S-N curve modeling method of Aluminum alloy welded joints based on the fatigue characteristics domain

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ABSTRACT. The scatter degree of the fatigue samples is reduced when the nodal force based structural method is used for steel welded joints, while it is still high for aluminum alloy welded joints. Statistical method and rough set theory is used to fatigue analysis so that fatigue characteristic domains are determined and S-N curves are fitted. Experiment results show that fatigue life of the aluminum alloy welded joints is under the influence of some key factors and the fatigue data with the same characteristics distribute in a relatively independent area. Accordingly, a novel S-N curve modeling method of aluminum alloy welded joints based on the fatigue characteristics domain is proposed. In the proposed method, the nodal force based structural stress method is used for stress calculation and neighborhood rough set theory is used for character extraction to obtain the key factors. Then fatigue characteristics domains are divided and S-N curves are fitted on each fatigue characteristics domain instead of on the whole domain so that a set of S-N curves are obtained. Statistical results show that selection of the S-N curve for the aluminum alloy welded joints according to different fatigue characteristic domain is more accurate.

KEYWORDS. Welding; Fatigue; Structural stress; Rough set theory; S-N curve.

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INTRODUCTION

As a traditional processing technique, welding has been widely used in many fields, such as mechanical manufacturing, aerospace, transportation, etc. The fatigue analysis and life prediction of a welding joint are directly related to the stability and safety of the whole structure. Currently, the nominal stress method and the nodal based structural stress method are two most commonly used welding fatigue analysis and prediction methods.

The nominal stress method is the first routine way to get theoretical and experimental research in fields of engineering fatigue design, strength assessment and life prediction of welded structures. In various industry fields, its method and data has been widely standardized, and it has been maturely applied to the actual project. But because of the existence of various preconditions and regulations, choice of the S-N curves is uncertain in this method. How to accurately select the S-N curve and to calculate the stress are the most important problems which cannot be solved in this method.

The nodal force based structural stress method is a new type of fatigue life prediction technology for welded structure proposed by Dong [1]. In this method, the finite element technique is used to compute the structural stress through nodal force. Currently, the nodal force based structural stress method is one of the most striking engineering technologies for fatigue analysis of welded structures due to its mesh-insensitive hot spot stress calculation, higher fatigue life prediction accuracy and the broad applicability [2]. Dong et al. reprocessed thousands of fatigue test data of the steel welded joints in the last 50 years [3]. According to the linear regression analysis, the main S-N curve of fatigue design based on equivalent structural stress (Eq. SS) range is determined.

In this study, first of all, fatigue data of aluminum alloy welded joints is collected and the fatigue database is obtained from related literatures. Then, S-N curves are fitted based on the nodal force based structural stress and the scatter degree of fatigue data is computed. Subsequently, neighborhood rough set theory is used for knowledge reduction to find the core among the many factors which influence the fatigue life of aluminum alloy welded joints. Finally, the fatigue characteristics domain is established according to the reduction result of neighborhood rough set theory and S-N curves are fitted subsequently in each domain.

RELATED WORKS

S-N curve is the main tool to analyze and predict fatigue lifetime of a metallic material, component or structure. A large number of domestic and foreign scholars have devoted themselves to the study of the S-N curve modeling method. Monotonic test based empirical fatigue formulae and a Wholer field mathematical model is combined and a new formula for developing full range stress life curves for medium strength steels is proposed [4]. The importance of employing material specific S-N curves with appropriate stress concentration factors for special connection details and correct damage accumulation methods is highlighted. The fatigue crack growth of a double fillet weld with the existence of a semi-elliptical crack is studied [5]. The constant amplitude loading is applied where the influence of the load ratio over the fatigue life is presented. A new probabilistic model is proposed [6], where the model parameters are estimated with an EM algorithm for which the Maximisation step combines Newton-Raphson optimization method and Monte Carlo integrations. A new method that assumes linear change of scatter according to stress levels is developed in [7]. The algorithm derives from maximum likelihood estimation and general Newton's method. A study has been carried out to establish which confidence level in the estimation of the characteristic S-N curve from limited data [8].The results of the study provide a new way to optimize fatigue design whenever it is costly or time-consuming to achieve many reliable test data. A unified statistical model which can take into account any number of failure mechanisms and the possible presence of the fatigue limit is presented [9]. The adaptability of the statistical model to the S-N curves proposed in the open literature is demonstrated by qualitative numerical examples.

