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MINIMUM STRENGTH MATCHING COEFFICIENT ANALYSIS OF X80 PIPELINE WELDED JOINTS UNDER DIFFERENT STRAIN DEMAND: A NUMERICAL STUDY

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Abstract. *Girth welds are a key weakness of oil and gas pipelines due to the dual discontinuity of geometry and material properties. In this paper, the double V groove welded joints of a large diameter 1422 mm X80 pipeline is taken as the research object, and the numerical simulation model of ultimate tensile strain with root welding fusion line crack is established. The model is parameterized based on PYTHON and ABAQUS co-simulation, and the effects of yield-tensile strength ratio of base metal, softening rate of heat affected zone and strength matching coefficient of weld material on the ultimate tensile strain of girth weld are analyzed quantitatively. Meanwhile, in order to facilitate engineers to obtain the ultimate tensile strain, a prediction model of the ultimate tensile strain of welded joints is established based on PSO-SVR hybrid machine learning method, and the correlation coefficient is more than 99%. On this basis, the minimum strength matching coefficient table of weld zone is obtained to meet the 0.5% -1% strain demand, which provides guidance for designing welding parameters of large diameter X80 pipeline welded joints based on strain.*

1 INTRODUCTION

Due to the double discontinuity of the position of the pipe girth weld in the geometry and material partition, the deformation bearing capacity of the girth welded joints is seriously weakened, and the girth welded joints have become a key weak link in the oil and gas pipeline [1-3]. In recent years, scholars have carried out a lot of research on the ultimate strain ability of oil and gas pipeline girth welded joints [4-17]. With the development of the ultimate tensile strain study of pipelines, several mature ultimate models for tensile strain have gradually been developed. The Pipeline Research Council International (PRCI) and the Center for Reliable Energy Systems (CRES) have established PRCI-CRES ultimate tensile strain prediction models for different analysis needs based on the criteria of cracking and ductility instability propagation [18-21]. ExxonMobil conducted an in-depth study of the crack propagation driving force from the perspective of a small-scale SENT test to a full-scale test multi-scale, and proposed a pipeline ultimate tensile strain prediction model [22-27]. In Appendix C of the Canadian standard CSA Z662 [28], a critical analysis method for pipeline engineering based on strain gauge design is formulated according to the research method proposed by PRCI, and the ultimate tensile strain of pipelines containing surface crack defects and buried crack defects is proposed within the limited parameters.

The above studies comprehensively consider the influence of the geometry of pipeline and weld, properties and strength matching of the material, type and size of the defect on the ultimate tensile strain of pipeline, which provide important guidance for the safety evaluation of welded joints with cracks. However, the calculation model of the ultimate strain capacity of the pipeline proposed in the above studies cannot consider the strength undermatch of the weld due to the increasement of the base metal`s strength and the difficulty of synchronous improvement of the metal strength of the weld, and cannot be applied to the fully automatic welding double-V composite groove. Therefore, aiming at the X80 1422 mm large-diameter pipeline composite groove girth welded joints of the China-Russia Eastern pipeline is assessed through the parametric programming of the finite element model and parallel batch calculation. The effects of paraments including the base metal yield ratio hereinafter referred to λ, the softening rate in the heat-affected zone hereinafter referred to μ, and the matching coefficient of weld strength hereinafter referred to ζ on the ultimate tensile strain of the girth welded joints are quantitatively analyzed in the above method. The PSO-SVR prediction model of ultimate tensile strain of high-steel grade pipe girth welded joints is established. Based on the recommended critical fracture toughness value of the project, the control requirements of the strength matching coefficient of the weld area and the prediction model of the minimum strength matching coefficient corresponding to the minimum strain demand of 0.5% of the project and the large strain demand of pipelines in geological disaster areas/mountainous areas are determined, which provide guidance for the parameter design and applicability evaluation of the X80 pipeline girth welded joints based on strain.

