125 88 32 109 -40 153 -124	Post-Pro	Josephere Her Treatin Her Treatin -12 -25 -8 -20 155 -2 2 155 -2 -18 -18 -22 -21 4 -31 -5 9 -194 23 -11 40 -108 85 -183 -183	Ata ata hent 2 301 301 195 285 292 468 311 249 253 291 293 316 265 308 265 118 312 253 265 308 265 318 326 328 328 328 3293	For 60 38 55 60 77 61 45 60 61 55 55 60 62 55 60 61 54 42 62 52 55 55 60 61 54 54 54 52 55 55 55 55 55 55 55 55 55 55 55 55	rge rge 19 18 15 16 17 19 13 16 12 13 16 12 13 14 15 16 17 18 19 13 14 15 16 17 18 19 11 10 11 12 13	Temp (°C) -39 -20 -30 -47 133 -28 -47 -45 -26 -48 -48 -48 -22 -46 -1 -19 -221 -8 8 -49 14 -135 58 -202	HIP Press (MPa) -38 -40 -41 -45 129 -26 -59 -43 -34 -46 -47 -21 -60 -13 -31 -220 -10 -56 15 -133 59 -212	h -77 -55 -50 -83 112 -64 -82 -81 -46 -84 -84 -86 -58 -68 -21 -35 -259 -18 -68 -22 -172 20 -220	H Treat Temp (°C) -56 6 -9 -62 -43 -43 -21 -60 0 -63 -64 -38 -64 -38 -64 -38 -34 3 7 -238 25 -24 -1 -150 41 -176	eat ment 3 h -1595 -215 -360 -1020 -929 -1012 -273 -1040 -224 -1246 -704 -1246 -704 -1375 -310 -918 -171 -1965 -240 -280 -991 -1170 -1145 -362
No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18] 7, [19] 8, [20] 9, [21] 10, [22] 11, [23] 12, [24] 13, [21] 14, [25] 15, [26] 16, [27] 17, [21] 18, [19] 19, [18] 20, [24] 21, [28] 22, [26]	Heat Treatmen Temp (° C) -142 -63 -90 -148 31 -129 -90 -146 -69 -149 -141 -124 -103 -62 -323 -44 -106 -87 -236 -45 -245	h 190 86 175 181 358 199 123 183 143 179 182 205 158 198 143 179 182 205 158 198 145 7 202 133 241 92 288 -44	Coo WQ -104 -2 -29 -110 73 -91 -29 -108 -8 -111 -86 -85 -42 -60 -1 -285 17 -285 17 -45 -49 -198 -7 -184	SC 9 5 15 1 175 19 4 3 16 -11 0 25 -12 16 23 -173 37 12 61 -87 105 -163	C CR 15 11 15 14 14 14 14 14 14 16 16 16 16 16 16 16 16 16 16	(%) (%) 53 15 51 52 56 56 37 44 68 224 68 53 30 77 48 04 55 50 229	HI Temp (°C) 56 51 55 48 223 67 29 50 54 47 48 73 38 85 57 -125 88 32 109 -40 153 -124	Post-Pro	Cecess Input I Herreatin Teemp (° C) –12 –25 –8 –20 155 –2 2 –18 –18 –18 –18 –22 –21 4 –18 –22 –21 –4 –31 –5 9 –194 23 –11 40 –108 85 –108	Pata at ment 2 h 301 195 285 292 468 311 249 253 291 265 301 249 253 316 268 308 253 333 204 333 204 398 70	For 60 60 35 55 60 777 61 44 62 55 60 60 62 55 55 60 60 62 55 55 60 60 62 55 55 60 60 62 55 55 60 60 60 777 777 61 61 61 61 60 777 777 61 61 60 777 777 61 61 61 61 61 61 61 61 61 61 61 61 61	rge ge 99 88 55 50 00 78 88 33 33 33 33 33 33 33 33 33 33 33 33	Temp (°C) -39 -20 -30 -47 133 -28 -47 -45 -26 -48 -48 -22 -46 -1 -19 -221 -8 -49 14 -135 58 -202	HIP Press (MPa) -38 -40 -41 -45 129 -26 -59 -43 -34 -46 -47 -21 -60 -13 -31 -220 -10 -56 15 -133 59 -212 475	h -77 -55 -50 -83 112 -64 -82 -81 -46 -84 -84 -86 -58 -68 -21 -35 -259 -18 -68 -21 -35 -259 -18 -68 -22 -172 20 -220	H Treat Temp (°C) -56 6 -9 -62 136 -43 -21 -60 0 -63 -64 -38 -34 -38 -34 -38 -34 -38 -21 -60 0 -63 -64 -38 -21 -60 0 -63 -64 -38 -21 -62 136 -61 -17 -60 0 -62 -136 -61 -62 -136 -62 -136 -62 -136 -62 -136 -62 -136 -62 -136 -62 -136 -62 -136 -62 -136 -62 -136 -62 -136 -62 -136 -63 -64 -63 -64 -63 -64 -138 -64 -138 -64 -138 -64 -138 -64 -138 -143 -143 -143 -145 -145 -145 -145 -145 -145 -145 -145	eat ment 3 h -1595 -215 -360 -1020 -929 -1012 -273 -1040 -224 -1246 -704 -1246 -704 -1375 -310 -918 -171 -1965 -240 -280 -991 -1170 -1145 -320 -991 -1170 -1145 -320 -991 -1170 -1145 -320 -991 -1170 -1145 -320 -991 -1170 -1145 -320 -991 -1170 -1145 -320 -991 -1170 -1145 -320 -991 -1170 -1145 -320 -991 -1170 -1145 -320 -991 -1170 -1145 -320 -320 -320 -320 -320 -320 -320 -320
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No., [Ref] 1, [9] 2, [14] 3, [15] 4, [16] 5, [9] 6, [18] 7, [19] 8, [20] 9, [21] 10, [22] 11, [23] 12, [24] 13, [21] 14, [25] 15, [26] 16, [27] 17, [21] 18, [19] 19, [18] 20, [24] 21, [28] 22, [26] 23, [25] 24, [29]	Heat Treatmen Temp (° C) -142 -63 -90 -148 31 -129 -90 -146 -69 -149 -141 -124 -103 -62 -323 -44 -106 -87 -236 -45 -245 361 -159	h 190 86 175 181 358 199 123 183 143 175 188 199 123 183 143 179 182 205 158 198 145 7 202 133 241 92 288 -44 692 -12	Con WQ -104 -2 -29 -110 73 -91 -29 -108 -8 -111 -86 -85 -42 -60 -1 -285 17 -45 -49 -198 -7 -184 399 -117	SC 9 5 15 1 175 19 4 3 16 -1 0 25 -12 16 23 -173 37 12 61 -87 105 -163 511	CR 11 11 14 14 14 14 14 14 14 14	(%) 53 55 51 51 52 54 62 55 44 56 44 56 44 56 44 68 24 63 30 77 48 55 50 29 55 3	HT Temp (°C) 56 51 55 48 223 67 29 50 54 47 29 50 54 47 48 73 38 85 57 -125 88 32 109 -40 153 -124 559 -64	Post - Pro	Ceess Input I H Treatn C°C -12 -25 -8 -20 155 -2 2 -18 -18 -18 -22 -21 4 -18 -18 -22 -21 4 -18 -22 -21 -21 -21 -21 -21 -21 -21 -21 -25 -2 -2 -21 -2 -2 -2 -2 -2 -2 -2 -2 -2 -2 -2 -2 -2	Pata att ment 2 h 301 195 285 292 468 311 249 253 291 263 316 265 318 3253 336 265 318 3253 338 265 338 265 308 3263 308 3263 308 3263 308 312 253 353 204 398 76 803 109	For For 55 55 60 77 61 45 60 55 60 60 55 60 61 55 60 61 62 55 60 61 62 55 60 60 60 60 60 60 60 60 60 60	rge ge 99 88 55 00 78 88 33 33 33 33 33 33 33 34 88 11 44 55 50 00 1 1 1 1 1 1 1 1 1 1 1 1 1	Temp (°C) -39 -20 -30 -47 133 -28 -47 -45 -26 -48 -48 -48 -22 -46 -1 -19 -221 -8 -49 14 -135 58 -202 463 -202 463 -128	HIP Press (MPa) -38 -40 -41 -45 129 -26 -59 -43 -34 -46 -47 -21 -46 -47 -21 -60 -13 -31 -220 -10 -56 15 -133 59 -212 464 -132	h -77 -55 -50 -83 112 -64 -82 -81 -46 -84 -84 -84 -86 -58 -68 -21 -35 -259 -18 -68 -22 -172 20 -220 425 -136	H Treat Temp (°C) -56 6 -9 -62 136 -43 -21 -60 0 -63 -43 -21 -60 0 -63 -64 -38 -34 -38 -34 -33 7 -238 25 -24 -238 25 -24 -1 -150 41 -176 447 -109	eat ment 3 h -1595 -215 -360 -929 -1012 -273 -1012 -273 -1010 -224 -1246 -704 -224 -1246 -704 -1266 -704 -1375 -310 -918 -171 -1965 -240 -280 -991 -1170 -1170 -1145 -362 -300 -300