Generally speaking, fatigue behavior of welded components is influenced by many factors such as temperature, material type, load type, ratio and etc. Up to now, many researchers have devoted themselves to this research and initial achievements have been obtained. For example, plate thickness factor is considered and a new analytical formula of fracture toughness is proposed based on the energy theory and linear elastic mechanics [10], which would significantly reduce the calculation cycle of remaining life of structures in structural integrity assessment of welded structures. Crack initiation potential in materials containing defects is investigated numerically by focusing on defect types, size, shape, location, and residual stress influences [11]. Results show that the crack initiation potency is higher in case of serious property mismatching between matrix and defects, and higher strength materials are more sensitive to soft inclusions. Near-threshold fatigue crack growth tests are conducted at various stress ratios and different pre-cracking locations of a 25Cr2Ni2MoV welded joint by using load-shedding procedure at room temperature to investigate the transition behavior of fatigue crack growth curve [12].

Results show that there exists a transition point in the fatigue crack growth curve in the near-threshold regime, and the stress intensity range of the fatigue threshold decreases with the increasing of stress ratio.
Currently, there is still a lack of an objective and comprehensive evaluation of the great many factors which influence the fatigue life of the welded structure. To establish the mathematical model of different influence factors, neighborhood rough set theory is used to find the core factors which influence the fatigue life of the aluminum alloy welded joints based on the data itself rather than on any other prior knowledge. Fatigue characteristics domains are then determined according to the key influence factors and the S-N curves are fitted in each domain subsequently.

METHODOLOGY

Basic Principle of the Nodal Force Based Structural Stress

The normal structural stress at each node from elementary structural mechanics theory is given by

$$\sigma_s = \sigma_m + \sigma_b \tag{1}$$

$$\sigma_m = f_y / t \tag{2}$$

$$\sigma_b = 6m_x / t^2 \tag{3}$$

where $f_y = F_y / l$, $m_x = M_x / l$ is the line force and moment in the weld tow shown as Fig. 1, F_y is the nodal force, M_x is the moment around the weld toe.

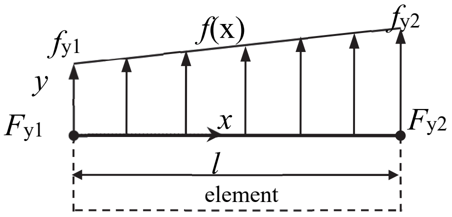

Figure 1: Definition of linear force.

Fracture mechanics is employed to estimate the fatigue life of welded joints. The stress intensity factor in crack propagation theory can be calculated as [2]:

$$\Delta K = \sqrt{t^*}\,[\Delta\sigma_m f_m(a/t) + \Delta\sigma_b f_b(a/t)], \tag{4}$$

where a is the crack depth, t^* is a ratio of actual thickness t to a unit thickness. $f_m(a/t)$ and $f_b(a/t)$ are membrane stress and bending stress as a function of crack growth degree respectively. According to the Paris crack growth law, the prediction of the life cycle from an infinitesimally small crack to final failure can be expressed as:

$$N = \int_{a/t=0}^{a/t=1} \frac{t^* d(a/t)}{C(M_{kn})^n (\Delta K)^m} = \frac{1}{C} t^{*1-\frac{m}{2}} (\Delta\sigma_s)^{-m} I(r), \tag{5}$$

where $M_{kn}=K / K_n$ is the notch stress magnification , K represents the total K due to both the far-field stress and the local notch stress effects and K_n represents only the far-stress contribution to the stress intensity factor. $I(r)$ is a dimensionless function of r and m is the crack growth exponent, which is set to be 3.6 in ASME [13]. A Master S-N curve can be established according to Eq. 6 based on a set of welding fatigue data. The Eq. SS can then be expressed as:

$$\Delta\sigma_\varepsilon = t^{*1-\frac{m}{2}} (\Delta\sigma_s)^{-m} I(r) \tag{6}$$

where t^* is dimensionless the equivalent $\Delta\sigma_\varepsilon$ retains a stress unit.

Neighborhood Rough Set Theory

Founded by Pawlak, rough set theory [14] aims to find the inner links of the massive, imprecise, incomplete and uncertain data, it has become an important tool to study granular computing theory nowadays [15]. However, the tradition rough set just works in discrete spaces and it can't deal directly with the numerical data that widely existed in the practical application. When dealing with the numerical data, discretization is first done to transform the numerical value into the symbol value [16, 17]. This transformation inevitably brings about information loss and the computing results usually depend largely on the effect of discretization algorithm. To deal with this problem, a neighborhood rough set model is proposed based on the definitions of δ neighborhood and neighborhood relations in metric spaces [18, 19]. Several foundation definition of neighborhood rough set theory including $\delta-neighborhood$, lower and upper approximations, dependency degree, significance of the attribute, reduction and core are first introduced here.