2 METHOD AND VERIFICATION

2.1 Finite element model

In this paper, a numerical simulation model of the ultimate tensile strain of a large-diameter X80 pipe girth welded joints containing root welding fusion line cracks is established with a large-diameter 1422 mm with wall thickness of 21.4mm fully automatic welding double-V composite groove as the object of study. Consider the complete geometry of the weld zone, including the base material, heat-affected zone, filler weld, and root welding four regions, and determine the shape of the welded joint and the dimensions of each material region based on macroscopic metallography. The model comprehensively considers the double discontinuity of the girth welded joints in terms of geometry and material structure, and believes that there is a maximum misalignment of 3mm allowed by the girth welded joints, and there is an annular surface crack (length 25 mm and depth 2 mm) [28] at the fusion line position of the root welding and heat affected zone, and the crack propagation driving force and ultimate tensile strain of the girth welded joints under the most severe structural conditions are obtained based on the static crack cracking criterion [29, 30].

Considering that the pipe is subjected to internal pressure and tensile or bending load, according to the symmetry of the structure and load, a 1/2 analysis model is established in order to improve the calculation efficiency. According to API 579 Appendix B [30], the hole method is used to describe the crack tip passivation behavior, while the local mesh encryption is used near the crack surface to improve the accuracy of the calculation results. The model has a total length of 6 m and is simulated using an eight-node reduced integration cell (C3D8R). Symmetry constraints are used for the symmetry plane, and the two end planes of the pipe are coupled to the corresponding reference points by kinematic coupling to ensure that both ends of the pipe always lie in one plane during the deformation process. The model is divided into two loading steps. Firstly, internal pressure is applied to the pipe, and secondly, displacement load is applied to the pipe to simulate tensile or bending action (Figure 1).

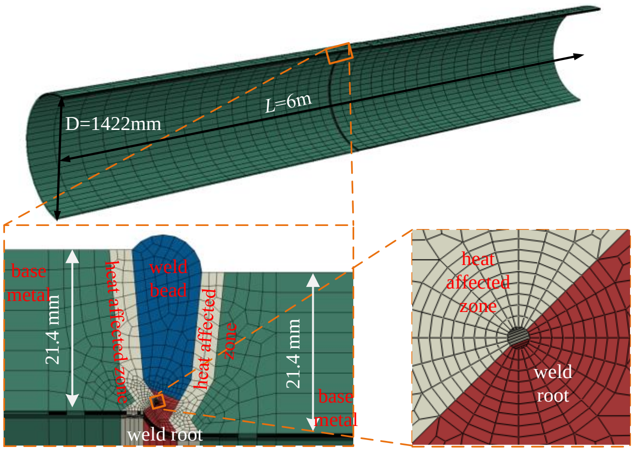

Figure 1: Finite element model.

Considering that the tensile strength of the base metal is 625 MPa, λ is 0.85~0.93. For the softening effect of the heat-affected zone, it is believed that it has the same hardening characteristics and yield ratio as the base metal, and μ is defined as one minus the ratio of tensile strength of the heat-affected zone to the tensile strength of the base metal, and μ range from 0%~10%. It is believed that both are in line with the Ramberg-Osgood constitutive equation [31]. In this paper, the ratio of the tensile strength of the weld zone to the tensile strength of the base metal is used to define the strength matching coefficient ζ of the weld area. The ζ [28, 32, 33] value range of the strength matching coefficient is 0.6~1.3, and the stress-strain curve of the weld area under different strength matching coefficients is determined based on the calculation formula of the stress-strain relationship (no yield platform) of the CRES weld area [33]. For the root welding zone, the ER70S-G root welding material properties (yield strength 509 MPa, tensile strength 536 MPa) were selected and determined using the same stress-strain curve equation as the weld zone [33].

2.2 Model verification

In this paper, the author verifies the reliability and rationality of the finite element model and simulation method based on the full-scale wide plate tensile test and numerical simulation inversion study (Figure 2) [3].