							Post-Pro	cess Input D	ata						
No., [Ref]	Heat Treatment 1		Coo	ling	CR	н	R	He Treatm	at ent 2	Forge		HIP		He Treatr	eat nent 3
	Temp (^o C)	h	WQ	SC	CR (%)	Temp (°C)	HR (%)	Temp (° C)	h	Forge	Temp (° C)	Press (MPa)	h	Temp (°C)	h
25, [30]	-513	-183	-475	-363	-220	-315	-363	-384	-71	236	-410	-409	-448	-427	-2000
26, [31]	-422	-94	-384	-274	-131	-226	-273	-295	18	325	-321	-319	-357	-336	-1575
27, [32]	135	468	178	285	430	333	285	264	578	887	238	239	199	221	-410
28, [20]	-481	-180	-420	-358	-218	-310	-363	-381	-70	239	-395	-408	-415	-391	-790
29, [23]	-65	260	-12	78	222	126	78	57	371	678	30	31	-8	14	-630
30, [27]	-557	-227	-519	-407	-264	-359	-407	-428	-115	192	-455	-454	-493	-472	-2035
31, [18]	-459	-130	-421	-310	-168	-263	-309	-331	-19	289	-358	-356	-394	-373	-1330
32, [14]	-153	69	-92	-65	54	-26	-74	-104	179	489	-108	-115	-126	-83	-357
33, [<mark>33</mark>]	329	658	368	478	621	526	479	457	769	1077	431	432	394	415	-879
34, [22]	488	817	526	637	779	684	638	616	928	1236	589	591	553	574	-1058
35, [<mark>34</mark>]	-234	95	-195	-85	58	-37	-84	-106	206	514	-132	-131	-169	-148	-1092
36, [27]	80	411	119	231	374	279	230	210	523	830	183	184	145	167	-1280
1t, [35]	-905	-674	-849	-803	-653	-780	-809	-807	-560	-255	-862	-868	-914	-856	-1284
2t, [26]	-85	120	-24	-2	137	35	-7	-17	240	520	-41	-53	-58	-16	-197
3t, [27]	-380	-50	-342	-230	-87	-182	-230	-251	62	369	-278	-277	-316	-295	-1965
4t, [25]	-196	137	-158	-45	99	3	-46	-66	247	557	-93	-92	-132	-110	-1298
5t, [19]	-146	-71	-142	-130	-41	-101	-127	-132	38	244	-131	-127	-133	-138	-175
6t, [25]	117	450	156	268	412	316	267	247	560	869	220	221	182	203	-1105
7t, [30]	-697	-364	-659	-547	-403	-499	-547	-568	-254	55	-595	-594	-633	-611	-1841
8t, [36]	-283	-51	-227	-181	-31	-158	-186	-185	62	368	-239	-246	-292	-234	-655
Ratio (%)	16	73	18	55	73	64	50	32	86	98	25	23	18	32	0