Definition 1 $\delta-neighborhood$

U is a non-empty finite set in the real number space, $\forall x_i \in U$, the δ-neighborhood of xi is defined as

$$\delta(x_i)=\{x\in U,\Delta(x,x_i)\le\delta\} \tag{7}$$

where Δ is a metric function, $\forall x_1,x_2,x_3\in U$, it satisfied $\Delta(x_1,x_2)>0$, $\Delta(x_1,x_2)=0$ if and only if $x_1=x_2$, $\Delta(x_1,x_2)=\Delta(x_2,x_1)$ and $\Delta(x_1,x_3)\le\Delta(x_1,x_2)+\Delta(x_2,x_3)$. The family of neighborhood granules $\{\delta(x_i)\,|\,x_i\in U\}$ forms an element granule system for a given metric space $<U,\Delta>$. We have $\forall x_i\in U,\delta(x_i)\ne\phi$ and $\bigcup_{x\in U}\delta(x)=U$. A neighborhood relation N can be written as a relation matrix $M(N)=(r_{ij})_{n\times n}$, where $r_{ij}=1$ if $x_j\in\delta(x_i)$ or $r_{ij}=0$ otherwise.

Definition 2 Lower and upper approximations

The lower and upper approximations of X in terms of relation N for a given $<U,N>$ are defined as

$$\underline{N}X=\{x_i\,|\,\delta(x_i)\subseteq X,x_i\in U\}, \tag{8}$$

$$\overline{N}X=\{x_i\,|\,\delta(x_i)\cap X\ne\phi,x_i\in U\}, \tag{9}$$

The boundary region of X is

$$BNX=\overline{N}X-\underline{N}X, \tag{10}$$

Definition 3 Dependency degree

The dependency degree of the decision attribute D to the condition attribute B is defined as

$$\gamma_B(D)=\frac{|\underline{N_B}D|}{|U|}, \tag{11}$$

It is obvious that $0\le\gamma_B(D)\le1$. If $\gamma_B(D)=1$, we say D completely depend on B otherwise D is γ-depend on B.

Definition 4 Significance of the attribute

Given a neighborhood decision table $<U,C,D,V,f>$, B⊆C,a∈C-B, the significance of a to B is defined as

$$SIG(a,B,D)=\gamma_{B\cup a}(D)-\gamma_B(D), \tag{12}$$

Definition 5 Reduction

Given a neighborhood decision table $<U,C,D,V,f>$, B⊆C, we say the subset of attributes B is a reduction of C if $\gamma_B(D)=\gamma_C(D)$ and $\forall b\in B,\gamma_B(D)>\gamma_{B-b}(D)$.

Definition 6 Core

Given a neighborhood decision table $<U, C, D, V, f>$, all reductions consist of $B_1, B_2, \ldots B_n$, the core of is defined as $core = \bigcap_{i=1}^{n} B_i$.

A kind of forward greedy reduction algorithm is used for the neighborhood decision table in this work, as is shown in the following Fig. 2, where ε is the threshold of the significance of attribute and its value is close to 0.

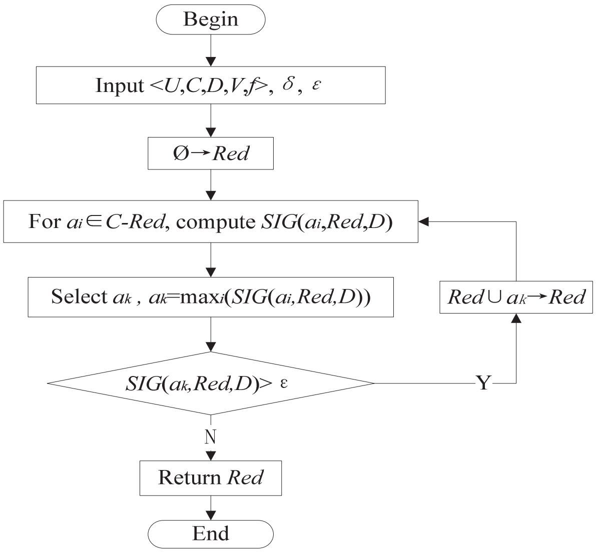

Figure 2: Reduction algorithm.