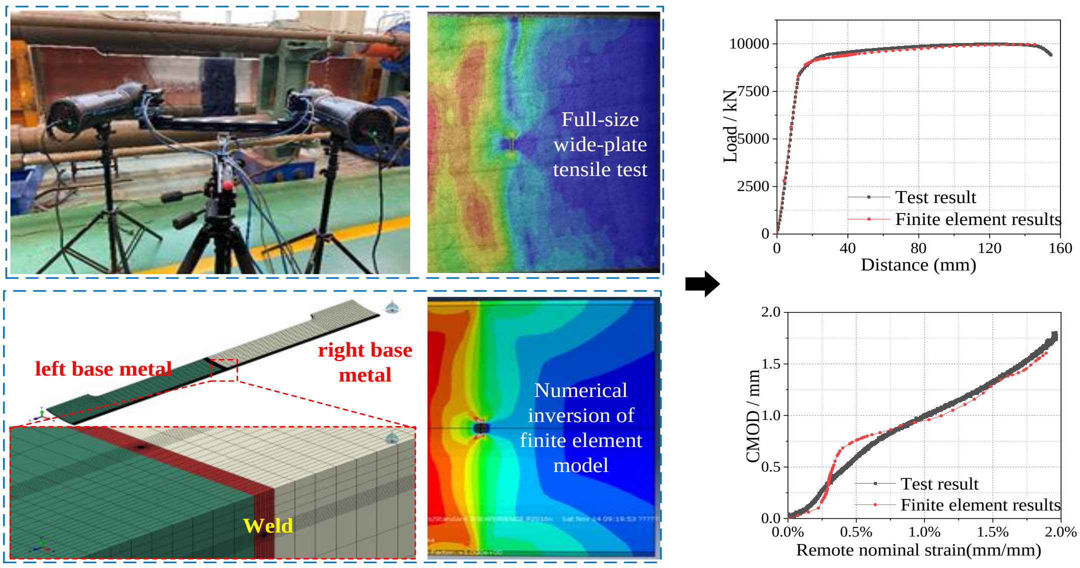

Figure 2: Full-scale wide plate tensile test and finite element model numerical inversion diagram [3].

The model comprehensively considers the double discontinuity of the girth welded joints in geometry and material structure. It is considered that the girth welded joint has a maximum 3 mm misalignment allowed by the project, and there is a circumferential surface crack at the fusion line between the root welding and the heat affected zone (25 mm long and 2 mm deep). Based on the static crack initiation criterion[29,30], the crack propagation driving force and ultimate tensile strain of the girth welded joints are obtained under the most severe structural conditions.

3 SIMULATION RESULT AND ANALYSIS

3.1 Driving forces of crack growth and ultimate tensile strain

Through numerical simulation calculation, the relationship between CTOD and strain of crack tip opening displacement under different material combination conditions is shown in Figure 3. It can be seen that under the condition of small strain (less than 0.25%), the overall effect of the girth welded joints on the driving force of crack propagation is still in the elastic stage, and the effect of λ, μ, and ζ on the driving force of crack propagation is small and negligible. When the strain is greater than 0.25%, the influence of the parameters of each material partition on the crack propagation driving force begins to appear.