Table 6. Cont.

* reference number. ** test data.

In TiZrHfNbX (X = V or Cr) HEA, the yield strength was increased when the Cr element was added instead of the V element [28]. The fact that the V element lowers the yield strength was similar to the conclusion calculated from the ANN and lasso model. In addition, the effect of Al on Al CoCrFeNi HEA was found to be positive. At low Al content, the alloys form FCC structures. When the Al amount is continuously increased, the formation of the BCC phase has been induced. It also increases the strength of the HEA with a modulated spinodal structure. The complete spinodal structure can be obtained in amounts of Al0.9-2.0. The cast Al0.9 alloy has a maximum hardness of HV 527 due to the optimal radial decomposition and interconnecting structure [38]. Positively affecting elements such as Al had the same positive effects on other HEAs. In addition, elements such as Fe, Ni, and Co also had a negative effect on other alloys.

In the post-process data of Table 6, the size of the data set is small, and inaccurate results are often shown. The HIP process reduces the tensile strength due to grain coarsening in AlxCoCrFeNi alloy of the transition metal group [39]. Table 6 also shows that hot isostatic pressing has a negative effect on yield strength. However, similar to other heat treatment temperatures, it is difficult to obtain accurate and detailed results because the experimental data by temperature or time conditions are not trained. In the case of trend prediction, cold rolling and forge were confirmed as variables to improve the tensile strength. This process is known to increase the yield strength of metals through work hardening. In the case of heat treatment, the result was that the tensile strength decreased as the temperature increased and the tensile strength increased with time. This result is also difficult to be trusted due to the lack of heat treatment data, and more accurate results can be obtained when more data are collected in the future.

4. Conclusions

In this paper, a new methodology for predicting the mechanical properties of HEA is proposed. The design of HEA is complicatedly entangled with material theories including thermodynamic and physical relationships between constituent elements and post-processing. To approach this process efficiently, the mechanical properties of the

alloy were predicted using only the mole fraction and post-process data using the ANN algorithm. The main results are as follows:

- 1. The ANN prediction model showed high accuracy only when learning the postprocess data together; the tensile strength showed an error rate of 19.7%, and the microstructure was consistent in all test data. Elongation prediction showed a high error rate of 40.2%.
- 2. In the case of the lasso linear regression, the error rate of the model trained with post-processing data was 31.1%, and the error rate of the lasso model trained only on the mole fraction was 26.1%, showing low accuracy. The linear regression model did not sufficiently reflect the complex causal relationships in the data as the variable increased.
- 3. When post-process data were trained with the element mole fraction, the model error rate decreased from 15.9% to 14% in the refractory metal group, and the error rate of the transition metal group decreased from 52% to 27% in the transition metal group. In contrast, the lasso model showed the opposite trend.
- 4. In the ANN model, Al, Cr, Cu, Nb, Ta, Ti, Zr, Mo, and W increased the strength as these components increased, and Co, Fe, Ni, Mn, Hf, and V decreased the tensile strength. In the lasso model, the same results were obtained except for Nb. In addition, in the post-process, cold rolling and forging improved the tensile strength.

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