Three Types of Fatigue Stress-life Relations

Up to now, there are three types of mathematical expressions to describe the S-N curve, including Basquin [20], Langer [21] and three parameters stress-life model [22]. Among which, Basquin model is the most commonly used form, as is shown as

$$S^m N = C, \tag{13}$$

where, m and C are constants related to material types. Take logarithm on both sides, we get

$$\lg S = A + B \lg N \tag{14}$$

where， A$= \lg C / m$， B$= -1/m$.

Besides Basquin model, Langer model and the three parameters model are the other two models commonly used for fatigue analysis. The Langer model is shown as Eqs. (15) and the three parameters stress-life model is shown as Eqs. (16).

$$e^{mS} N = C \tag{15}$$

$$(S - S_f)^m N = C \tag{16}$$

In this work, three types of the fatigue stress-life relations are all used for S-N curve fitting of the aluminum alloy welded joints. Then, statistical results of the three relations are compared and the best one is selected.

NOVEL S-N CURVE MODELING METHOD

Establishment of Fatigue Database

After a review of relevant literature [23, 24], fatigue data of aluminum alloy welded joints is collected and fatigue database is built up. The total number of samples in the database is 64, and *S-N* curves are fitted on basis of these samples. Totally, there are four types of welding methods including MIG, GMAW, TIG and Manual Arc, five kinds of material types including 5083H11, AlMg4MnCr,AlMgSi1,NP5/6 and HP30, four kinds of plate thicknesses including 10*mm*,2.5*mm*,3*mm* and 4.8*mm*, three kinds of *Ratio* including 0, 0.1 and 0.5, two kinds of load types including 4B and T, three types of joint types including TJ:p, LJ_DS:p, and SJ_DS:p. Limited to the space, only part of the experiment data is shown as below in Tab.1. It only includes fatigue data of crack initiation from weld toe, excludes that from weld and base metal.

Material type	**Welding method**	**Thickness (*mm*)**	**Ratio**	**Load type**	**Joint type**	**Nominal stress (*MPa*)**	**Eq.structural stress range (*MPa*)**	**Life Cycles**
5083H11	MIG	10	0.1	4B	TJ:p	120	161	62700
5083H11	MIG	10	0.5	4B	TJ:p	90	121	213750
AlMg4MnCr	GMAW	2.5	0.1	T	LJ_SS:p	45	174	31260
AlMg4MnCr	GMAW	2.5	0.1	T	LJ_SS:p	35	135	52040
AlMgSi1	TIG	3	0	T	LJ_DS:p	53	160	85920
AlMgSi1	TIG	3	0	T	LJ_DS:p	32	97	323460
NP5/6	Manual Arc	4.8	0	T	SJ_DS:p	46	116	188000
NP5/6	Manual Arc	4.8	0	T	SJ_DS:p	31	77	1250000
HP30	Manual Arc	4.8	0	T	SJ_DS:p	62	155	188000
					……			

Table1: Part fatigue data of the aluminum alloy welded joints.

Fitting of S-N Curves

According to the three fatigue stress-life relations mentioned in the three types of fatigue stress-life relations section, *S-N* curve fitting results using the nodal force based structural stress are obtained in Fig. 3. Comparison of goodness-of-fit statistics including *SSE*, *R-square*, *Adjusted R-square* and *RMSE* is shown in Tab. 2.

Where, sum of squares due to error measures the total deviation of the response values from the fit to the response values. It is also called the summed square of residuals and is usually labeled as *SSE*.

$$SSE = \sum_{i=1}^{n} \omega_i (y_i - \hat{y}_i)^2, \tag{17}$$

R-square is the square of the correlation between the response values and the predicted response values. It is also called the square of the multiple correlation coefficients and the coefficient of multiple determinations. *R-square* is defined as the ratio of the sum of squares of the regression (*SSR*) and the total sum of squares (*SST*). *SSR* is defined as

$$SSR = \sum_{i=1}^{n} \omega_i (\hat{y}_i - \bar{y})^2, \tag{18}$$

SST is also called the sum of squares about the mean, and is defined as

$$SST = \sum_{i=1}^{n} \omega_i (y_i - \bar{y})^2, \tag{19}$$

Where, $SST = SSR + SSE$. Given these definitions, R-square is expressed as

$$R\text{-}square = \frac{SSR}{SST} = 1 - \frac{SSE}{SST}, \tag{20}$$

R-square can take on any value between 0 and 1, with a value closer to 1 indicating that a greater proportion of variance is accounted for by the model.