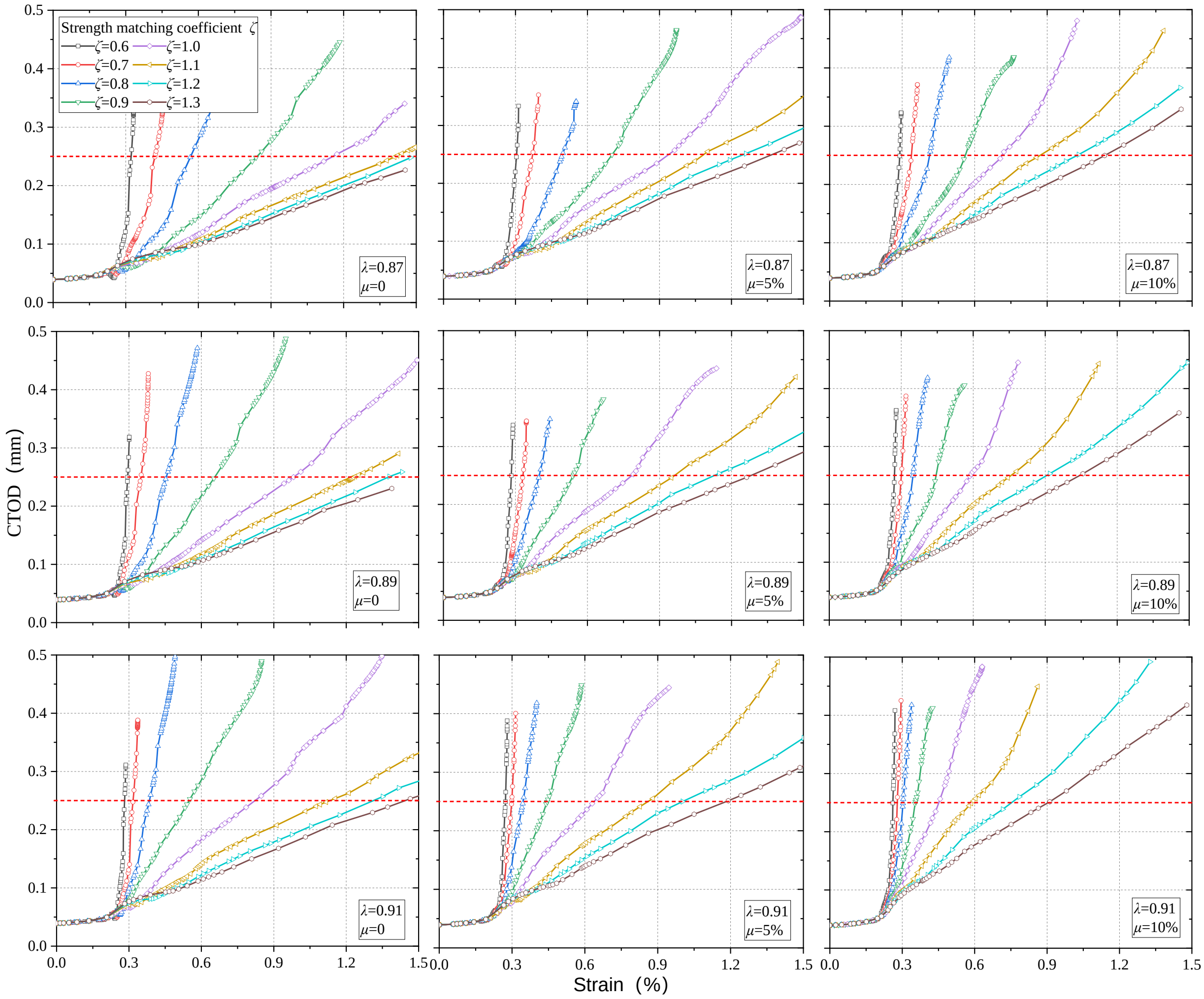

Figure 3: Variation of CTOD with strain under different combination conditions.

Under the same conditions of μ and ζ, the smaller λ is, the smaller the crack tip opening displacement under the same strain conditions is, and the greater the ultimate tensile strain under the same critical CTOD conditions is. It is found that the softening effect of the heat affected zone significantly reduces the strain bearing capacity of the girth welding joints. Under the same condition of λ and ζ, with the increasement of the softening rate of the heat-affected zone, the crack propagation driving force becomes larger, and the ultimate tensile strain of the girth welded joints decreases. At the same time, it can be found that the softening of the heat affected zone reduces the ultimate tensile strain of the ring welded joint, which is more obvious under the condition of high strength matching.

Strength undermatch condition (ζ=0.6/0.7/0.8/0.9) crack propagation driving force with strain increases exponentially, A small strain increment causes the crack tip opening displacement to exceed the allowable critical CTOD value, which is due to the 3mm misalignment of the girth welded joints and the strength undermatch combination, resulting in greater deformation of the weld area, and rapid opening and deformation of the crack surface; With the increasement of ζ of the weld area, the CTOD of the girth welded joints decreased, indicating that the increase of ζ of the weld area has a good improvement effect on alleviating the opening deformation of the crack surface.