The *adjusted R-square* statistic is generally the best indicator of the fit quality when you compare two models that are nested, that is, a series of models each of which adds additional coefficients to the previous model.

$$\text{adjusted R-square} = 1 - \frac{SSE(n-1)}{SST(\nu)}, \tag{21}$$

where the residual degrees of freedom ν is defined as the number of response values *n* minus the number of fitted coefficients *m* estimated from the response values. The *adjusted* R-*square* statistic can take on any value less than or equal to 1, with a value closer to 1 indicating a better fit. Negative values can occur when the model contains terms that do not help to predict the response.

Root mean squared error (*RMSE*) is also known as the fit standard error and the standard error of the regression. It is an estimate of the standard deviation of the random component in the data, and is defined as

$$RMSE = \sqrt{MSE} = \sqrt{\frac{SSE}{\nu}} \tag{22}$$

Similar with *SSE*, an *MSE* value closer to 0 indicates a fit that is more useful for prediction.

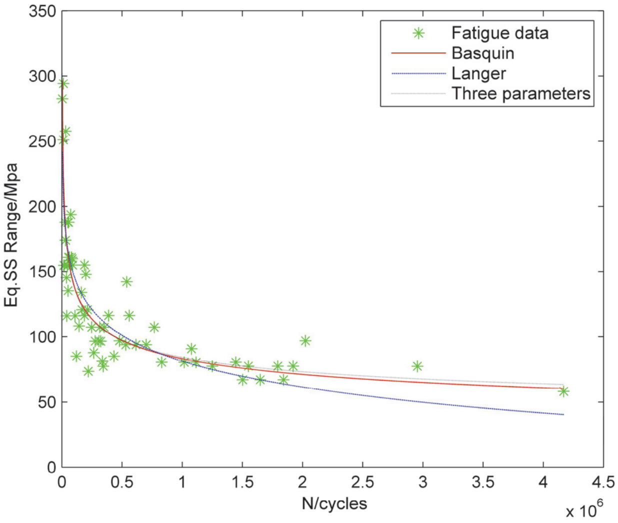

Figure 3: Fitting results of the three relations.

	Basquin	Langer	Three parameters
SSE	4.043e+04	4.853e+04	4.03e+04
R-square	0.7661	0.7192	0.7668
Adjusted *R-square*	0.7623	0.7147	0.7592
RMSE	25.54	27.98	25.7

Table 2: Goodness-of-fit statistics.

As could be seen from Fig. 3 and Tab. 2, the fitting effect of Langer is the worst thus it isn't suitable for this group of fatigue data. Fitting results of Basquin and three parameters are close. From the perspective of higher application security, we choose the Basquin model as the fatigue stress-life relation for this group of fatigue data of aluminum alloy welded joints. Thus in this paper, Basquin model is used and the mean *S-N* curve is fitted by the least square method based on the nodal force based structural stress according to the collected fatigue data of aluminum alloy welded joints. Scatter of fatigue data based on nominal stress and the mean *S-N* curve based on equivalent structural stress in log-log coordinates are shown in Fig. 4 and Fig.5. The goodness-of-fit statistics including *SSE, R-square, adjusted* R-*square* and *RMSE* by using nodal force based structural stress are shown in Tab. 3.

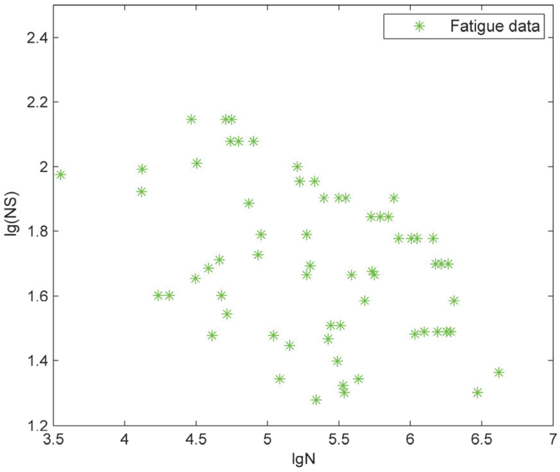

Figure 4: Fatigue data scatter based on nominal stress.