3.2 Prediction of ultimate tensile strain of girth welded joints

Taking the recommended 0.25 mm[34-39] as the allowable critical CTOD value, the critical ultimate tensile strain of the ring welded head of high-steel grade pipes under different material combinations is shown in Figure 4. It can be found that reducing yield-tensile strength ratio of base metal λ and softening rate of heat effect zone μ, and increasing strength matching coefficient of the weld area ζ have an effect on improving the overall strain bearing capacity of the girth welded joints. The smaller the yield ratio of the base metal λ is, the more obvious the weakening effect of the strength undermatch strain ability in the weld area is. The weakening effect of the increase of the yield ratio of the base metal λ and the deepening of the softening rate of the heat-affected zone μ are more obvious under the condition of high strength matching.

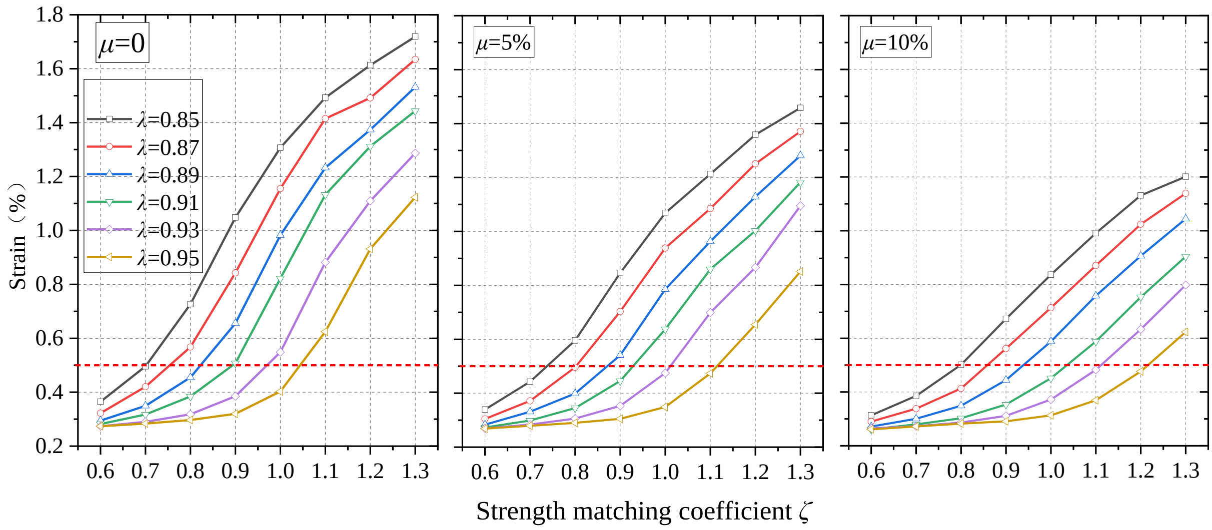

Figure 4: Effect of different combination conditions on critical limit tensile strain.

Based on the numerical simulation results of the ultimate tensile strain of the girth welded joints of high-grade pipeline with cracks, the initial values of the penalty function c and the kernel function parameter g in a certain range are determined by cross-validation method with the idea of normalization. Based on the particle swarm optimization (PSO) algorithm, the parameters c and g are optimized. The parameter optimization is completed when the mean square error (MSE) between the predicted value and the finite element calculation value is less than or equal to 0.0001. Then the support vector regression (SVR) is trained by the optimal value of the parameters, and the prediction results are obtained and output. The predicted value is inversely normalized. The output means square error MSE and the output regression coefficient R^2 are determined by comparing the predicted value with the finite element calculation value.

As shown in Figure 5, it is the result of training the ultimate tensile strain database of girth welded joints based on PSO and SVR, and the correlation coefficient R is 99.8917%. It can be seen that the error between the prediction results and the numerical simulation model is less than 10%, and the error of most prediction results is less than 5%.