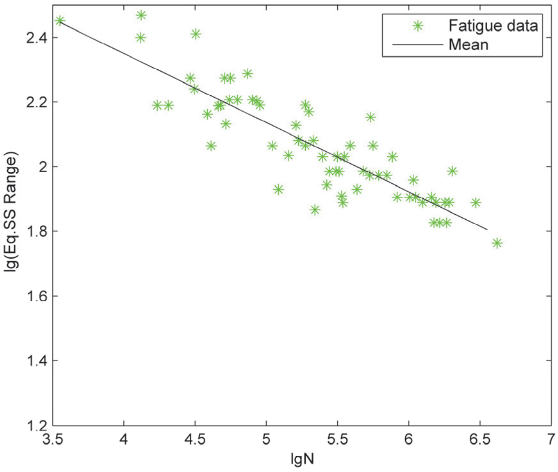

Figure 5: *S-N* curve based on Eq. SS Range.

	Mean
SSE	0.388
R-square	0.772
Adjusted R-square	0.7683
RMSE	0.0791

Table 3: Goodness-of-fit statistics by using Eq.SS Range.

In the Eq. SS method, the structural stress is analyzed by nodal forces approach by considering the welded toe structural stress concentration effect. The stress calculation results are insensitive to the finite element type, mesh shape and dimensions in this method, so the welded toe structural stress concentration conditions for different welded joints could be distinguished effectively. The stress parameter relevant to the fatigue lives of welds directly are defined by using the fracture mechanics and the formula for Eq.SS transformation is determined subsequently. Based on the method of stress calculation and transformation, the fatigue data of aluminum alloy welded joints are analyzed. Then the single fatigue design master *S-N* curve, which is necessarily important in the fatigue strength assessment and life prediction, is established as in Fig. 5. As could be seen from Fig. 4 and Fig. 5, the dispersion of the fatigue data has been reduced when Eq. structural stress is used compared with using nominal stress. Such problems as how to select *S-N* curves and to accurately calculate the stress existed in the nominal stress method have been overcome when the nodal force based structural stress method is used.

Features Extraction Based on Neighborhood Rough Set Theory

Besides the main stress factor, fatigue life of welded joints is also affected by other factors such as the geometry of the welded joints, material types, welding method, load type, Ratio, thickness of the plate et al.. While at present, the analysis of the related factors that influence the fatigue life of the welded joints is generally independent and the correlation between each other is rarely studied. We have tried successfully to establish the mathematical model of the influence of related factors on fatigue life by classical rough set theory [25, 26], where attribute discretization algorithm is used for the continuous attribute. Due to the use of discretization algorithm for continuous attributes inevitably causes the loss of information, in this work, neighborhood rough set theory is used to deal with the continuous attribute for features extraction, according to which fatigue characteristics domain is determined and *S-N* curve in each domain is fitted.

On basis of the fatigue database established as Tab.1, the neighborhood decision table S is built up, which could be expressed as $S=(U,C,D,V,f)$. Where U is the data set of all the aluminum alloy welded joints called the universe, $A=C\cup D$ is a non-empty finite set of attributes, C is a non-empty finite set of the factors which influence the fatigue life of the aluminum alloy welded joints called condition attributes, and D is the set of the fatigue life called decision attribute. Each attribute $a\in A$ can be viewed as a function that maps elements of U into a set V_a. The set V_a is called the value set of attribute a. In the decision table S, each row describes a solder fatigue life test sample of the aluminum alloy welded joints and each column indicates an attribute. Considering the advantages of the nodal force based structural stress, take it as the stress factor that influence the fatigue life of the aluminum alloy welded joints in S. Thus the fatigue decision system S of the aluminum alloy welded joints is built up in this paper, where the condition attributes of S is C={material type(C_1), welding method(C_2), thickness(C_3,mm), Ratio(C_4), load type(C_5), joint type(C_6), Eq. structural stress(C_7, MPa)}, the decision attribute of S is D={lgN}. Part data of the decision table is shown as Tab. 4.

U	**Condition attributes**							**Decision attributes**
	C_1	**C_2**	**C_3**	**C_4**	**C_5**	**C_6**	**C_7**	**D**
1	5083H11	MIG	10	0.1	4B	TJ:p	161	4.7973
2	5083H11	MIG	10	0.5	4B	TJ:p	121	5.3299
3	AlMg4MnCr	GMAW	2.5	0.1	T	LJ_SS:p	174	4.4950
4	AlMg4MnCr	GMAW	2.5	0.1	T	LJ_SS:p	135	4.7163
5	AlMgSi1	TIG	3	0	T	LJ_DS:p	160	4.9341
6	AlMgSi1	TIG	3	0	T	LJ_DS:p	97	5.5098
7	NP5/6	Manual Arc	4.8	0	T	SJ_DS:p	116	5.2742
8	NP5/6	Manual Arc	4.8	0	T	SJ_DS:p	77	6.0969
9	HP30	Manual Arc	4.8	0	T	SJ_DS:p	155	5.2742
					……			

Table 4: Part data of the decision table.

In the experiment, $\delta(C_i)=STD(C_i)/\lambda$, $\lambda=2$, $\varepsilon=0.01$ .After attributes reduction, the reduction result of the neighborhood decision system of the aluminum alloy welded joints is obtained, namely{ C_1(Material type), C_4(Ratio), C_7(Eq. structural stress)}.

S-N Curve Modeling Based on Fatigue Characteristics Domain

In Eq. SS method, one master S-N curve is obtained at last thus the uncertain problem of S-N curve choice has been overcome. Compared with the nominal stress method, dispersion of the fatigue data samples in the nodal force based structural stress method has been greatly reduced. But from the design point of view, the dispersion degree of the fatigue data samples indicated by the value of $RMSE$ is still relatively high, which is about 0.0791 here.

In this work, a novel S-N curve modeling method is put forward by using the nodal force based structural stress. In the proposed method, fatigue characteristics domains are divided on basis of the reduction result of the welding fatigue decision system obtained by using rough set granularity theory. Subsequently, S-N curves are fitted on each fatigue characteristics domain rather than on the whole domain. As a result, a series of S-N curves instead of only one master S-N curve are obtained at last. In the process of welding fatigue design, we should also design according to each fatigue characteristics domain rather than in the whole fatigue domain.

The fatigue characteristics domains of the aluminum alloy welded joints are determined according to the reduction result, that is, {C_1(Material type), C_4(Ratio), C_7(Eq. structural stress)} obtained by using rough set theory. All the fatigue data samples are divided into 6 series from S_1 to S_6, where S_1: $\{X \in U \mid X_{C1=5083H11}$ and $X_{C4=0.1}\}$ $S2$: $\{X \in U \mid X_{C1=5083H11}$ and $X_{C4=0.5}\}$ $S3$: $\{X \in U \mid X_{C1=AlMg4MnCr}$ and $X_{C4=0.1}\}$ $S4$: $\{X \in U \mid X_{C1=AlMgSi1}$ and $X_{C4=0}\}$ $S5$: $\{X \in U \mid X_{C1=NP5/6}$ and $X_{C4=0}\}$ $S6$: $\{X \in U \mid X_{C1=HP30}$ and $X_{C4=0}\}$, among which, each series of fatigue test samples corresponds to a specific fatigue characteristics domain and the determine of the fatigue characteristics domains is shown as Fig. 6.

Fitting the S-N curve in each fatigue characteristics domain and 6 Mean S-N curves from Mean$_1$ to Mean$_6$ are obtained as is shown in Fig. 7. As could be seen from Fig. 7, fatigue data with the same characteristics scatter in a relatively independent area. For example, the scatter of green asterisk '*' which denote all the fatigue samples whose material name is 5083H11 and Ratio is 0.1 in the fatigue experiment are relatively concentrated, corresponding with characteristic domain S_1. Accordingly, the whole fatigue test samples of aluminum alloy welded joints are divided into six fatigue characteristics domains from S_1~S_6. The dispersion degree of the fatigue samples are further reduced when S-N curves are fitted according to each series instead of the whole fatigue samples. Six mean S-N curves from Mean$_1$~Mean$_6$ are obtained in the proposed method at last. The coefficients of the Basquin equation of Mean and Mean$_1$~Mean$_6$ are shown in Tab. 5.

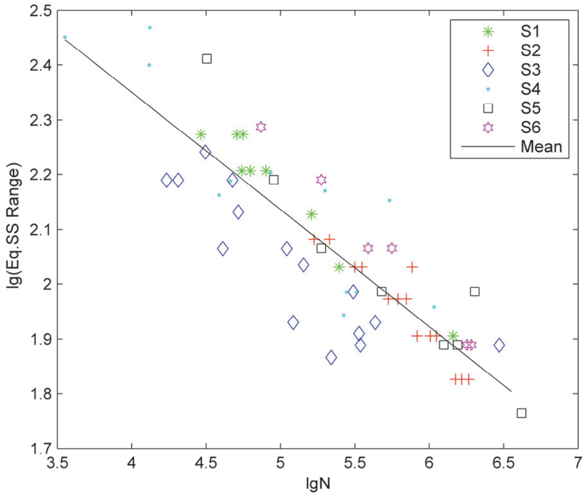

Figure 6: Determine of the fatigue characteristics domains.