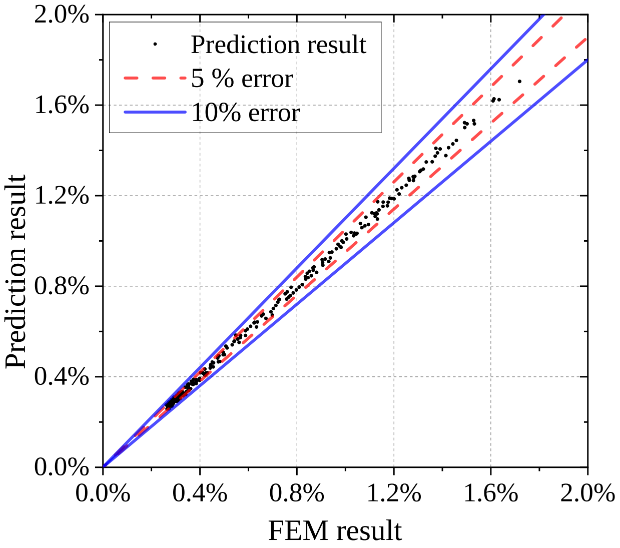

Figure 5: Prediction of ultimate tensile strain PSO-SVR.

4 MATCHING COEFFICIENT OF GIRTH WELDED JOINTS

The welding strength matching coefficient ζ has a great influence on the crack propagation driving force and ultimate tensile strain of pipeline welded joints, which provides guidance for clarifying the welding parameters and providing guidance for the applicability evaluation of the girth weld under the minimum strain demand of the project and the large strain demand of geological disaster areas/mountainous areas. It obtains a 25 mm×2 mm surface type crack defect with a diameter of 1422 mm and a wall thickness of 21.4 mm for pipelines with a fully automatic welding process with a misalignment of 3 mm and a 25mm×2mm surface type crack defect at the position of the fusion line in the root welding and heat affected zone. The minimum strength matching coefficient ζ_{min} under the conditions of fracture toughness CTOD value of 0.25 mm, 12 MPa operating internal pressure, and tensile load, to meet different strain demand ε_d demand is shown in Table 1.

Table 1: Minimum strength matching coefficient.

λ	μ	minimum strength matching coefficient ζ min under different strain demand ε_d					
		ε_d=0.5%	ε_d=0.6%	ε_d =0.7%	ε_d =0.8%	ε_d =0.9%	ε_d =1.0%
	0	0.70	0.75	0.79	0.82	0.85	0.89
	2%	0.71	0.77	0.81	0.85	0.88	0.92
0.85	5%	0.74	0.8	0.84	0.88	0.92	0.97
	7%	0.76	0.82	0.87	0.92	0.97	1.01
	10%	0.8	0.86	0.92	0.98	1.04	1.11
0.87	0	0.74	0.78	0.85	0.88	0.92	0.95

	2%	0.78	0.83	0.87	0.91	0.94	0.97
	5%	0.8	0.85	0.9	0.94	0.98	1.04
	7%	0.83	0.88	0.94	0.98	1.03	1.08
	10%	0.86	0.93	0.99	1.06	1.12	1.18
	0	0.82	0.87	0.91	0.94	0.97	1.01
	2%	0.84	0.89	0.93	0.96	1.00	1.04
0.89	5%	0.87	0.92	0.97	1.01	1.06	1.12
	7%	0.90	0.95	1.00	1.06	1.12	1.18
	10%	0.94	1.01	1.07	1.13	1.20	1.27
	0	0.87	0.93	0.96	0.99	1.03	1.06
	2%	0.91	0.95	0.99	1.03	1.07	1.11
0.91	5%	0.93	0.98	1.03	1.07	1.13	1.20
	7%	0.96	1.03	1.08	1.14	1.19	1.26
	10%	1.02	1.11	1.17	1.23	1.29	/
	0	0.97	1.02	1.05	1.08	1.11	1.16
	2%	0.99	1.03	1.07	1.11	1.16	1.21
0.93	5%	1.01	1.06	1.10	1.16	1.21	1.26
	7%	1.05	1.12	1.17	1.23	1.28	/
	10%	1.12	1.18	1.24	1.30	/	/

Note: In the bottom line part of the table, in order to meet the control degree of the actual strength matching coefficient of the project ($\zeta \leq 1.1$), the yield ratio λ of the base metal and the softening rate μ of the heat affected zone are combined; the slash part is the case where the critical strength matching coefficient $\zeta \geq 1.3$.