	Mean	Mean$_1$	Mean$_2$	Mean$_3$	Mean$_4$	Mean$_5$	Mean$_6$
A	3.206	3.369	3.483	2.972	3.268	3.509	3.689
B	–0.2139	–0.2398	–0.2626	–0.1844	–0.2213	–0.2607	–0.2866

Table 5: Coefficients of the Basquin equation

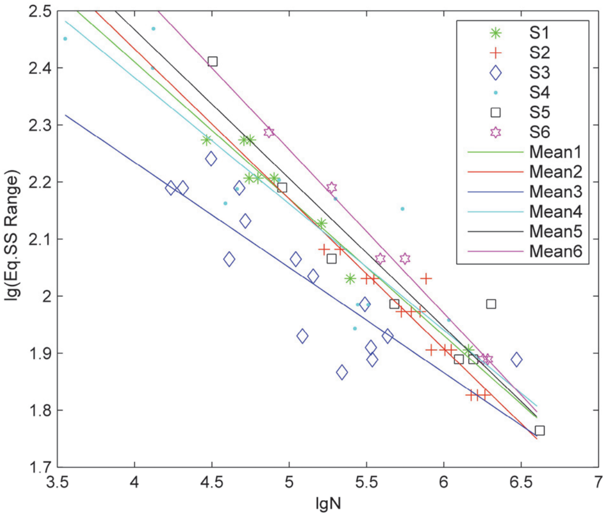

Figure 7: *S-N* curve modeling based on the fatigue characteristics domain

In the process of statistical analysis, the goodness-of-fit statistics including *SSE, R-square, adjusted R-square* and *RMSE* of Mean$_1$-Mean$_6$ are shown in Tab. 6.

	Mean$_1$	Mean$_2$	Mean$_3$	Mean$_4$	Mean$_5$	Mean$_6$
SSE	0.0068	0.0129	0.0648	0.08228	0.0291	0.0013
R-square	0.9465	0.8795	0.7263	0.7877	0.8983	0.9897
Adjusted R-square	0.9389	0.8695	0.7053	0.7665	0.8813	0.9871
RMSE	0.0312	0.0328	0.0706	0.09071	0.0696	0.0181

Table 6: Goodness-of-fit statistics of Mean$_1$-Mean$_6$.

Experiment Results and Analysis

As could be seen from Tab. 3 and Tab. 6, the values of *SSE* from Mean_1 to Mean_6 based on the fatigue characteristics domain are all smaller than that of the Mean in the whole domain. Except Mean_3, the value of *R-square* of Mean_1 to Mean_6 is closer to 1 than Mean in the whole domain. Each value of *Adjusted R-square* of Mean_1 to Mean_6 is closer to 1 than Mean in the whole domain. Except Mean_4, the value of *RMSE* of Mean_1 to Mean_6 is closer to 0 than Mean in the whole domain, which indicates that the scatter degree of the fatigue data is further reduced when fatigue characteristics domain is divided and *S-N* curves are fitted in each independent domain. Thus fatigue life prediction by using *S-N* curve modeling method based on the fatigue characteristic domains would be more accurate than that by traditional master *S-N* curve.

CONCLUSION

In this work, on one hand, nodal force based structural stress is used in the S-N curve modeling method based on the fatigue characteristics domain, thus such problems as how to accurately select the S-N curve and to calculate the stress that existed in the traditional nominal stress method have been overcome in the proposed method. The fatigue characteristics domain is determined by using rough set granularity theory, which can achieve knowledge acquisition relying only on the data itself without depending on the prior knowledge or experience knowledge.

On the other hand, the entire fatigue test samples of aluminum alloy welded joints are divided into 6 characteristics domains according to the attributes reduction result of the rough set theory, and the Mean *S-N* curves form Mean_1 to Mean_6 are fitted respectively. As could be seen from Tab. 6, the value of *SSE* which indicates the dispersion in each fatigue characteristics domain is significantly lower than that of the single master *S-N* curve obtained in the nodal force based structural stress method. Statistical analysis results show that dispersion of the fatigue data is reduced while the proposed *S-N* curve modeling method based on fatigue characteristics domain is used. Therefore, compare with the single master *S-N* curve in the nodal force based structural stress method, to determine the design *S-N* curve according to the fatigue characteristics domain is more targeted with a lower dispersion degree. Thus the fatigue calculation results will be more accurate if the proposed *S-N* curve modeling method based on the fatigue characteristics domain is used.

Future work will be concentrated on the aspects of the application of the proposed *S-N* curve modeling method based on fatigue characteristics domain in the practical engineering practice.

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