It can be seen that under the conditions of $\lambda \leq 0.93$ and $\mu \leq 10\%$, the strength matching coefficient ζ of pipeline welded joints with a composite groove diameter of 1422 mm in the automatic welding process should be controlled at 1.12 to meet the minimum strain demand of 0.5% of the engineering requirements. Under the condition of $\mu \leq 10\%$, the control degree of the actual strength matching coefficient of the project ($\zeta \leq 1.1$) is the restriction, and $\lambda \leq 0.91$ can be controlled to ensure that the minimum strain demand of the project can be met; if the yield ratio of the base metal is controlled to $\lambda \leq 0.89$, the strain capacity of the composite groove welded joint can reach 0.7%. Figure 6 shows the prediction results of the minimum strength matching coefficient of the ring welding joint, and the correlation coefficient R is 99.8595%. It can be seen that the overall error between the prediction results and the calculation results of the numerical simulation model is less than 5%, and the error of most prediction results is less than 2%.

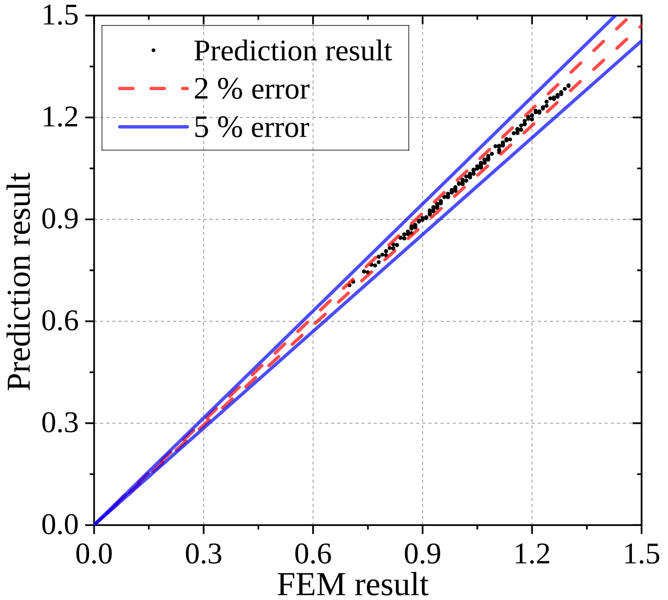

Figure 6: Prediction of minimum strength matching coefficient.

5 CONCLUSION

Through the verified numerical simulation model of the ultimate tensile strain of the high-precision and high-grade pipe girth welded joint, the following conclusions are obtained for the fully automatic welding double V groove girth welded joints with a diameter of 1422 mm X80 with a 3 mm misalignment in the eastern route of China and Russia.

(1) Reducing yield-tensile strength ratio of base metal λ, reducing softening rate of heat effect zone μ, and increasing strength matching coefficient ζ of the weld area all have an improving effect on the overall strain bearing capacity of the girth welded joints.

(2) The smaller the yield-tensile strength ratio of base metal λ, the more obvious the weakening effect of the strength undermatch strain capacity in the weld area; The weakening effect of the increase of the yield-tensile strength ratio of base metal λ and the deepening of the softening rate of the heat-affected zone μ are more obvious under the condition of high strength matching.

(3) A limit tensile strain prediction model considering the strength undermatch of the weld area and suitable for the double V groove girth welded joints is proposed, which provides a reference for the applicability evaluation of the actual automatic welding joint in the project.

(4) Under the condition that the actual yield-tensile strength ratio of base metal ($\lambda \leq 0.93$) and the softening rate of the heat-affected zone are $\mu \leq 10\%$, the strength matching coefficient of the pipeline welded joint with a composite groove diameter of 1422 mm in the automatic welding process should be controlled at 1.12 to meet ζ the minimum strain demand of 0.5% of the engineering requirements; Under the condition that the actual strength matching coefficient control degree of the project ($\zeta \leq 1.1$) and the softening rate of the heat-affected zone are $\mu \leq 10\%$, the yield-tensile strength ratio of base metal $\lambda \leq 0.91$ needs to be controlled to meet the minimum strain demand of the project. The analysis obtained the control requirements of the ζ strength matching coefficient of the weld area of the X80 pipeline double V-shaped groove girth welded joints under different strain demand under different base metal yield ratio and heat-affected zone softening rate, which provides guidance for the design of fully automatic welding parameters.

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